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Enhancing Undergraduate Labs for Experiential Learning

Can we design labs to better teach employable skills in core mechanical engineering courses?

by

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Abstract

The learning laboratory is a common and important component of contemporary Canadian post-secondary engineering education, intended to relate practice and theory, provide a practical experience in what can be a largely theoretical program, and motivate students. However, a significant minority of mechanical and manufacturing engineering students in a third-year materials science course at the University of Calgary have, across the last decade, reported on their end-of-course surveys that they do not perceive any connections between their laboratories and either their careers or their lectures. Simultaneously, there have been calls from local industry, the provincial government of Alberta that regulates and funds the program, and University administration for more experiential opportunities to be included in undergraduate programs to better prepare students for their future employment.

Given that engineering education is directly related to professional engineering practice, it is key that students perceive connections between their program and industrial applications. Therefore, the research question is, how can established educational scholarship be applied to undergraduate engineering laboratories in order to improve students' perception of their learning experience?

Established educational scholarship and expectations from the Government of Alberta and the University of Calgary were reviewed. Qualitative surveys were developed using this scholarship and released to University of Calgary students currently enrolled in the third-year materials science course, asking them to identify and assess learning levels in their laboratories past and present and how course actions affected their assessment. A second series of surveys was released to members of local engineering industry with experience managing students and graduates of the University program, identifying what value they see in engineering learning laboratories. Analysis of results and scholarship provided a set of recommendations for improving the student laboratory learning experience.

The core principles of these recommendations are to communicate clearly and explicitly with students, to constructively align all components of the laboratory experience, and to include hands-on participatory experiences whenever possible. Further recommendations targeted implementation of these principles in the laboratory pedagogy, within the laboratory itself as experienced by students, in the laboratory assessment,

and in laboratory facilitators such as teaching assistants and technicians.

Preface

This thesis is the original, unpublished, and independent intellectual work of the author, M. Love. The surveys described in Chapters 3 and 4 are covered under the University of Calgary's Conjoint Faculties Research Ethics Board, application identification REB21-1958, approved February 16, 2022.

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The author would also like to thank Robyn Mae Paul, who has been a partner throughout this work. Her insights into engineering education practice and research have simply been indispensable.

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Finally, the author would like to acknowledge the assistance of the University of Calgary's Conjoint Faculties Research Ethics Board. In conducting an ethics approval process of the surveys used in this work, they offered helpful ethical insights that greatly improved the veracity and ethical footing of this study.

Dedication

This work is dedicated to my parents, without whom this work or I wouldn't have been possible.

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Chapter 1

Introduction

1.1 Introduction

Undergraduate engineering programs form the foundation of professional engineering practice in Canada. In addition to years of professional experience and a demonstration of competency and integrity, professional engineers in Canada also require a bachelor's degree from a professionally accredited engineering program (Engineers Canada, n.d.-b). Accreditation is given by Engineers Canada, a composition of all the professional engineering associations in Canada (Engineers Canada, n.d.-a). In this way, engineering education and engineering practice are inextricably intertwined, with professional Canadian engineers drawn solely from individuals who have completed an accredited Canadian engineering program or an international equivalent.

Learning laboratories are a common part of Canadian engineering education. The American Society for Engineering Education, or ASEE, states that the goals of learning laboratories in undergraduate engineering education are to relate theory and practice, provide a practical experience in what can be a largely theoretical academic program, and motivate students (Feisel and Peterson, 2002).

However, feedback from mechanical engineering students at the University of Calgary indicate that learning laboratories are not meeting this goal. The University of Calgary administers end-of-semester surveys for each and every course (University of Calgary, n.d.-c). These surveys, called Universal Student Ratings of Instruction or USRIs, directly gather quantitative and qualitative feedback on the course and instructors from the enrolled students, and are the primary formal mechanism for students to offer feedback on their courses.

One of the required courses in the Department of Mechanical and Manufacturing engineering undergraduate program is a third-year materials science course. Since 2014, nearly half of students have stated on their

USRIs that they do not perceive connections between their learning laboratories and their course lectures, or between the laboratories and their future careers.

Additionally, there is a large contemporary push for undergraduate engineering education to include more experiential programming that prepares students for employment. The provincial Ministry for Advanced Education and University of Calgary administration have called for undergraduate programming to include practical hands-on experiences (Government of Alberta, 2021; Kaipainen et al., 2020).

Given this background, there is a clear need for learning laboratories in undergraduate engineering programs to include more experiential learning opportunities and be better perceived as such. An educational intervention of this kind is also an opportunity to improve the student learning experience.

There is already a contemporary effort to improve experiential learning opportunities at the University of Calgary's Schulich School of Engineering. As well, "experiential learning" does not currently have a strict formal definition. Given these factors, it was decided that a formal research effort to improve experiential learning opportunities at the University of Calgary would be redundant. It is also important to note that this study relies on an interpretivist research paradigm, which values subjective impressions of an experience. Therefore, it was decided to focus on the student learning experience rather than on experiential learning for this study.

This study is funded by the University of Calgary's scholarship for teaching and learning, a contemporary educational effort to integrate education research and teaching practice (Taylor Institute for Teaching and Learning, 2023). Therefore, this study seeks to identify established educational scholarship, verify that it has an evidentiary basis and is scientifically rigorous, and apply this scholarship to improving engineering laboratories. Given that the engineering program at the University of Calgary is a professional program that seeks to produce employment-ready graduates, and that the Canadian engineering profession is regulated by Engineers Canada, this study will focus on laboratory learning outcomes, or the skills and traits that successful students gain through the laboratories, and their relationship to employment in the engineering industry.

1.2 Research Question

Given this background, the research question is, how can established educational scholarship be applied to undergraduate engineering laboratories in order to improve students' perception of their learning experience? The final goal is to develop a methodology for applying the identified educational scholarship to undergraduate engineering laboratories, composed as a set of recommendations.

1.3 Structure of the Document

A literature review on experiential education, engineering education, and other foundational educational concepts was conducted. Documentation from the University of Calgary and the provincial Ministry for Advanced Education were also reviewed. The findings of this review are presented in Chapter 2.

Chapter 3 outlines the study approach and research design, including the study paradigm and methodology, data collection and analysis methods, ethical concerns, and the scope of this work.

Chapter 4 presents the survey results. One set of surveys was administered to University of Calgary mechanical engineering students enrolled in a mandatory third-year materials science course. An additional set of surveys was released to members of engineering industry with experience managing current students and recent graduates of the University of Calgary's engineering program.

Chapter 5 details the qualitative content analysis of the survey results, drawing from the reviewed literature.

Chapter 6 draws from the survey results, the conclusions of the analysis in Chapter 5, and further literature to develop and present the proposed revisions for engineering learning laboratories.

Chapter 7 provides a condensed form of the proposed laboratory revisions, followed by an overview and reflection on the research process and potential future work to follow up on this study.

The chapters of this work are followed by a bibliography. The anonymized student and manager survey results are presented in Appendices A and B, respectively. Appendix C presents the laboratory manual for the series of laboratories in the surveyed materials science course.

Chapter 2

Literature Review

The development of this study requires foundational knowledge in experiential learning, its applications within the context of engineering education, as well as an understanding of the expectations of the University of Calgary and the Province of Alberta regarding its application.

This chapter begins by explaining the relevant epistemologies that form the foundation of this study in Section 2.1. Section 2.2 describes the theories of learning employed in this work. The relevant frameworks for applying these theories to research are outlined in Section 2.3. Additional important definitions are provided in Section 2.4. Finally, documentation from the University of Calgary and Government of Alberta contextualizing this study is reviewed in Section 2.5.

2.1 Epistemologies

An epistemology is a theory of knowledge. Epistemologies seek to define the difference between truth and belief, to identify what makes knowledge valid, and to find how humans can attain this valid knowledge. Essentially, epistemologies are perspectives on what constitutes truth. It is important to define the epistemologies employed in this research endeavour, as they provide the criteria for what knowledge is considered true and valid when developing the study methodology and analyzing results.

Positivism, the dominant engineering paradigm, will first be explained, along with the reasons as to why it is not employed in this study. The selected alternative epistemologies, interpretivism and critical theory, will then be explored.

2.1.1 Positivism

Positivism is the dominant philosophical paradigm in engineering, and indeed in all Science, Technology, Engineering, and Mathematics or STEM disciplines (Romero et al., 2013). This is true in engineering education in post-secondary institutions, in research in engineering fields, and in the professional and private practice of engineering (Love, 1999). It is therefore important to explore this epistemology in developing this study.

A positivist epistemology states that knowledge is genuine when it is either true by definition or is positive (Macionis and Gerber, 2010). There are three elements required to understand this epistemology. First, if a statement is "true by definition" it means that the statement is derived from logic and reason. Second, "positive" here means a statement that is made factually, without a value judgement. A positive statement can be factually incorrect, such as stating that the sky is green; as long as a value judgement is not made, the statement is positive. Finally, this is an empirical philosophical theory, stating that knowledge derives from an objective sensory experience (Psillos and Curd, 2010). Other epistemologies see knowledge as deriving from other sources; rationalism views reason as the source of knowledge (Blanshard, 2022), while skepticism sees all knowledge as inherently questionable (Comesana, 2019).

Taken together, this means that positivism views knowledge as genuine when it is logical and reasonable, when it is factual rather than a value judgement, and when it is derived from objective sensory experience. Genuine knowledge is unaffected by its surrounding context. Two people looking at the same painting will observe the same image. The value of pi remains the same whether it is stated in a contemporary junior high mathematics course or in a lecture in ancient Rome.

Despite being the dominant mode of thought in engineering education, research, and practice, positivism is not utilized in this work. The first reason can be seen in the preceding example of two individuals looking at a painting and perceiving the same image. One of them may be colour blind, or require corrective lenses, and their personal contexts and histories may highlight different elements of the painting as significant. In short, sensory experience cannot be assumed to be objective. In developing the new laboratory methodology, allowing for subjective sensory experiences broadens the laboratory to be more inclusive towards individuals whose sensory perception differs from what most students are expected to possess. This lends itself to the following point on equity, diversity and inclusion.

There has been a recent push for equity, diversity and inclusion in societal structures. Professional engineering in Canada contains systemic exclusionary biases that prevent all members from society from participating equally in its practice, a view endorsed by Ontario's provincial regulatory association, the Ontario Society of Professional Engineers (Fair Play Talks, 2020). If the processes and institutions involved in professional engineering practice contain systemic bias, then it follows that individuals engaging in this practice produce results that are also biased. This directly contradicts positivism's claim that knowledge is objective and unbiased. Even in cases where the knowledge used in engineering practice is itself free from bias, the use of that knowledge will itself carry bias. Consider a contemporary example: it is a well-known phenomenon that generative artificial intelligence programs can be biased when they are trained with biased data, to such a degree that the World Economic Forum has published guidelines on reducing this bias (Seneor and Mezzanotte, 2022). Each individual data point is objective, indeed an image accurately recording an individual's facial features. Yet the algorithm that uses these data points to identify individuals from facial features exhibits a strong bias towards light-skinned males, who are identified with an error rate 34% lower than dark-skinned females (Najibi, 2020). Positivism provides the dangerous assumption that the knowledge possessed by an individual is not subject to error or bias. There are well-known examples of this bias in other fields leading to extensive and long-lasting harm, such as the Stanford prison experiment (Zimbardo, n.d.) or the Tuskegee syphilis study (for Disease Control and Prevention, 2022). Therefore, positivism's exclusion of subjective human issues does not aid in tackling these problems. As engineering is the process of applying scientific and mathematical principles to solve problems and is a position that holds public wellbeing as its highest ethical obligation, an epistemology that allows for subjectivity is preferred over the objectivity of positivism for developing the new learning laboratories.

An expansion of this point provides another reason positivism is not employed in this work. Assuming that one's knowledge is not subject to error or bias encourages intellectual laziness. Another obligation of the professional Canadian engineer, as per the Engineers Canada code of ethics (Engineers Canada, 2016), is to maintain competency in their area of expertise. New discoveries are made that upend old discoveries. New technologies are introduced that require new ways of thinking to fully employ. Changes in society prompt a shift in professional obligations and priorities. A positivistic mindset that assumes knowledge to be objective and free of societal context does not mesh with professional obligations that are fundamentally subjective in nature. An engineer who accepts the contextual nature of their knowledge is more prepared when that knowledge is disrupted by new technologies, discoveries, or societal sea changes. As this study seeks to improve engineering education and the quality of the engineering graduate, an epistemology that is better equipped to meet an engineer's professional obligations is preferred.

Finally, this study seeks to improve learning outcomes and the learning experience in undergraduate engineering laboratories. Chapter 3 will present the construction and administration of surveys to current undergraduate engineering students and to the managers who can expect to hire them following graduation, both of whom are key stakeholders in the laboratories under question. These surveys investigate the skills and laboratory activities that these stakeholders see as holding educational value. Assigning value is subjective and will differ depending on who is surveyed. As such, positivism's focus on objectivity is considered detrimental to this research endeavour, diminishing the value of the subjective and qualitative feedback from the surveyed stakeholders.

In summary, while positivism is the dominant epistemology in engineering, it is not utilized in this work. It risks harming societal efforts for equity, diversity, and inclusion, contributes to a fixed mindset that does not align with an engineer's professional obligations to maintain their competencies and safeguard a society with fluctuating needs, and detracts from the subjective feedback provided by stakeholders that forms the core of this research endeavour. However, given positivism's dominance in engineering practice, it is important to discuss it, even though it is not utilized in this work.

2.1.2 Interpretivism

The primary research paradigm utilized in this work is interpretivism. Interpretivism states that reality is subjective, socially constructed, and is a composite of multiple lenses (Rogers, 2020). This stands in stark contrast to positivism and can be considered its dialectical opposite. Under this philosophy, knowledge is not objective fact, but rather relative to the time, place and culture it emerged from. Knowledge cannot be separated from this context and cannot be truly understood without it.

While this paradigm explicitly acknowledges the uniqueness of learners and appears suited to answering subjective societal issues, there are critiques of the theory that must be noted. First, by attempting to gain a deep understanding of a phenomena within its context, interpretivist research can encounter difficulties in generalizing results to other people and contexts (Pham, 2018). Second, the ontological view of interpretivism, or how this theory views reality (Hofweber, 2021), tends towards subjectivity and is unquestionably affected by the researcher's own belief systems, meaning that significant biases can make their way into interpretivist research (Pham, 2018). Finally, since interpretivism is focused on understanding the current context, it can neglect issues of power and agency, and can fail to address the political and ideological impact on knowledge (Pham, 2018). This last criticism is answered using critical theory, explored in the following section.

Interpretivism is utilized in this work to allow for the subjective experiences and value judgements of stakeholders to be incorporated into the research effort, expressed as qualitative survey results from students and engineering industry managers. A positivist position would see these survey responses as value-free and logically derived from the sensory experiences of laboratory participants and engineering managers. Interpretivism allows for the personal context of respondents to be incorporated into the research, which is of particular value when analyzing how to improve the subjective learning experience. This is also of value in determining what traits and skills engineering managers desire in recent graduates, which are also subjective and contextual to the manager being surveyed.

2.1.3 Critical Theory

The secondary paradigm used in this research is critical theory. Critical theory attempts to find underlying societal assumptions that prevent fully understanding how the world works and uses these findings to critique and alter society (Nickerson, 2022). After being applied to legal theory, critical theory gave rise to commonly known branches such as critical race theory. It is important to incorporate this theory into research to address and challenge social issues and aid in the current engineering industry and broader societal push towards inclusion, equitability and diversity.

As with interpretivism, it is important to acknowledge the pitfalls of utilizing critical theory. The dominant criticism is that this theory fails to provide rational standards showing it to be superior to other systems of thought (Nickerson, 2022); however, the reader should note that this and the other epistemologies detailed here are not expressed as dominant or superior to other epistemologies, but rather as best suited to this particular research effort. Critical theory can also tend to focus on discourse around issues rather than the experience of individuals in those contexts and can avoid grappling with those issues directly. Another critique is that critical theories can be as narrow and oppressive as the systems they seek to change, failing to recognize themselves as one voice among many (Brickhouse, 2001); rather than liberating people from societal systems of thought, critical theories can potentially risk dominating people in a new system.

For example, while critical theory can be of great assistance in identifying and dismantling existing power structures, the theory is less focused on developing new, more equitable power structures. The theory also ignores areas where a power imbalance may be beneficial or even necessary. Consider a kindergarten classroom: these are young children currently learning the details of how to conduct themselves in society. The teacher may require a power dynamic weighted in their favour to keep the classroom orderly when students do not understand or appreciate the value of following instructions and keeping the learning environment respectful and equitable towards their fellow students. If one child starts throwing wooden blocks at another's head, the teacher benefits from a perception of authority to stop the behaviour.

Critical theory is utilized in this work to recognize power structures within the learning laboratory. In seeking to improve the learning experience, it is important to acknowledge the power dynamic between students and their academic institution. Understanding this dynamic allows an analysis of institutional factors limiting improvement of the learning laboratory experience and learning outcomes, and for recommendations targeted towards the student-instructor relationship.

2.2 Theories of Learning

Just as any engineering discipline will take the discipline-specific scientific and mathematical principles and apply them to a given problem, so too must engineering of a learning experience utilize the science of learning.

Theories of learning establish a viewpoint from which to observe and analyze the learning process. However, learning is a complex phenomenon, and many theories of learning have been proposed and utilized in education in the last century. The International Bureau of Education, an institute operating under the United Nations Educational, Scientific, and Cultural Organization, identifies the following as the most influential theories of learning: behaviourism, constructivism, social learning theory, socio-constructivism, experiential learning, multiple intelligences, situated cognition theory and communities of practice, and 21st-century learning or skills (International Board of Education, n.d.). Note that socio-constructivism is a subset of the broader theory of constructivism, focused specifically on how learning occurs in social interactions.

This study utilizes situated cognition theory, constructivism, experiential learning theory, and self-determination theory. The selected theories of learning will first be explored, and their use in this research endeavour explained. The alternative learning theories will then be briefly covered, and the reasoning for not including them in this work will be explained.

2.2.1 Situated Cognition Theory

Situated cognition theory is used in this work to explain the value of context in redesigning the engineering laboratories. This theory shows the importance of connecting the learning laboratory experience to the broader course, program, and professional career contexts.

Situated cognition or situativity theory was developed by Brown, Collins, and Duguid (Brown et al., 1989) out of an observation that contemporary schools prioritized abstract, decontextualized formal concepts. Situated cognition theory argues that knowledge, thinking, and learning are all situated in experience. An experience consists of the participants, the culture, and both the physical and non-physical environment in which the experience takes place. These components are all interdependent and cannot be understood individually.

Under situated cognition theory, knowledge is viewed as a tool that is inseparable from the situations it is learned and used in. Take the example of a hammer, which can be used to build or to destroy. The hammer is interdependent on its environment, its user, and the culture it arose from; use of the hammer will alter the tool itself, the user, and the surrounding environment and culture. This allows for non-linear outcomes, since they arise from complex interactions between the participant and context, both of which evolve with the encounter (Durning and Artino, 2011). An example is a Scrabble board: each word and tile chosen directly influences the future actions players will take, and the board is constructed by both players.

Situated cognition theory has a strong history in tackling social issues in scientific education. The theory has been used to identify structural components in scientific education and industry that contribute to gender inequality (Brickhouse, 2001), finding that “what is taken to be universal, value-free truths is actually situated knowledge... embedded in cultural values, including gendered ones” (Brickhouse, 2001, pp. 284). This placement of knowledge within its cultural context is a key reason why situated cognition theory is applied in this work, providing a useful change in perspective. For example, take a quote from a work on situated cognition theory: “The question, “How can we make science more appealing to women?” is replaced with the question, “What is it about existing science cultures and methods of inquiry that excludes women?”” (Mayberry, 1998, pp. 450). Situated cognition theory pivots the subject of analysis from the participant to the experience itself, and in this example, this change in perspective fundamentally alters how one approaches gender inequality. This theory can therefore be used to understand how the context around laboratories affects student learning.

Situated cognition theory is also applicable to racial barriers. In a study on South African post-secondary science students having their first internship experience in the scientific industry, situated cognition theory was used to identify structural components of science work and education that enforced racial inequality (Case and Jawitz, 2004). The theory was found to explain the complex social interactions when first entering a workplace and its impact on learning and cognition. The authors of this study note that understanding this social component of the workplace was key to identifying structural barriers that reinforce racial inequalities; this shows the importance of subjective and social elements of the learning experience, further supporting the decision to not implement positivism in this work.

Situated cognition theory has been found to support the inclusion of experiential learning in the form of hands-on participatory experiences. A common practice in industrial design is to dissect a product to better understand it before undertaking design efforts. In a study comparing two post-secondary engineering design classes, one with a product dissection and one without, it was found that the inclusion of this experience made students more creative, more likely to implement more design concepts, and focused equally on a product’s form and function, as opposed to the control group who primarily focused on form (Grantham et al., 2010). This is a valuable insight in redesigning participatory experiences, such as the laboratories analyzed in this work, showing how consideration of context can enhance a learning experience. Note as well that design is an integral engineering skill and is therefore part of the professional career context of engineering education (Engineers Canada, 2019).

It has been observed that, as science and technology become increasingly integrated into society and public discourse, situated cognition theory becomes a valuable tool in scientific education in addressing this context (Roth and McGinn, 1997). Scientific education should be focused on the world that students will inhabit, and including information perceived as irrelevant is detrimental to student engagement. "If we, as science educators, take elitist views on the matter... we are likely to continue with a science education that many students consider irrelevant" (Roth and McGinn, 1997, pp. 498).

Situated cognition theory is used in tandem with interpretivism (see Section 2.1.2) to understand the student experience and incorporate perspectives of potential employers. Engineering is a professional discipline, and engineering education is therefore contextualized by common industry practices. The direct relationship between engineering education and practice is recognized through accreditation of Canadian engineering programs by the Canadian Engineering Accreditation Board, which belongs to Engineers Canada, the agglomeration of Canadian professional engineering associations (Engineers Canada, n.d.-a). Engineering students expect that they are learning industry-relevant skills. What makes elements of this education "relevant" or "irrelevant" is therefore contextual, dependent on how that element relates to professional practice. As well, note the nuance in the quote from Roth and McGinn in identifying elements that students *consider* irrelevant, rather than being inherently irrelevant in and of themselves. It follows that elements of engineering education must be contextual to engineering practice, and that this connection must be perceived by students, to be considered relevant. If students are unaware of the connection to engineering practice, regardless of whether it actually is present in the educational element, they can view that element as irrelevant. This irrelevancy or lack of saliency directly correlates to reduced participant engagement (McCay-Peet et al., 2012).

Consider an example: writing reports is a common practice in engineering education at the University of Calgary, both in learning laboratories and for course projects. Reports can be a valuable tool for communication between companies and clients in engineering practice as well. However, if this professional context is not explained, from the viewpoint of the students, the skills they are developing in writing reports do not have an application beyond the academic context.

This carries an important implication for redesigning engineering laboratories: the inclusion of elements students see as irrelevant may decrease engagement within the laboratory, resulting in a more negative perception of the overall experience.

2.2.2 Constructivism

Another important theory of learning applied to this work is constructivism. Constructivism began with the work of Piaget (Piaget, 1952), who initially developed a theory of cognitive development in children before synthesizing existing cognitive and behavioural theories of learning.

The core tenet of constructivism is that learning is the process of constructing meaning (Piaget, 1952). Knowledge is not directly transmitted through passive processes, but is constructed through experience and social interaction. New knowledge is integrated into the learner's prior knowledge. The benefit of the theory to this work is in factoring in students' prior knowledge and existing misconceptions to more effectively teach, actions essential to any application of constructivism (Moreno et al., 2007); note that learning in an educational experience is always influenced by this prior knowledge or existing knowledge base (Cobern, 1993). Students' prior knowledge determines what they recall, what hypotheses are generated, and, ultimately, what students identify as learning issues (Hendry et al., 1999). These factors will be incorporated into the new laboratory methodology.

The process of integration is an intriguing one. Constructivist stances state that learning occurs when the learner encounters a challenge to the way they think, they experience a state of disequilibrium (Piaget, 1952) or cognitive dissonance. Balance is restored when the learner assimilates the new knowledge by associating it with their existing knowledge. If this does not occur, then the learner must restructure their present knowledge into a higher order of thinking. This carries a valuable insight that challenges are not only expected in learning, but are fundamental to the experience.

An example will help to illustrate this process of integration. A modern engineering education involves courses in coding and in physics. These topics require radically different approaches. A central tool in classical mechanics problems is a free-body diagram, which is used to visualize the forces acting on a body. Force balance equations are then used in tandem with other equations from kinematics, energy balances, or other sources to solve the problem. Developing a computer code requires a different base of knowledge and a different approach. Computer codes will only enact the exact commands that they are given in sequential order. A common tool to aid in developing code is a flow chart, which helps visualize this sequential aspect of coding. Codes are generally subject to constant revision, taking several debugging passes to develop a working code. These two subject areas require different approaches. A first-year student who performed well in high school physics courses will still encounter disequilibrium in their coding courses, as their previous base of knowledge is insufficient to solve these new challenges. A new understanding of the problem-solving process is necessary to approach coding.

Appropriately, constructivism has been applied within computer science education. A reason for this application was that this theory provides a greater scope than traditional learning theories in realizing the possible learning benefits of an academic experience (Hadjerrouit, 2005). A computer science course implementing constructivist pedagogy was found to give deeper knowledge and higher motivation in students (Moreno et al., 2007).

Constructivism is used in this work to understand how students develop their varying competencies in the learning laboratories. In developing their framework of knowledge, students require adequate prior knowledge when entering a learning experience. This theory also lends itself to the use of constructive alignment (see Section 2.3.3) and the zone of proximal development (see Section 2.3.4), theoretical frameworks utilized extensively in the analysis of survey data (see Section 5.1).

2.2.3 Experiential Learning Theory

As mentioned previously in the introduction (see Section 1.1), there have been calls from the provincial government (Government of Alberta, 2021) and the University of Calgary (Kaipainen et al., 2020) for more experiential learning opportunities to be included in undergraduate education. Both groups are key stakeholders in funding and administering the University's engineering program, and these calls form a portion of the motivation for this research. Experiential learning theory must therefore be explored and contextualized to this study.

Experiential learning theory can be summarized as "learning by doing". Experiential learning theories view experience as central to the learning process (Kolb and Kolb, 2013). Based on existing experiential learning theories from Lewin (Lewin, 1946), Dewey (Dewey, 1938), and Piaget (Piaget, 1952), D.A. Kolb developed an experiential learning cycle (Kolb, 1984); this cycle is now considered a foundational concept in the field of learning sciences, holding 23,000 citations on the ResearchGate journal publication platform as of the time of writing (ResearchGate, n.d.).

D.A Kolb (Kolb, 1984) identified commonalities between existing experiential learning theories to determine the shared characteristics. From these, Kolb proposed that learning is inherently a tense and conflict-filled process. The development of new skills, knowledge, and attitudes is done through confrontation between four modes of experiential learning:

- Concrete experience, the engagement in new experiences mindfully and without bias.
- Reflective observation, the act of reflecting and observing one's experiences from a multitude of perspectives.
- Abstract conceptualization, the creation of concepts that integrate observations into logically sound theories.
- Active experimentation, the use of these theories to make decisions and solve problems.

Taken in the order above, these four modes form Kolb's experiential learning cycle.

Connecting back to this research endeavour, engineering learning laboratories can naturally be viewed as practical experiences if they demonstrate the application of theories learned in lecture to an experiment that imitates real engineering practice. However, the primary motivation of this study, that students do not perceive connections between their laboratories and future careers, shows that the laboratories in the course under consideration are not accomplishing this goal.

Use of Kolb's cycle can improve the perception of laboratories as practical experiences and improve learning outcomes. In a mathematics course redesign based on Kolb's cycle, it was found that "students learn more and derive intellectual satisfaction from the experience" (Stice, 1987, p. 296). A study applying Kolb's cycle to a community service experience project found that use of the cycle transformed and internalized the experience for participants, promoting deep learning and each learning mode through real-world experience (Chan, 2012). This study also found that a real-world experience connected the subject matter to student emotions and values. Other studies have found that students enjoy learning experiences built on Kolb's model (Muscat and Mollicone, 2012), and that implementation of this cycle improved student performance (Lee et al., 2008). Muscat's (2012) study found over half of students want to learn through hands-on experiences; an important finding for developing laboratory pedagogy is that most theoretical lectures should be supported by laboratories or coursework that give students the opportunity to experiment.

Critiques

Despite widespread use, experiential learning theory and Kolb's cycle have been extensively criticized.

One critique is that the theory is unscientific. A scientific theory has been repeatedly tested and corroborated with the scientific method (American Museum of Natural History, n.d.). Contemporary experiential learning theory was not based on a hypothesis of how learning occurs that was verified and refined through research, but was rather developed as a philosophy and technique. The theory was developed from commonalities between existing models developed by Lewin, Piaget, and Dewey (Kolb, 1984). While valuable, some of these foundational models are no longer considered scientific and have rather been contemporaneously characterized as perspectives of historical importance to learning sciences (Seaman, 2008). Furthermore, these theories were explicitly developed to assist colleges in awarding credit to adult students based on their prior life experiences, as well as aid instructors utilizing techniques such as simulation games (Chickering, 1977;Pearson and Smith, 1985). Experiential learning theory is therefore an agglomeration of existing theories that are not fundamentally scientific, and has inherited these preceding flaws.

Another issue is that the core definition of experiential learning theory - "learning through experience" - appears trivial and does not meaningfully explain how learning occurs. It seems quite obvious that an experience is required for learning, as knowledge and skills do not spontaneously develop. This is a fundamental assumption of contemporary education. Theoretical topics such as trigonometry or literary analysis are taught in traditional seated classrooms, while "hands-on" skills such as automotive repair or how to play a musical instrument are taught through participatory experiences in workshops. An experience is required for learning to occur, so the fundamental definition of experiential learning theory is not scientifically significant in and of itself.

In its defense, experiential learning theory, specifically Kolb's cycle, does attempt to explain how learning occurs. However, the core concept that learning occurs sequentially in four distinct modes has been subject to extensive criticism, with numerous studies showing that learning does not necessarily adhere to Kolb's model. Kolb does not adequately explain how his four modes of learning correspond to phases in a cycle or to each other (Miettinen, 2000). This criticism is supported by the work of educational psychologists, who find that Kolb's theory does not correspond to the cognitive architecture underpinning learning; a meta-analysis of studies implementing this theory found that the improvement in learning was "not sufficient to meet standards of predictive validity to support the use of the measures or the experiential methods for training at work" (Kirschner et al., 2006).

Experiential learning theory has faced persistent criticism for the so-called "black box problem" (Seaman, 2008). This is the gap between the improvements in learning witnessed in experiential learning programming and the ability of experiential learning theory to explain this learning (Kraft, 1990;Wichmann, 1980). While a potential explanation is that experiential learning is "too mysterious a phenomenon to fully comprehend" (Conrad and Hedin, 1990, p. 6), such an explanation appears unsatisfactory and unscientific. If true, experiential learning theory should still be investigated until its "mystery" is fully resolved.

In conclusion, experience is indeed central to learning; even if it is as simple as using a search engine to look up information on a topic, learning requires an experience. However, the manner in which experiential learning theory expands on this point is scientifically flawed. Furthermore, while learning experiences modelled using Kolb's cycle have been found to improve the learning experience and deepen learning (Stice, 1987; Chan, 2012; Muscat and Mollicone, 2012; Lee et al., 2008), given the flaws with the core concept, educators cannot know the extent to which these improvements are intended effects of utilizing the cycle, as opposed to incidental effects due to cognitive mechanisms the educator is unaware of.

It is not the role of this work to develop a new theory of experiential learning. Given the contemporary focus of the education research community, the University of Calgary, and the Government of Alberta on experiential learning, as well as the demonstrated efficacy of learning experiences modelled using Kolb's cycle, the theory remains a valuable tool in improving undergraduate engineering laboratories. This critique is intended to acknowledge the flaws with this theory and align this work with the scholarship of teaching and learning, which is foundational to this research. Critiques such as this are necessary to align with the scholarship and its focus on situating teaching methods with evidence-based research.

2.2.4 Self-Determination Theory

Self-determination theory examines the role that motivation plays in human behaviour (Deci and Ryan, 1985). It is important to once again note that engineering education is a professional program explicitly directed towards employment in the engineering industry, with professional internships being a common educational element and the general program structure being dictated by Engineers Canada (Engineers Canada, n.d.-a), who ensure consistent standards between the provincial associations that regulate Canadian engineering practice. Engineering students therefore expect their education to lead to employment, and this connection is understood to motivate and engage students in their education. For engineering students, the question, “Why are we learning this?”, is expected to be answered with professional and industrial principles and practices.

Self-determination theory was developed out of studies comparing intrinsic, or internal, and extrinsic, or external, motivations, which will be later explored in Section 2.4.1. The essence of the theory is that individuals make their own choices (Deci and Ryan, 1985). While a seemingly simple statement, it has important implications. Therapists following self-determination theory acknowledge their responsibilities are ultimately limited because they cannot make decisions on behalf of their patients. Educators subscribing to this theory believe that they cannot make their students learn; they can only provide an environment and resources that are conducive to learning. This is a valuable conclusion in developing the new laboratory methodology: learning outcomes cannot be guaranteed, but the environment and resources made available to students can make these learning outcomes more achievable.

Self-determination theory states that all humans have three fundamental psychological needs that affect growth and development: autonomy, or the perception that one has choice in and willingly endorses their behaviour; competence, or the experience of mastery and effectiveness in a given activity; and relatedness, or the feeling of connectedness and belonging in a group (Ryan and Deci, 1985). These needs are directly impacted by the social environment an activity takes place in, which by extension reinforces the previous assertion that altering the educational environment will affect student cognition and learning.

Addressing these needs has been found to improve intrinsic motivation (Trenshaw et al., 2016). For post-secondary students, the need for relatedness is found to be the most important component of academic motivation (Trenshaw et al., 2016). Improving academic autonomy, such as through implementation of project-based learning, also improves motivation, better satisfying the needs of students and improving their perception of their learning experience (Stolk et al., 2018). These factors will therefore be incorporated into the new laboratory methodology as a tool to improve intrinsic motivation.

2.2.5 Alternative Learning Theories

Mention should be made of the alternative learning theories mentioned in Section 2.2. Note that these theories are listed by the United Nations not for their efficacy or scientific veracity; indeed, several theories have faced significant criticism for failing to produce scientifically-verified evidence for their core hypotheses. Rather, they are included due to their contemporary popularity or historical importance. An additional theory mentioned here is universal design in learning; as it is experiencing some contemporary popularity, it is important to mention. While employing certain theories of learning, it is important to acknowledge that there exists a broad spectrum of viewpoints from which to understand learning.

Universal Design in Learning

Universal design for learning, or UDL, is a theory and framework for developing learning environments. The framework was developed by the Center for Applied Special Technology, now simply titled CAST. Rooted in cognitive neuroscience, UDL is an application of universal design, which intends to design a product, building, or environment so that it is readily usable by the widest possible range of users (Rose et al., 2006). Barriers are eliminated through initial design rather than later adaptations by users. Universal design has only been applied to teaching and learning recently since while the core concept readily translates to education, the existing techniques and principles do not.

UDL has three fundamental principles: multiple means of representation, multiple means of expression, and multiple means of engagement. The theory goes on to expand these principles into a set of guidelines for implementation (Rose et al., 2006).

UDL is not utilized in this work. First, there is a dearth of evidence showing that implementation of UDL actually improves learning outcomes (Murphy, 2021). Second, the theory's basis in neuroscience has shown to be constructed on an incorrect understanding of the field (Murphy, 2021).

Behaviourism

Behaviourism views human behaviour as either a reflex to environmental stimuli, or as a function of an individual's history, especially with regards to prior punishments or reinforcements (Skinner, 1976). The most prominent proponent of this theory was B.F. Skinner, who developed the theory of radical behaviourism. This revised theory also considers internal thoughts, feelings, and other private events in understanding human behaviour.

Following a paper criticizing Skinner's work (Chomsky, 1959), behaviourism has been largely replaced by cognitive psychology theories of learning. The primary criticism of behaviourism is that it does not include mental processes in analyzing human behaviour, which is a central tenet of situated cognition, constructivism, and self-determination theory. The theory of behaviourism is not utilized in this work due to these criticisms and the broad replacement of behaviourism as a learning theory.

Social Learning Theory

Social learning theory is based in behaviourism. Similar to the preceding theory, social learning theory proposes that human behaviours are the product of past rewards or punishments to stimuli (Bandura and Walters, 1977). Social learning theory places this process in a social context, allowing for individuals to learn by observing the behaviours of others and how those actions are punished or rewarded. While this theory finds heavy empirical support, it is not used in this work due to similar criticisms attributed to behaviourism, described previously.

Social Constructivism

Social constructivism proposes that certain ideas regarding physical reality are based in collaborative consensus rather than pure observation of reality (Berger and Luckmann, 1966). Essentially, there are certain concepts that cannot exist without people or language that validate those concepts. An example is currency, which holds value because people have agreed that it holds value.

This analysis of the relationship of social contexts to experienced reality is incorporated in this study through the use of constructivism and situated cognition theory; the general principles of social constructivism are therefore already incorporated in this work, and the theory itself is not incorporated so as to avoid redundancy and an overly-complex analysis of the survey results.

Multiple Intelligence Theory

Multiple intelligence theory proposes that human intelligence is not a single general ability, but rather a group of modalities, such as visual or musical intelligence (Gardner, 1983). This theory has not found traction in mainstream psychology due to the lack of empirical evidence and the theory's dependence on subjective judgement (Waterhouse, 2006); therefore, it will not be applied in this work.

Communities of Practice

Communities of Practice (CoPs) is a concept that has applications in multiple areas. In the context of social learning theories, CoP views learning as taking place in a social context, where participation and reification, or making something concrete, is required to make learning meaningful (Wenger et al., 2002). The importance of participation is explored in the use of experiential learning theory (see Section 2.2.3), while the importance of the social context is included in this work through the psychological need for relatedness incorporated in self-determination theory (see Section 2.2.4). CoP is therefore not applied in this work.

21st Century Learning

21st century learning is a broad movement to critically evaluate the applicability of traditional learning theories to the evolving digital landscape of the modern age. There is no core work or theory associated with this movement; this work in itself can be considered to be ‘21st-century learning’. Due to the vague nature of this movement, it will not be applied in this work.

Having discussed the theories forming the foundation of this research endeavour, their specific application in the form of theoretical frameworks can now be explored.

2.3 Theoretical Frameworks in Education

Theoretical frameworks are specific applications of broader theories, providing a structure from which to develop a research methodology and methods. This helps to ensure that the study is rooted in an accepted research basis. Just as an engineer must utilize a certain model of fluid behaviour when conducting research in computational fluid dynamics, so too must an engineering education researcher use specific frameworks of learning theories to explore learning behaviour.

The following sections describe the frameworks utilized in this research endeavour, namely the revised Bloom’s taxonomy, the Describe, Examine, Articulate Learning or DEAL framework, constructive alignment, and the zone of proximal development.

2.3.1 Bloom’s Taxonomy

Bloom’s taxonomy is a widely applied and cited work in education and provides a valuable tool for framing the learning process (Anderson and Krathwohl, 2001). Bloom’s taxonomy is used in this work as a framework for classifying learning outcomes, and creates a shared language between researcher and survey participant in understanding laboratory learning outcomes. The taxonomy is also applied to laboratory pedagogical materials such as course outlines to derive the desired learning outcomes for a given activity.

The Original Taxonomy

The original idea for what would become Bloom’s taxonomy (Bloom, 1956) was an initiative to develop a framework to facilitate communication between college examiners. After discussion, it was decided this framework could best be approached by classifying the goals of the educational process, developing the titular taxonomy.

Bloom's original taxonomy (Bloom, 1956) consists of six major classes of educational goals: knowledge, comprehension, application, analysis, synthesis, and evaluation. The taxonomy is hierarchical; objectives of each class build upon objectives of the preceding classes.

The first class of goal in the taxonomy (Bloom, 1956) is *knowledge*, defined as the remembering of ideas, material, or phenomena. Objectives in this class include knowledge of specifics, such as terminology; knowledge of ways and means of dealing with specifics, such as knowledge of conventions or trends; and knowledge of the universals and abstractions in a field, including principles and generalizations.

The *comprehension* class in Bloom's original taxonomy (Bloom, 1956) is the expectation that students know what is being communicated to them in class and the ability to make some use of the ideas conveyed. Bloom identifies three types of comprehension behaviour: translation between languages, contexts, and forms of communication; interpretation, which involves dealing with a communication as a particular configuration of ideas and which may require reordering for comprehension; and extrapolation, estimating or predicting based on understanding of trends or conditions.

The next class developed by Bloom (Bloom, 1956) is *application*, which is a step beyond comprehension in that the student can apply appropriate concepts to a particular context without having to be prompted on the appropriate concept.

Bloom's (Bloom, 1956) fourth class is *analysis.* Analysis can be applied to educational material or to the techniques or devices used to communicate the material. Bloom breaks analysis down into three levels. In the first level, the student is expected to break down the material and classify its elements. The next level involves explicitly identifying the relationships between the constituent elements. Finally, the organizational principles of the material are recognized.

The fifth class developed by Bloom (Bloom, 1956) is *synthesis*, defined as "the putting together of elements and parts so as to form a whole" (Bloom, 1956, p. 162). Previous experiences are combined with new material to construct an integrated whole that wasn't clearly identifiable before. Bloom distinguishes between different kinds of synthesis based on the desired synthesized product. Sub-categories include synthesizing a unique communication that presents a distinct combination of the material and method of communication; creating a plan to be carried out by combining proposed operations and the necessary processes; generating a set of abstract relations, such as a hypothesis or deduction; and finally, relating concepts and processes.

The sixth and final class of Bloom's (Bloom, 1956) educational objectives is *evaluation*, or making a value judgement of a particular idea, work, etc. It involves the use of criteria and standards to judge an item along one or more metrics. This stage involves some combination of all the previous behaviours.

The Updated Taxonomy

An updated version of Bloom's taxonomy was published in 2001, intended to add relevance for education in the 21st century (Anderson and Krathwohl, 2001). The new framework was developed over six years by a group of cognitive psychologists, curriculum theorists and instructional researchers, and testing and assessment specialists.

The most obvious change is in terminology, changing the previous nouns to verb forms (Anderson and Krathwohl, 2001). Knowledge became remembering, comprehension became understanding, application became applying, analysis became analyzing, synthesis became evaluating, and evaluation became creating. These new terms are defined as follows:

- *Remembering* is "retrieving, recognizing, and recalling relevant knowledge."
- *Understanding* is "constructing meaning from... messages through interpreting... and explaining."
- *Applying* is "carrying out or using a procedure through executing, or implementing."
- *Analyzing* is "breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.'
- *Evaluating* is "making judgements based on criteria and standards through checking and critiquing."
- *Creating* is "putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing."

(Forehand, 2012, p. 43)

As with the original taxonomy, the updated version is hierarchical, with each level building off the previous. A commonly-used depiction of the modern Bloom's taxonomy is presented in Figure 2.1.

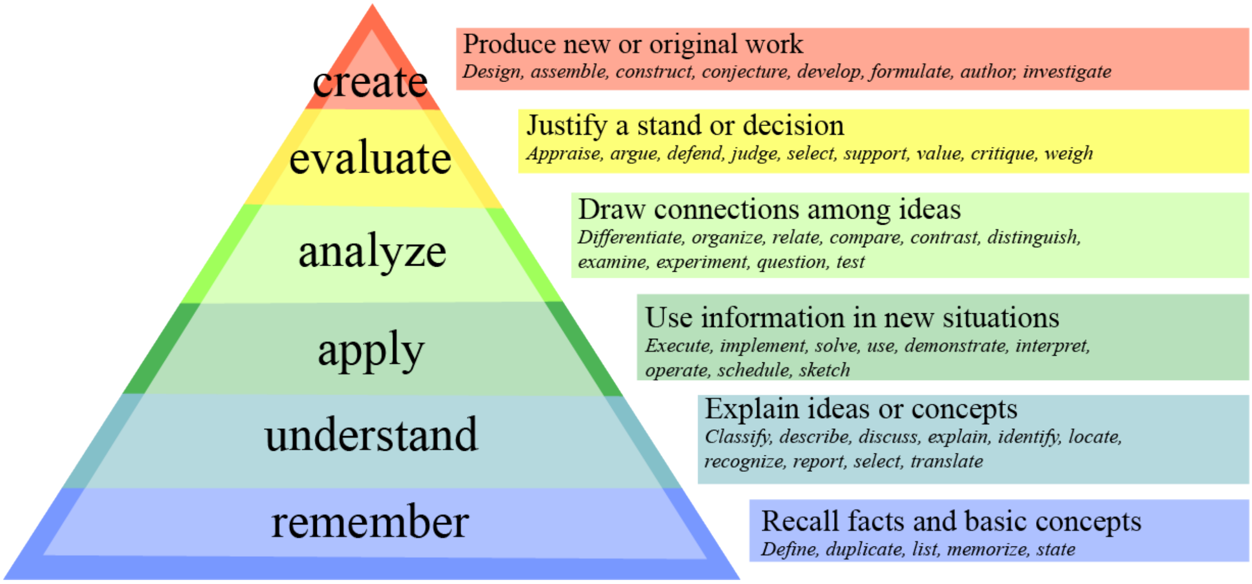


Figure 2.1: The modern Bloom's taxonomy (Vanderbilt University Center for Teaching, n.d.)

Bloom's taxonomy has a strong history in classifying post-secondary educational learning levels, particularly in the area of software engineering (Goel and Sharda, 2004)(Britto and Usman, 2015). A mapping study of existing research in applying Bloom's taxonomy to undergraduate software engineering courses found that the taxonomy has been equally applied to design and to assessment of a course, indicating that the taxonomy is a valuable tool in either case (Britto and Usman, 2015).

Another study asked students to apply the activity verbs from Bloom's taxonomy to their courses (Goel and Sharda, 2004). The activity verbs were ranked in order of how frequently course activities applied the verb, and in order of perceived importance. This study found that most activities were of an "apply" or "analyze" level, appropriate for courses where students develop software. Students' impressions correlated highly to exam activities, indicating that students understood the expected level of learning. There was also a high correlation between the desired level of learning for students and what industry professionals expect the level of learning to be. However, there was a negative correlation between the level of learning desired by students and professionals and the level of learning assigned to course tasks. The study concluded that flexible curricula that engage students in higher-level activities foster creativity, critical thinking, and innovative problem-solving.

2.3.2 DEAL Framework

A common thread in experiential learning literature is reflection. Ash and Clayton (Ash and Clayton, 2009) identified this shared component and developed a model for integrating critical reflection and assessment, called the Describe, Examine, Articulate Learning or DEAL model. This model is used to structure qualitative surveys and guide student reflection, as well as a framework for implementing critical reflection within the laboratories themselves.

Ash and Clayton identify several potential shortcomings of ELT. As mentioned before (see Section 2.2.3), in and of itself, experience does not necessarily result in learning; "experience alone can, in fact, be a problematic teacher" (Ash and Clayton, 2009, p. 25), reinforcing stereotypes, developing simplistic solutions, and inaccurately generalizing based on limited information. As well, the orientation of experience may cause participants to miss the most significant learning from their experiences. An undergraduate researcher may be frustrated by the slow process of research and not appreciate that this process is intentionally slow. An engineering intern at a major firm may be frustrated by the amount of low-level work, not understanding that more advanced work requires further experience and education, and that the low-level work is still crucial to the functioning of the firm. Furthermore, Ash and Clayton point out that students may leave applied learning experiences without understanding how to apply what they have learned into practice, giving the example of an intern who, after participating in a frustrating collaborative project, may repeat patterns of poor teamwork in future group work. Finally, students in experiential learning opportunities may not be able to fully appreciate the nature or significance of their learning. Ash and Clayton identify this as an opportunity for students to learn about their own learning processes, developing the meta-cognitive skills required for lifelong, self-directed learning.

In each of these areas where experiential learning may fall short, Ash and Clayton (Ash and Clayton, 2009) state that the student would benefit from a process of strong reflection to avoid what is described as "we had the experience but missed the meaning" (Eliot, 1943, q. 2). Learning does not happen solely through experience; critically reflecting on the experience promotes significant learning. When reflection is weak, students' "learning (may be) haphazard, accidental, and superficial" (Stanton, 1990, p. 185). By contrast, a well-designed critical reflection "promotes significant learning, including problem-solving skills, higher-order reasoning, integrative thinking, goal clarification, openness to new ideas, ability to adopt new perspectives, and systemic thinking" (Ash and Clayton, 2009, p. 2).

With critical reflection being a key component of experiential learning, there is a clear need for a framework for integrating critical reflection into a curriculum and subsequently evaluating this reflection. To this end, Ash and Clayton (Ash and Clayton, 2009) developed the DEAL model. This model has been used at all levels of education from kindergarten to graduate school, and has also been applied to professional training settings.

The DEAL model consists of three sequential steps that guide critical reflection:

1. “**D**escription of experiences in an objective and detailed manner;
2. “**E**xamination of those experiences in light of specific learning goals or objectives; and
3. “**A**rticulation of **L**earning, including goals for future action that can then be taken forward into the next experience for improved practice and further refinement of learning.”

(Ash and Clayton, 2009, p.41).

In practice, each step of the DEAL model is accompanied by prompts that lead students to critical reflection (Ash and Clayton, 2009). The DEAL model is illustrated in Figure 2.2. Note that critical reflection is not a step within this framework; rather, the entire framework itself guides the critical reflection process.

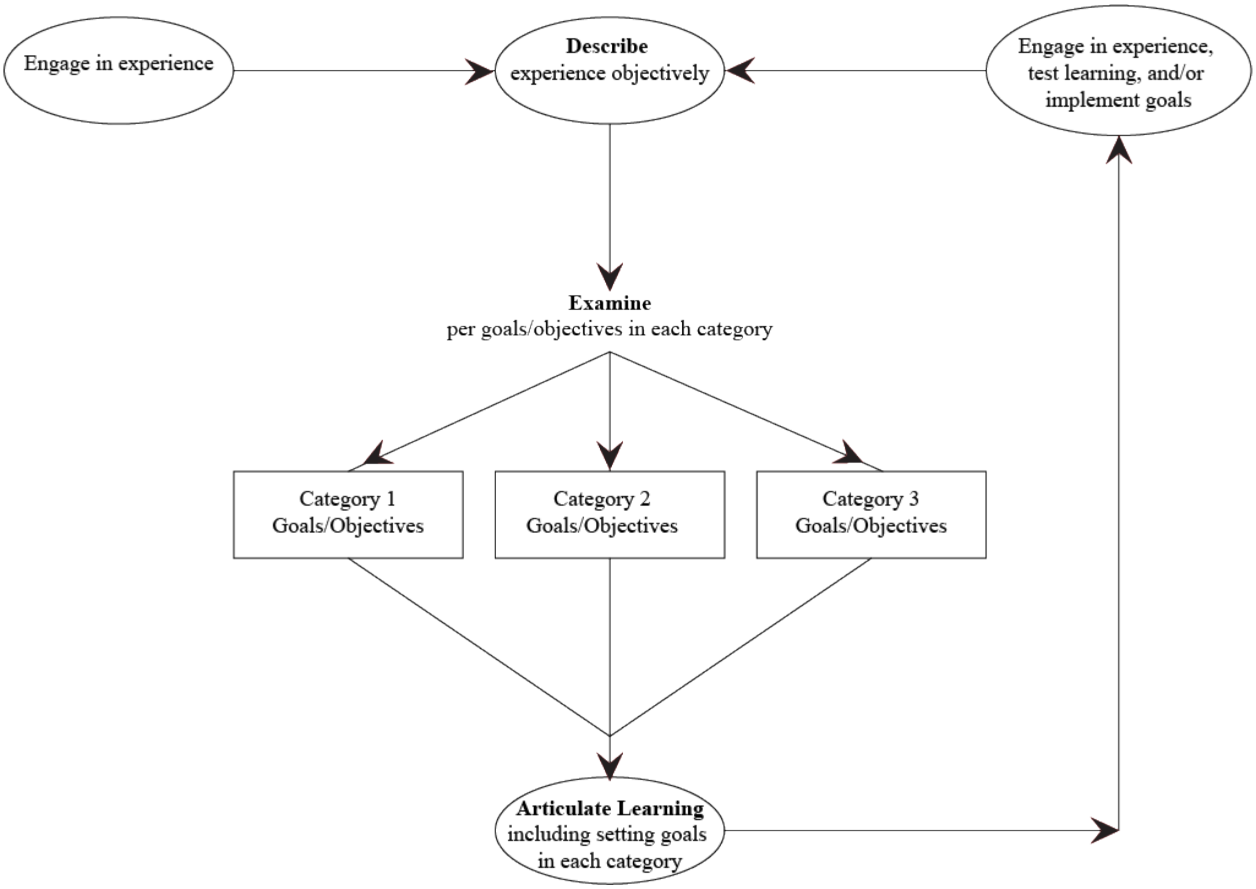


Figure 2.2: Schematic overview of the DEAL model for critical reflection (Ash and Clayton, 2009, p.41)

The Describe step consists of an objective and detailed description of the experience. Ash and Clayton (Ash and Clayton, 2009) intend for this step to make the experience present and ensure students access the entirety of the experience during their reflection. Students may prefer to jump immediately into interpretation and may overlook significant details; this step both requires and develops mindfulness skills. Prompts associated with this step ask questions such as where and when the experience took place, who was present, what the experience consisted of, and so on.

The Examine step is intended to move students from summarizing to meaning-making (Ash and Clayton, 2009); prompts are explicitly linked to the desired learning outcomes for the activity.

The final step, Articulate Learning, has students state what they have learned in the previous two steps and provides further guidance to deepen that learning (Ash and Clayton, 2009). There are four prompts associated with this step: “what did I learn?”, “how did I learn it?”, “why does it matter?”, and “what will I do in light of it?”

Critical reflection is a key component of experiential learning curricula. DEAL has enjoyed particularly wide adoption in service learning, real-world learning experiences where students perform a service to a larger community (Yan et al., 2019) (Croft et al., 2013). Critical reflections are important follow-ups to lecture activities, improving non-technical graduate attributes and forming personalized connections between new and existing ideas (Croft et al., 2013). These reflections enhance experiential learning by relating the experience to a broader context (Yan et al., 2019).

DEAL has also been used within the classroom. When critical reflection and case studies were applied to a nursing program, feedback based on students’ DEAL reflections increased the quality of student reasoning and understanding (Brooks et al., 2010). The applied learning experience was enhanced through critical reflection, which connected the classroom learning to professional experience.

DEAL is also usable as a diagnostic tool, measuring learning outcomes and helping students and instructors to make meaning of their experiences (Bettencourt, 2015).

Given its use in enhancing critical reflection and deepening analysis of an experience, DEAL is used in Section 3.2 to design the qualitative student survey questions.

2.3.3 Constructive Alignment

Constructive alignment is utilized in Section 6.2.3 as a tool for implementing recommendations developed from the survey results. Constructive alignment integrates the three components present in any course, or in any sub-unit or experience included thereof: the learning outcomes, set by the instructor as the goals that successful students will have accomplished by the conclusion of the experience; the course activities, which are the actual activities students are expected to accomplish; and the assessment of students’ learning, the activity set by the instructor to evaluate whether students have successfully completed the learning activity and accomplished the desired learning outcomes (McGuire, 2015). Rather than viewing these components as sequential and independent, constructive alignment considers these components as complementary and forming a whole learning experience between them. A constructively-aligned course has clearly-stated learning outcomes that identify specific activities that students are to accomplish in a specific context. The learning activity and assessment directly address these learning outcomes, and the manner of assessment employs skills developed through the learning activity. Essentially, this framework bridges the gap between the learning intended by students and the methods used to accomplish it (Biggs, 1996), and is found to improve student graduation rates (Khumalo, 2018).

An important part of constructive alignment is properly phrasing learning outcomes; historically, unclear learning outcomes have been a barrier to improving engineering learning laboratories, as it is difficult to improve a process when the goals are unknown (Feisel and Peterson, 2002). A common structure is the Verb-Content-Context (VCC) model developed and used by the University of Waterloo (University of Waterloo, n.d.), as well as by the Maritime Provinces Higher Education Committee (Richard, 2016), Brock University (Brock University, 2017), and the University of British Columbia (University of British Columbia, n.d.), to name a few. The learning outcome starts with a verb describing the specific action students will perform, then the actual content of the learning outcome, followed by the specific context the outcome takes place in.

Take a poorly-phrased example learning outcome tailored to the surveyed materials science course in this study: “Appreciate the relationship between material properties and manufacturing processes.” It is difficult for a student to demonstrate their appreciation or for their instructor to verify it. As well, the relationship between material properties and manufacturing processes is a very broad subject, essentially amounting to the entire study of materials science. A better learning outcome would be, “Explain the relationship between heat treatment processes and material properties for the steel specimens covered in Unit 3.” Students are provided with a specific action they will perform, and the content and context are sufficiently narrow in scope.

The key component of constructive alignment is developing learning activities and assessments that support the stated learning outcomes. For the previous learning outcome, learning activities should teach the relationship between the manufacturing processes and material properties and involve a component where students explain this relationship. This allows them to develop competencies relevant to the learning outcome. As well, the assessment should involve explanation, taking forms such as written response questions on an examination or an oral examination. Under this model, the learning activity specifically addresses the learning outcomes and develops competencies that students can employ in their assessment. A poor example would be a design course where stated learning outcomes involve teamwork and communication skills, and learning activities involve group projects, but assessments are written examinations completed individually. Students do not have an opportunity to demonstrate their teamwork and communication skills in their assessment, and the instructor cannot verify that the learning outcome has been met.

Note that, in this example, written examinations may still have a place; another learning outcome may be, "Explain the principles of the design process for engineering projects." The written examination would be able to evaluate this outcome. Not every learning activity and assessment in an aligned course must meet every learning outcome; indeed, this could harm the learning experience by overwhelming students and requiring skills that they will only develop in a later unit of the course. Likewise, multiple different activities and assessments can align to a single learning outcome. Constructive alignment simply means that every learning outcome has some learning activity and assessment associated with it in a constructive manner.

2.3.4 The Zone of Proximal Development

The zone of proximal development is used in this work as a tool to develop learning outcomes and activities that further develop student competencies without being too easy or too challenging to the student. It is used in analysis of the survey results (see Section 5.1) in conjunction with the revised Bloom's taxonomy (see Section 2.3.1). Together, these frameworks explain how learning outcomes in the engineering laboratories may be too high or too low to meaningfully develop student competence.

The concept of the zone of proximal development is a simple one. Learners can conduct learning activities in one of three zones based on their level of competency in the activity and the level of instructor assistance required (Vygotsky, 1978). When students are completely competent in a given activity, they occupy a zone where they can operate independently without assistance. At the other end of the spectrum where students have no competency in the given activity, they occupy a zone consisting of activities they are simply unable to complete even with assistance. In between these two zones is the zone of proximal development, where a student is able to exhibit some competency but needs instructor assistance to complete the given activity (Vygotsky, 1978). Vygotsky proposes that it is in this zone that learning occurs. The zone of proximal development is illustrated in Figure 2.3.

Aligning learning activities with students' zones of proximal development is found to improve student mastery over unaligned learning tasks (Baker et al., 2020). In conjunction with the revised Bloom's taxonomy, learning outcomes with students' zones of proximal development are found to be more effective (Sideeg, 2016). Given the demonstrated utility of aligning learning with the zone of proximal development, this framework is used in Section 5.1.4 to aid in analyzing how to improve learning outcomes in the laboratories.

This carries important implications for course design. If learning occurs in the zone of proximal development, then course materials positioned outside of this zone do not result in learning. As will be explored later in Chapter 5, positioning learning activities in the zone where students can complete the activity unaided can result in a perception of tedium and result in disengagement, while activities that students are unable to complete can result in frustration.

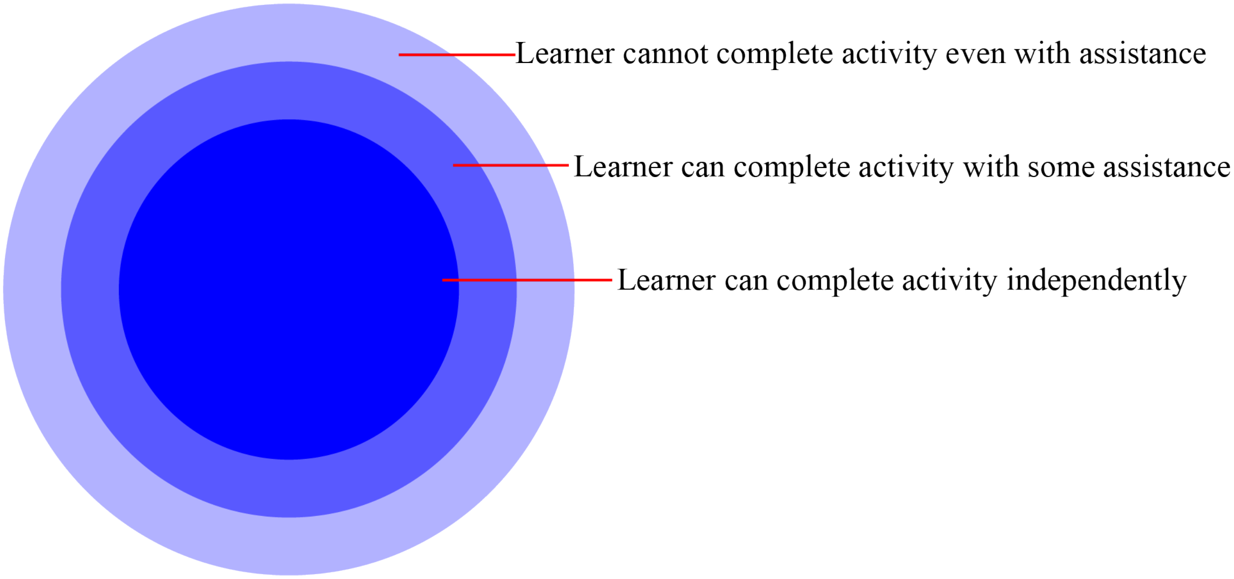


Figure 2.3: Visualization of the zone of proximal development.

2.4 Important Definitions

In developing this study, it is important to understand common definitions of motivation and of assessment. While not extensive enough to be considered theoretical frameworks or theories of learning, these are valuable concepts in redesigning a learning experience. The distinction between intrinsic and extrinsic motivation, and between formative and summative assessments, will be explored, and their use in this study explained.

2.4.1 Intrinsic and Extrinsic Motivation

So far, the nature of learning has been examined in terms of the learning experience and the reflection that follows. However, it is also valuable to explore the input to the learning experience: the learner themselves. Given that one goal of this study is to improve the learning experience, it is important to understand student engagement and motivation in the learning laboratories.

Engagement in an experience is dependent on the level of the learner's motivation, which can be defined using self-determination theory (see Section 2.2.4) and the concepts of intrinsic and extrinsic motivation. These concepts are used as a framework to understand and improve student engagement in laboratories.

Motivation is "to be moved to do something" (Ryan and Deci, 2000, p. 54). Ryan and Deci identify that motivation varies between individuals in terms of level and orientation; orientation of motivation is determined by the underlying attitudes and goals in the individual.

Ryan and Deci (Ryan and Deci, 2000) broadly classify motivations under two categories: intrinsic and extrinsic. **Intrinsic motivation** is internally sourced and causes an individual to do something because they find it inherently interesting or enjoyable; in contrast, **extrinsic** motivation is externally sourced and leads to a separable outcome not directly derived from the experience.

An example will serve to illuminate this difference. Consider a child learning to play the piano. They may be learning because they enjoy playing music and want to improve their ability; this is intrinsic motivation. However, they may also be learning because their parents want them to; this is extrinsic motivation, and the outcome of satisfying the parents is separable from the means of learning the piano.

Research has repeatedly shown that intrinsic motivation is considerably more powerful than extrinsic motivation in generating high-quality learning and creativity (Ryan and Deci, 2000). However, extrinsic motivation can also be a sufficient motivator, and no task will instil intrinsic motivation in every participant. It is therefore important not to neglect extrinsic motivation in curricular development.

The spectrum of human motivation from extrinsic to intrinsic motivation is illustrated in Figure 2.4. While the primary definitions of intrinsic and extrinsic are the primary contribution of this section to this study, these finer definitions are also used in places to relate motivation in the learning laboratories to motivation for the course, overall degree program, and professional careers, utilizing situated cognition theory (see Section 2.2.1).

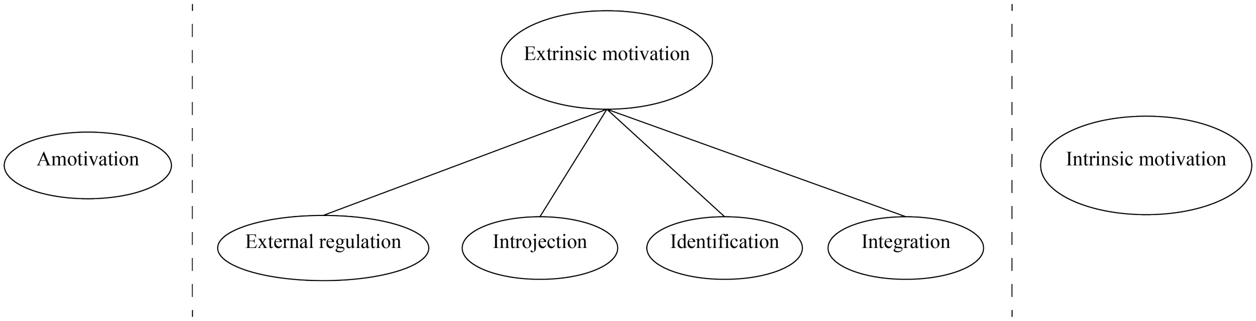


Figure 2.4: The spectrum of human motivation (Ryan and Deci, 2000, p. 61)

From Figure 2.4, **amotivation** is a lack of motivation, therefore holding the lowest amount of motive power, and may arise from not valuing an activity, feeling incompetent, or believing the activity won't result in a valued outcome (Ryan and Deci, 2000). An amotivated piano student has lost interest, possibly due to struggling in their practice or not seeing the point in improving their proficiency. It is clear that amotivation in students is to be avoided.

Again from Figure 2.4, the weakest form of extrinsic motivation is **external regulation**, which are behaviours performed for an external demand or reward (Ryan and Deci, 2000). At this point, the piano student may only be practising due to pressure from their parents.

Next, Ryan and Deci (Ryan and Deci, 2000) define a stronger form of extrinsic motivation called **introjected regulation** or **introjection**, where an individual is regulated by self-esteem due to social pressures. At first glance this may appear to be identical to external regulation; however, the self-esteem component is based on gaining social rewards or to avoid guilt and anxiety, which are outcomes separable from the behaviour. A piano player experiencing introjection may only practice because their parents are approving of the practice, or because their friends are musically inclined and they want to fit in.

Ryan and Deci's (Ryan and Deci, 2000) next form of extrinsic motivation is **identification**, in which the individual identifies the importance of an extrinsically motivated activity with a broader intrinsically motivated goal. This marks the inflection point between shifting away from extrinsic motivation and shifting towards intrinsic motivation. The authors illustrate this with an example: a child memorizing spelling lists because they want to become a writer is engaging in identification; intrinsic motivation is present for the larger goal of becoming a writer, but the child is only motivated to memorize spelling lists because they perceive it as key for their larger goal. The piano player mentioned previously may experience identification in practicing scales and chord progressions. While this activity isn't enjoyable in and of itself, the player understands that the activity improves the overall proficiency that they value.

The most autonomous form of extrinsic motivation identified by Ryan and Deci (Ryan and Deci, 2000) is **integrated regulation**, where the learner assimilates identified regulations. This occurs through self-examination and bringing new regulations into congruence with one's values and goals. While the piano player is still practicing due to external factors like parental pressure, they now see value in the practice and are investigating what constitutes proficiency and skill in playing piano.

Further assimilation and integration of these external regulations results in an individual's actions becoming more self-determined (Ryan and Deci, 2000). However, the authors clarify that this behaviour is still a form of extrinsic motivation because the behaviour is done to obtain a separable outcome. The piano player only exhibits intrinsic motivation when they are practising because they want to improve and because they personally value proficiency.

2.4.2 Formative and Summative Assessments

The last part of the learning experience to examine is how learning is assessed. Here, **assessment** is used to describe any activity intended to evaluate student learning. This evaluation of assessment types will be used in developing the new laboratory framework. Combined with constructivism (see Section 2.2.2) and situated cognition theory (see Section 2.2.1), this distinction shows how assessments aid in developing student competencies and how they can be related to professional applications.

When people think of assessments, they are likely thinking of what Dixson and Worrell (Dixson and Worrell, 2016) identify as summative assessments such as term projects or final exams. **Summative assessments** are intended to evaluate learning outcomes and make placement or promotional decisions, such as using a high school student's final test score to determine eligibility for a university program. These assessments are generally formal and high-stakes and are always a cumulative assessment occurring after instruction on a topic has concluded. These assessments seek to ascertain if students understand the material, and if they are prepared for the next level of activity.

Dixson and Worrell (Dixson and Worrell, 2016) explain that **formative assessments**, on the other hand, are intended to improve teaching and learning and diagnose any difficulties students may be having. These assessments are generally informal and continuous, taking place before and during instruction. The stakes are considerably lower, as the instructor is seeking to know what is working and what needs to be improved within the course. Formative assessments can be more formalized such as homework, but can also be quite informal, possibly as simple as the instructor asking students if they understand the material.

Higher education courses can be quite large, consisting of hundreds of students across several sections. A challenge encountered at this scale is monitoring the individual sections and ensuring consistency across the course in instruction and grading (Glazer, 2014).

It has been found (Glazer, 2014) that a combination of formative and summative assessment can help cope with this challenge. A benefit of this setup is that a summative assessment administered by the course coordinator across all sections helps to reduce subjectivity and bias in grading. Another benefit is that students are more prepared for summative assessments due to the numerous formative assessments across the course of the semester.

Situated cognition theory argues that learning and knowledge are context-dependent, while constructivism puts forth that learning is the process of adding to and verifying one's internal knowledge structure. In this context, formative assessments can be seen as a tool to construct an understanding of the assessment process, which is then tested in summative assessments. Both assessment types and the necessary skills they require are contextualized in engineering education by professional engineering applications. This concept was explored further in Section 2.3.3.

It is important to note that, despite the perceived benefits, formative assessments are not a panacea to improving the learning experience and learning outcomes. Due to the high stress and pressure in any given university course, if assessments are not for marks, many students either do not complete the assessment to the best of the ability, or do not complete it at all (Edwards, 2022). Therefore, inclusion of formative assessments must be balanced with the student tendency to disregard assessments that are not factored into the broader course grading scheme.

2.5 The Educational Context

The components of the learning space have been examined. Now, the context of that learning will be explored. This research endeavour takes place at the University of Calgary in Alberta, Canada, and examines the undergraduate mechanical engineering laboratories. As such, it is important to understand the educational expectations of the University of Calgary and of the Provincial Government of Alberta, which provides significant funding and regulatory oversight to the University.

2.5.1 Expectations from the University of Calgary

Experiential Learning Plan for the University of Calgary

Experiential learning has become a focus of educational institutions in the years since Kolb's initial paper (Kolb, 1984). The University of Calgary has expressed an interest in applying experiential learning to the courses offered by the university and has published an Experiential Learning Plan (Kaipainen et al., 2020), which provides the following definition of experiential learning:

> "Experiential learning (EL) is learning-by-doing that bridges knowledge and experience through critical reflection. EL activities are intentionally designed and assessed. As such, they empower learners to enhance individual and collaborative skills such as complex problem solving, professional practice skills, and teamwork. Reflecting critically on these activities helps individuals develop higher-order thinking to challenge and advance their perspectives. The EL process prepares students to take on roles as active citizens and thrive in an increasingly complex world."
>
> (Kaipainen et al., 2020, p. 3).

The University of Calgary's Experiential Learning Plan also provides three priorities for enhancing experiential learning: expanding capacity and reducing barriers, increasing student opportunities, and tracking and ensuring high-quality experiential learning (Kaipainen et al., 2020). This research endeavour aids in addressing the final goal.

Guiding Principles for Assessment

The Taylor Institute for Teaching and Learning at the University of Calgary published a document outlining the guiding principles for assessment of students' learning (Lindstrom et al., 2017). Selections from these principles outline how laboratory assessments can be improved to enhance student learning outcomes.

First, assessments should be planned so as to provide practice opportunities and allow students to receive feedback on their learning (Lindstrom et al., 2017); as laboratories are intended to develop student learning rather than evaluate it, formative assessments should be implemented to enhance student learning outcomes. This supports the framing of laboratory assessments as more formative than summative. Second, assessments should reflect the work of their disciplines (Lindstrom et al., 2017). Supporting the professional context of engineering explored in Section 2.2.1, this shows that laboratory assessments should therefore be similar to the work students are expected to complete in industry. Third, assessments should include reflection, self-assessment and goal setting, focusing on how students can use assessment results to influence future work (Lindstrom et al., 2017). This further supports the assertion that laboratory assessments should be more formative than summative. Sixth, the rationale for selected assessment strategies should be explained to students; a debriefing and reflection strategy around assessments can strongly impact both teaching and learning decisions (Lindstrom et al., 2017). This may aid in improving student motivation by better meeting the psychological need for competence, as explored in self-determination theory: if students better understand how and why they are being assessed in a particular way, they should feel more competent in completing that assessment. This also highlights the importance of clearly communicating course elements to students. Seventh, the use of varying assessment strategies builds communication skills and provides the opportunity for students to demonstrate their learning in different ways. Recall from self-determination theory that having a choice in how students are assessed improves student autonomy and therefore motivation. Ninth, provide resources to meaningfully develop assessment skills in assessors, with the goal being to provide a fair and consistent assessment strategy. This shows the importance of balancing educational interventions with available resources.

Drawing from these guiding principles, Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) go on to summarize key findings regarding their impact on teaching and learning, and how to integrate these principles for broader impact. These findings are used in developing laboratory recommendations in Chapter 6.

The first key finding from Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) concerns enhancing teaching and learning culture. It is argued that explicit guiding principles in assessment are a response to an increasing need for accountability and transparency in grading. Since assessments are generally the last portion of a curriculum to be developed but are students' first concern in a course, student assessment can be repositioned as a strategic tool for enhancing teaching and learning. Using well-designed assessment principles align with a more learning-centred approach to teaching and learning. This shows the importance of intentionally aligning the assessment with the rest of the learning experience.

The next key finding from Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) is the importance of these guiding principles in developing teaching practice and course design. These principles assist teachers in realigning assessment practices to be more responsive to student needs. Guiding principles of assessment aid in organizing assessment practice, identifying effective practices, and utilize information to enhance the educational experience and focus the individual and collective goals and activities of the teachers at an institution. The authors emphasize that "the use of assessment information to improve learning cannot be separated from the instructional system within which it is provided" (Lindstrom et al., 2017, p. 12), again highlighting the importance of alignment with the rest of the learning experience.

Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) identify self-assessment strategies as a powerful tool in students' learning and their overall university experience. Self-assessment helps students understand what constitutes good work.

The authors (Lindstrom et al., 2017) state that assessment principles can actively inform the course design process, helping to align authentic learning experiences, assessment, and course outcomes. These principles better enable instruction and equity in learning opportunities, promoting collaboration and dialogue, and highlighting that assessment reform is holistic in nature, requiring input from multiple stakeholders. With regards to this guiding principle, the final note from the authors is that dissemination of the results of assessment reform contributes to a literature base that teachers and scholarship of teaching and learning practitioners rely upon.

The next key finding from Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) is how these guiding principles aid in developing skills for learning, work and life. Implementing research-based inquiry in assessment can provide academic institutions with the means to improve student experience, better developing academic skills and preparing learners for their future careers. Sustainable assessment is positioned as a way of thinking rather than of doing, recognizing that learning does not occur in isolation from a student's experiences. Integration of learning makes it available to students beyond the course context and throughout their lives. This supports the use of the scholarship of teaching and learning in ensuring teaching methods are based in evidence.

Next, Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) identify these guiding principles as enhancing formative assessment. Guiding principles for assessment support students in becoming self-regulated learners and emphasize the importance of feedback on motivation and self-esteem; there is a strong connection between self-regulated learning and assessment, and students' motivation in that motivation is constructed based on a student's appraisal of the teaching, learning and assessment context. This is particularly important in engineering, where practitioners are expected to maintain their professional competencies (Engineers Canada, n.d.-b). The quality and frequency of feedback can influence retention in first-year studies and can promote self-regulation of learning. An important aspect of this is positioning students as active agents in assessment of their learning, rather than passive receivers of the results of an assessment; the authors state that students' actions with regards to feedback may be more important to learning than the actual quality and content of feedback.

The next key finding from Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) is in fostering academic integrity. Instances of plagiarism are minimized by selecting assessment tasks, creating transparency in assessment criteria, and avoiding ambiguous or unclear feedback. Formative assessment feedback focused on the self-regulation of learners can mitigate the factors that contribute to plagiarism; namely, lack of clarity regarding assessments and lack of student confidence in achieving a learning goal.

The final key finding made by Lindstrom, Taylor and Weleschuk (Lindstrom et al., 2017) is the integration of principles and practice. Principles and practice exhibit a reciprocal relationship; insights from critical examinations of assessments can generate guiding principles for assessment. Evidence-based principles of assessment can bridge the gap between the recent changes in teaching strategies and theories, and the relatively static and unchanging area of assessment approaches. These principles help in forming the basis for assessment to focus learning on students. The gap between principles and practice involves a three-way interaction between personal practice, public principles, and a shared network of practice; this interaction is essential to improving both principles and practice.

2.5.2 Expectations from the Government of Alberta

As a major source of funding for the University of Calgary, the provincial government was identified as a major stakeholder in engineering education in an early stage of the study. Literature from the Ministry of Advanced Education was reviewed, and the Ministry was contacted regarding the study in April 2022. The Ministry response primarily referenced public training programs and did not make mention of engineering education in particular or laboratories, and is therefore excluded from this literature review.

The Ministry of Advanced Education Business Plan

The claim that the Government of Alberta wants more industry-relevant opportunities to be included in post-secondary education is supported by the Ministry for Advanced Education Business Plan (Government of Alberta, 2021). Aligning post-secondary education developments to provincial goals is a key factor in the development of this study ; given the substantial reductions in provincial post-secondary funding in the 2021 provincial budget (French, 2021), ensuring alignment with the provincial government provides a greater likelihood for increased institutional funding.

In their business plan the provincial government (Government of Alberta, 2021) identifies a key objective:

“Strengthen the alignment of post-secondary programs to employment and meet Albertans’ skills development needs to support their transition to the labour market.” (Government of Alberta, 2021, p.4).

This supports the alignment of engineering education with professional engineering practice, previously explored in Section 2.2.1.

Chapter 3

Study Approach and Design

Now that the theory underlying this research endeavour has been explored, the study approach and design can be discussed. This chapter will first describe the research approach in Section 3.1. The application of this approach to the design of the research endeavour will then be discussed in Section 3.2. Finally, the scope of this research and the results will be outlined in Section 3.3.

3.1 Research Approach

This section outlines the approach to this study. Building upon the epistemologies outlined in Section 2.1, qualitative surveys are selected as the research method in Section 3.1.1, and qualitative content analysis is selected as the methodology in Section 3.1.2.

3.1.1 Qualitative Surveys as the Research Method

Recall from Section 1.1 that this study is motivated by current mechanical and manufacturing engineering students at the University of Calgary stating that they do not perceive connections between their laboratories and their courses, or between the labs and their future careers, in a mandatory third-year materials science course. As well, there are calls from the Provincial Government of Alberta and the University of Calgary for undergraduate curricula to contain more experiential learning opportunities. Finally, there are calls from local engineering industry for engineering education to include more practical and career-oriented learning opportunities.

From this motivation, four key stakeholders are identified:

1. Students currently enrolled in the course and experiencing the laboratories. These are the most im-

portant stakeholders as the laboratories are intended to serve their educational needs.

2. Members of engineering industry who will employ students following their graduation. Student career prospects are directly dependent on how they are perceived by the companies and individuals who will be employing them.
3. University administration and faculty, who are invested in improving student learning outcomes and having graduates be perceived as educated and employable.
4. The provincial Ministry of Advanced Education, which is a significant source of post-secondary funding. This is considered to be the least important stakeholder, as funding is not provided to specific courses or laboratories, and the province is more interested in general educational and career outcomes.

Information on stakeholder goals was available from the provincial Ministry of Advanced Education and University administration and faculty and was presented in Section 2.5. However, information was needed on the goals and desires of engineering industry and the students themselves.

Viewed from a situated cognition perspective (see Section 2.2.1), these two groups are the most important stakeholders in the learning laboratories. The importance of students is clear, as they are the ones experiencing the laboratories and being assessed, and the success of the laboratories are dependent upon those students achieving the stated learning outcomes. Managers from local industry are also a key stakeholder because engineering is a professional discipline, and engineering education is situated within that disciplinary context. These managers will be interviewing and hiring these students, and so the success of the laboratories as a learning experience is dependent upon the career-relevant learning outcomes achieved by students.

The importance of these stakeholders is clear, but their desires and goals in the learning laboratories is not. Research is needed to identify these goals.

Qualitative surveys were selected as the method for finding student and manager goals, relationships, and experiences with engineering learning laboratories. Following this study's use of interpretivism (see Section 2.1.2) and situated cognition theory (see Section 2.2.1), qualitative methods were selected over quantitative ones. The student learning experience is viewed as situated within the laboratory and is a subjective experience open to interpretation. Qualitative surveys allow this subjective experience to come through; the more rigid structure of a quantitative survey, asking students to rate aspects of their experience on a scale and seeking numerical survey results, would limit this subjectivity and exclude aspects of the student experience that the researchers did not account for.

3.1.2 Qualitative Content Analysis as the Research Methodology

Given the choice of qualitative research methods, the chosen methodology for this study is qualitative content analysis. The following section provides a general overview of this framework and how it is applied in this work.

Qualitative content analysis is a systematic and objective process for analyzing qualitative data such as survey responses or interview transcripts (Elo and Kyngas, 2008). The many words present in the text under analysis are classified into significantly smaller content categories which can then be used in analysis. This method of analysis was chosen because it is content-sensitive and flexible, allowing for content to be analyzed based on themes originating both in the area of research and from the content under analysis.

The first step is to select the unit of analysis. This is the section of data that will be assigned to a category or theme, and can be as large as an entire document or as small as a single letter; the amount of time an interview took or the number of participants in discussion can also be used. Selecting the size of the unit is important. It must be large enough that it entirely captures the meaning contained within the analyzed work, but small enough to meaningfully break down the work into themes. Consider an example of analyzing a book. One might decide that each chapter constitutes a unit of analysis, but if each chapter contains sections that can be analyzed on their own, a chapter may be too large. Likewise, the researcher may decide to take each sentence as a unit of analysis. This may be too small, as each sentence may not make sense without the context of the larger chapter. As well, the book may contain thousands or tens of thousands of sentences, complicating the analysis. Analysis can also solely consider the manifest content that has been recorded, or latent content, such as posture and tone during interviews.

For this work, each individual survey response was used as a unit of analysis. A larger unit would require that each response be associated with its particular respondent, which was not available in the Qualtrics survey platform utilized for this study. A smaller unit, such as a single sentence within a response, would lose the context of the broader response.

Two analytical approaches are available (Elo and Kyngas, 2008). An inductive approach is used when former knowledge regarding the phenomenon under question is minimal or fragmented. Inductive analysis draws content categories from the data being analyzed; themes are developed based on the impressions formed by reading and rereading the content under analysis. A deductive approach is used when there is a strong theoretical background present and the study is intended to test theories; before the content is read through, themes are developed based on literature.

An inductive approach is used in this work to allow categories to be generated from survey responses. This follows the use of the interpretivist epistemology described in Section 2.1.2, valuing the subjective experience of survey respondents. An additional advantage is that the inductive approach combines particular instances of themes in responses into a larger whole, allowing the theories explored in Chapter 2 to be applied to the specific phenomena present in the course being analyzed.

After an analytical approach is chosen, the next step is to make sense of the data and gain an understanding of the entire data set. The researcher is to keep in mind the following questions:

- Who is telling?
- Where is this happening?
- When did it happen?
- What is happening?
- Why?

The written material is read through several times until a complete understanding is gained.

For the selected inductive content analysis process, the researcher now organizes the qualitative data. Notes are taken while reading through the data, seeking to describe all aspects of the content. These headings, categories and themes are then collected; similar headings are collapsed together and listed under broader content categories. This process continues until the content is completely described by the categories and sub-headings.

This collection of codes is then used in further analysis to facilitate discussion and draw conclusions. In this work, the frequency of codes is used to determine the relative emphasis respondents placed on different laboratory themes.

The qualitative coding process is visually summarized in Figure 3.1.

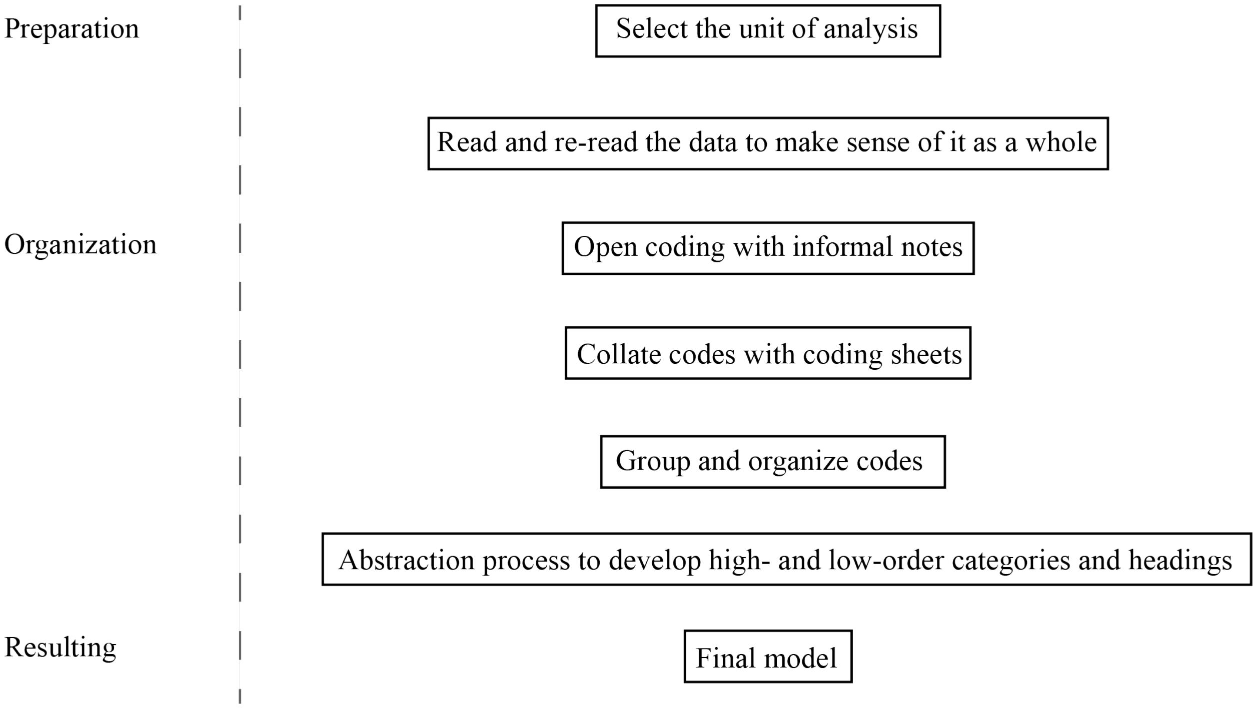


Figure 3.1: Flow chart of the qualitative coding process.

Having described the general research approach, the specifics of the research design will now be explored.

3.2 Research Design

This section describes how the research approach described in the preceding section is applied to this particular research endeavour. The participant selection criteria is explained in Section 3.2.1, followed by the construction of the qualitative surveys in Section 3.2.2. Data collection, processing, and analysis are described in Sections 3.2.3, 3.2.4, and 3.2.5, respectively.

3.2.1 Survey Participant Selection Criteria

Students

Recall from Section 1.1 that the students whose end-of-semester surveys partially motivated this study were enrolled in a mandatory third-year materials science course, designated ENME421, in the Department of Mechanical and Manufacturing Engineering at the University of Calgary. This course was selected for the qualitative surveys. While engineering students taking laboratories in other courses may have the same complaints as past students enrolled in this course, this course motivated the study. Further preceding surveys would be required in other courses to determine if they were experiencing the same issues, increasing the amount of time required for this study. As well, choosing multiple courses would result in an overly large dataset that could present difficulties in analysis due to the limited time available.

Students were eligible to participate in the surveys if they were currently enrolled in the mandatory third-year materials science course during the Fall 2022 academic semester, which ran from September to December of 2022.

Managers

In analyzing the goals of engineering industry in relation to the course under question, it was decided that participants would be members of industry employed by an Albertan engineering company that practiced in the area of materials science. Individuals were eligible for participation if they had experience managing recent University graduates, defined as individuals who had graduated from the program within the past five years, or student interns currently enrolled in the program. Participating companies were drawn from professional networks and from those who had participated in the University's engineering internship program, which takes place between a student's third and fourth year.

3.2.2 Research Methods

For both the manager and student groups, the qualitative surveys described in Section 3.1.1 were delivered online via the Qualtrics survey platform, as this platform is preferred by the University of Calgary. Online surveys allowed flexibility in delivery, not requiring printed materials or an in-person presence for administration.

Student Surveys

Student surveys were structured along Ash and Clayton's DEAL model, described previously in Section 2.3.2, asking students to objectively describe their laboratory experience before examining the experience in-depth, followed by articulation of their learning. Note that the articulation step is minimal in the surveys; while students experienced learning in their laboratories, the surveys themselves are not intended to be a learning experience for participants. Rather, the 'Describe' and 'Examine' steps are utilized to aid and deepen student reflection on the laboratory experience. The revised Bloom's taxonomy, described previously in Section 2.3.1, was used as a tool for students to assess their learning outcomes. An identification question asked for names and identification numbers for administration purposes, but is removed in this work for anonymization purposes. The relevant student survey questions are as follows:

1. Please objectively describe your experience in your recent Laboratory 2 in [surveyed materials science

course]. When and where did this laboratory take place? Who facilitated or led the laboratory? What experiment did you conduct in this laboratory? How was this laboratory assessed?

2. A common tool to classify learning outcomes is Bloom's taxonomy, which classifies educational goals from the most basic to the most complex. Given these definitions, please indicate which level of learning you were asked to apply in this laboratory. Do you find this to be an appropriate learning outcome for the laboratory and course? Are there actions the facilitator could take to enhance the level of learning? Are there actions being taken that reduce your level of learning?

3. Thinking back to laboratories you've taken in the past, whether at the high school or university level, what was the best or most positive experience you have had in a laboratory? Using Bloom's taxonomy, what level of learning were you asked to apply? What actions did facilitators take to make this a memorable experience?

4. Thinking back to laboratories you've taken in the past, whether at the high school or university level, what was the worst or most negative experience you have had in a laboratory? Using Bloom's taxonomy, what level of learning were you asked to apply? What actions did facilitators take to make this a negative experience?

5. Did this most recent [surveyed materials science course] laboratory impart skills and knowledge that you believe are useful in your academic and professional career? These benefits do not need to be "hard" skills such as a particular piece of materials science knowledge, they can also be "soft" skills such as skills in group work or in report writing.

6. Please consider the survey you have just completed. If you have any observations or comments on the [surveyed materials science course] laboratories or engineering laboratories in general that was not covered in these questions, please provide them here.

Manager Surveys

Surveys released to managers in local engineering companies were developed to ask participants about their perception of university graduates in terms of employability, as well as identify if participants were aware of certain related University or provincial initiatives.

An identification question asked for names and companies for administration purposes, but is removed in this work for anonymization purposes. The relevant manager survey questions are as follows:

1. Please briefly describe what your company does.

2. What experience do you have in directly supervising recent graduates of the University of Calgary's engineering program?
3. How well do you feel that recent graduates are prepared for a career in materials science?
   - Unprepared
   - Somewhat prepared
   - Neither prepared nor unprepared
   - Somewhat prepared
   - Greatly prepared
4. In your opinion, what does the University of Calgary do well in terms of preparing engineering students for a career in materials science? What knowledge and skills does the program impart that are useful for this career?
5. In your opinion, what could the University of Calgary do better in terms of preparing engineering students for a career in materials science? Are there specific skills or knowledge that you expect graduates to have, but don't?
6. In your opinion, what techniques, skills and knowledge should be taught in undergraduate materials science laboratories to properly prepare students for employment in the materials science industry?
7. What does experiential learning mean in your workplace or to yourself?
8. Are you aware that it is part of the University of Calgary's Eyes High strategy to have at least one experiential education experience during a student's undergraduate degree?
   - Yes
   - No
9. Do you think laboratories count as an experiential learning experience?
   - Yes
   - No
10. If not, why? Please explain.
11. Are you aware that the Government of Alberta will be assessing the performance of the University of Calgary partially on the number and quality of experiential learning opportunities made available to students?

  - Yes
  - No

12. Do you believe that experiential learning opportunities are an important component for the training of new recruits into your firm?

13. In your opinion, should universities emphasize theory and knowledge when educating new engineers, or focus on more practical applications that are common in industry?

14. Since every company or industry has varying requirements and skillsets for potential recruits, do you have any opinions or ideas on balancing widely valued skills with more company- or industry-specific job skills?

15. Do you have any other comments or concerns regarding undergraduate engineering education in materials science that were not addressed in this survey? If so, please record them here.

3.2.3 Data Collection

The surveys were approved by the University of Calgary Conjoint Faculties Research Ethics Board under the identification number REB21-1958. All research at the University of Calgary involving human participants is required to receive ethics approval before research can commence.

For the student surveys, a researcher went to a lecture for the materials science course under question during the first week of class in the Fall 2022 academic semester to discuss the project with students and request their participation. Interested students contacted the researcher via email, following which they were provided with an informed consent document. When this document was signed, dated, and returned to the researcher, a link to the survey was provided. Please note that participation in this study was encouraged through the use of incentives; each student participant was given a $10 Starbucks gift card upon completion of the survey.

For the manager surveys, potential employer participants were contacted via email and provided with an overview of the study. Upon expressing interest, participants were provided with an informed consent document. When this document was signed, dated, and returned to the researcher, a link to the survey was provided. Manager surveys were released between May 2022 and April 2023.

Responses to both surveys were automatically collated by the Qualtrics platform. When the surveys were closed, responses were saved to separate documents, which were then used for analysis.

3.2.4 Data Processing

After survey responses were saved, they were anonymized, a process by which all personally identifying information was removed from responses. Participant names, company names, dates and locations of laboratories attended, facilitator names, and course codes were removed from the responses and replaced with generic identifiers. The coding sheet linking participant names to the identifiers used in publication was stored on a secure, encrypted University server, separate from the anonymized data and the original dataset.

3.2.5 Data Analysis

The data was analyzed using the qualitative content analysis process described previously in Section 3.1.2. When the process of assigning themes to responses was complete, the frequency of the total number of survey responses each theme was found in was expressed as a percentage of the overall number of survey responses. This frequency percentage is used to determine how strongly a given theme represents student sentiment. As well, response themes that only appeared a single time are excluded from this analysis. Certain response themes appeared both in the positive, as an action whose inclusion enhances the laboratory learning experience, and in the negative, as an action whose exclusion harms that laboratory learning experience. Themes that were affirmed both positively and negatively are considered to be more prominent than themes that occurred solely in the negative or positive.

3.3 Research Scope and Participant Limitations

This study is limited by the scope of the solicited participants. Student participants were drawn from a single third-year materials science course, and results do not necessarily represent the entire body of Canadian engineering students.

As well, a portion of the analysis conducted in this study is based in linking laboratory actions to career outcomes. However, the students being surveyed have not been employed by engineering companies in a professional context, and the surveyed managers have not employed the surveyed students. Results in this area may not necessarily reflect this link. A follow-up study with the student cohort under question, taking place either after their internship or full-time employment, is recommended to better capture this link.

Finally, participants were asked to describe their subjective experience and perspective in their laboratories. These laboratories may have occurred anywhere from a few days prior to the response being written in the case of the current surveyed materials science course, to several years prior in the case of past laboratory experiences. The interpretivist stance described in Section 2.1.2 values these individual perspectives, but it is important to acknowledge that memories can change over time and that responses may not accurately describe the experience in question. As well, when evaluating their skills and learning outcomes, students are self-reporting and may under- or overestimate their competencies.

Chapter 4

Results

The results of the surveys will now be presented, beginning with the student surveys in Section 4.1 and then the manager surveys in Section 4.2.

4.1 Student Surveys

This section will first describe the qualitative coding matrix generated from student surveys, then the response frequency percent of the identified themes. Raw anonymized student survey results are provided in Appendix A. Of the approximately 100 student class, 21 individuals participated. Excluding the identification question from the survey, this generated 87 unique responses; each theme's response rate is expressed as a percentage of this total response rate.

The student surveys are in response to a series of laboratories included in the mandatory third-year materials science course, ENME421. This consisted of four laboratories. In the first, students familiarized themselves with material selection software. Most participants completed the survey following the second laboratory, which involved cold rolling, sectioning, and heat treatment of a brass plate. The third laboratory prepared and analyzed metallographic samples of the previously-used brass plates. These same plates were also subject to mechanical testing in the fourth laboratory. The full laboratory manual is provided in Appendix C.

It is important to note that, as explained previously in Section 3.2.2, these surveys included questions both on the students' current series of ENME421 laboratories and past positive and negative laboratory experiences. The latter questions are used in Chapter 5 to aid in analyzing the student laboratory learning experience.

4.1.1 The Student Qualitative Coding Matrix

The themes contained in student responses were found to fall into three high-order categories: actions affecting the laboratory learning experience, the level of learning in laboratories according to Bloom's taxonomy, and the benefits of the laboratories to future engineering careers. Learning actions were found to belong to one of four low-order categories: pedagogy, or the design and intention of the laboratory; the laboratory experience itself; the facilitators who led the laboratory; and the graded assessment of the laboratory. Additionally, responses indicated actions whose presence either enhanced or detracted from the learning experience. Laboratory learning levels were expressed as either appropriate or inappropriate due to being too high or too low. The breakdown of themes into these categories is shown in Table 4.1.

Table 4.1: The qualitative coding matrix for student survey results.

High-Order Category	**Low-Order Category**
Actions Affecting the Learning Experience	Pedagogy
	The Laboratory Experience
	Assessment
	Facilitator
Laboratory Learning Levels	Current Laboratories
	Past Positive Laboratories
	Past Negative Laboratories
Benefits to Engineering Career	*No Low-Order Category*

With this explanation of the coding matrix, the themes and their response frequency can now be presented.

4.1.2 Student Survey Results

Raw anonymized student survey results are provided in Appendix A.

As mentioned in Section 3.2.5, response themes that occurred in only a single response are excluded from analysis.

The frequency of response themes relating to actions affecting the laboratory learning experience are presented in Figure 4.1. "Actions affecting the learning experience" refers to specific actions taken or not taken by the course coordinator, instructors, and laboratory facilitators. The most prominent themes by frequency are the inclusion of a hands-on experience, efficient use of time and reduction of time pressure, and professionalism in facilitators.

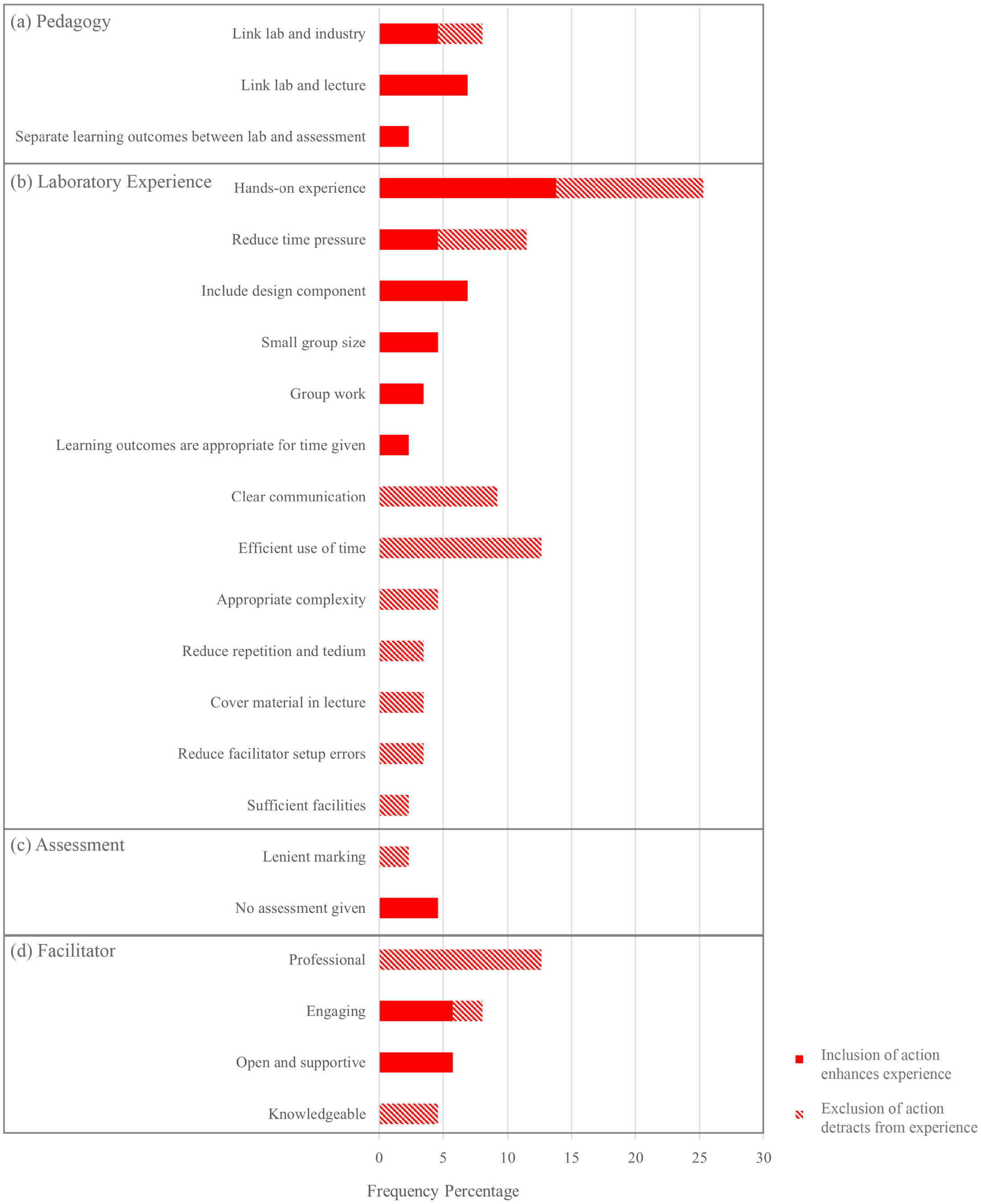


Figure 4.1: Student survey response theme frequency of laboratory actions in the (a) “pedagogy”, (b) “laboratory experience”, (c) “assessment”, and (d) “facilitator” categories.

These themes are organized along the low-order categories shown in Table 4.1: pedagogical actions, actions within the laboratory assessment actions, and facilitator actions, shown in Figure 4.1(a) through (d), respectively.

The frequency of response themes on the perceived career benefits of laboratories are presented in Figure 4.2. These themes are the skills and knowledge developed by the laboratory that students perceive to be valuable in their careers following graduation. This figure shows that the career benefit of laboratories is primarily perceived to be industry practices and knowledge, also known as "hard skills". Hard skills are highly technical and industry-specific, such as understanding how to operate a tensile testing machine to identify mechanical properties of a material. Soft skills, on the other hand, are more general and applicable to a wide variety of roles, such as written and oral communication.

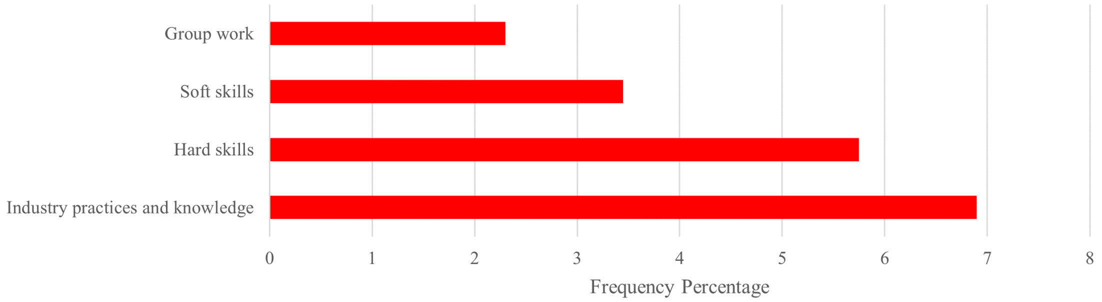


Figure 4.2: Student survey response theme frequency of perceived career benefits.

The frequency of response themes relating to the perceived level of learning in laboratories and their appropriateness for the experience are presented in Figure 4.3. Students identified learning levels in their laboratories, as per the revised Bloom's taxonomy, in the surveyed materials science course, in a past positive laboratory experience, and in a past negative laboratory experience; these themes are shown in Figure 4.3(a) through (c), respectively. Students also assessed these levels as an appropriate learning experience or inappropriate for being too high or too low. In the laboratories from the surveyed course, students identified the level of learning as lying between 'understand' and 'evaluate', and generally found this to be appropriate. In past positive laboratory experiences, students overwhelmingly experienced a 'create' level of learning. In past negative experiences, students experienced every level of the taxonomy, generally finding the lower areas of 'recall' and the higher levels of 'create' to be too low or too high, respectively.

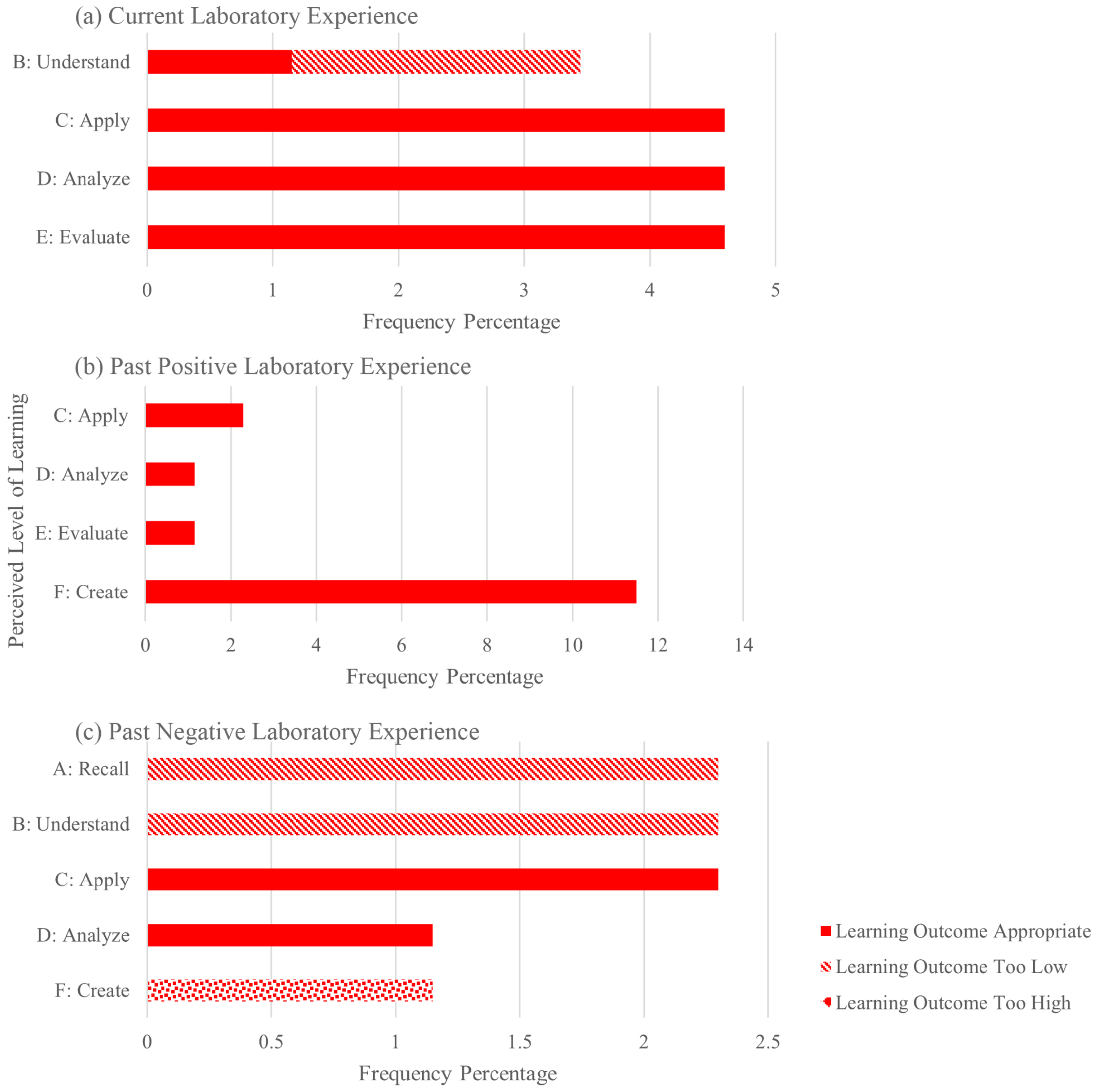


Figure 4.3: Student survey response theme frequency of learning levels and their appropriateness in (a) the current surveyed materials science course, (b) past positive, and (c) past negative laboratory experiences.

4.2 Manager Surveys

A total of 10 individuals responded to the manager surveys. The original anonymized responses to the manager surveys are provided in Appendix B. The coding matrix for these surveys will be described, followed by a presentation of the final results of the qualitative content analysis process.

4.2.1 The Manager Qualitative Coding Matrix

Manager responses were also analyzed using the qualitative coding analysis process described in Section 3.1.2.

Responses fell into several high-order categories: the professional context of the survey respondents, their assessment of the University of Calgary engineering program and its graduates, and perceived connections between the program and professional engineering practice. Respondents were contextualized by their area of practice, their degree of relevant supervisory experience, the relevance of experiential learning in their workplace, and their awareness of relevant government and University strategies for experiential learning. With regards to respondent assessment of the University of Calgary engineering program, respondents provided their perception of graduate preparedness and their general opinion on the program and its laboratories. Respondents also identified what they felt the program does well and what could be improved. Finally, in connecting engineering education and practice, respondents stated what an ideal program would do and their recommendations for attaining this program.

The coding matrix is shown in greater detail in Table 4.2.

Table 4.2: The qualitative coding matrix for manager survey results.

High-Order Category	**Low-Order Category**
Survey Respondent Context	Area of practice Degree of relevant supervisory experience Degree of understanding of experiential learning theory Perceived value of experiential learning in training new recruits Industrial applications of experiential learning theory Awareness of relevant strategies
Assessment of Program and Its Graduates	Preparation of recent graduates General opinion of program Do laboratories count as experiential learning opportunities What is done well What can be improved
Connecting Engineering Education and Practice	What an ideal program does Preferred focus between theory and practice Recommendations

The results of the manager surveys will now be presented.

4.2.2 Manager Survey Results

A total of ten managers responded to the survey. Each theme and code is reported as the frequency of each theme and code as a percentage of the total responses for the relevant question.

The themes present in student surveys were found to occur in responses to multiple questions, allowing those themes to be reported as a frequency percentage of the total 87 responses; for example, the theme of “hands-on experience” occurred in responses analyzing both past and present laboratory experiences. However, themes in the manager survey responses were found to be highly contextual to the question they were in response to. Therefore, manager survey results are reported as a percentage of the total responses in answer to the specific question the theme or code occurred in.

The first high-order category for manager results is the professional context of the respondents. Respondents stated their area of practice, shown in Figure 4.4. Given that recruitment for the surveys focused on Alberta employers and that the primary provincial industry is oil and gas, it is unsurprising that most respondents are employed in this sector.

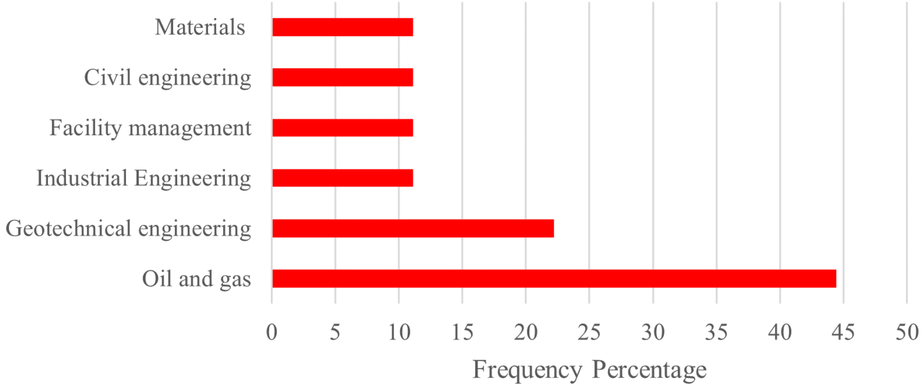


Figure 4.4: Manager respondents' areas of professional practice.

Respondents also detailed their level of supervisory experience, shown in Figure 4.5. Respondents with minimal experience had little to no managerial experience indicated in their responses. Moderate experience was assigned to those who had indeed managed engineering students and recent graduates, but the experience occurred several years ago or only occurred once. Those managers with extensive experience regularly managed numerous engineering students and graduates across multiple internship and employment terms. Rated on a five point scale, respondents had an average relevant experience of 3.3, indicating moderate to extensive supervisory experience.

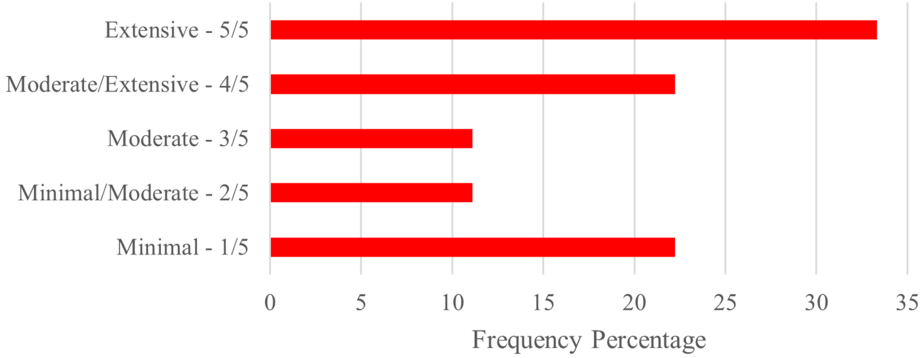


Figure 4.5: Manager respondents' degree of relevant supervisory experience.

Managers also described their understanding of experiential learning theory, allowing the coder to identify how correct their understanding of the theory is and how valuable they perceive experiential learning to be in training engineers. These results are shown in Figures 4.6 and 4.7, respectively. The former figure shows managers had a moderate understanding of the theory and highly valued experience in learning. However, it should be noted that these are based purely on the respondents' assessment of their own understanding; a definition of experiential learning was not provided, a weakness of the survey identified by several respondents.

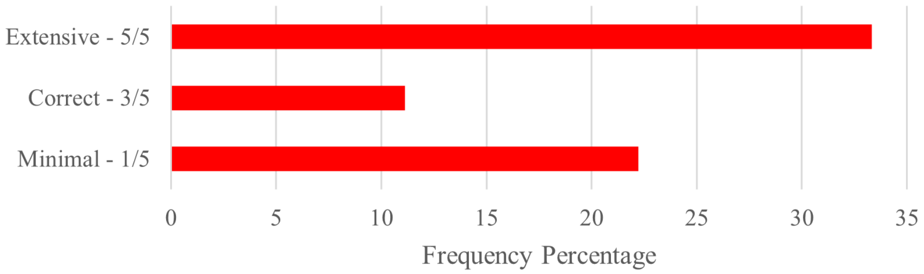


Figure 4.6: Manager respondents' understanding of experiential learning theory.

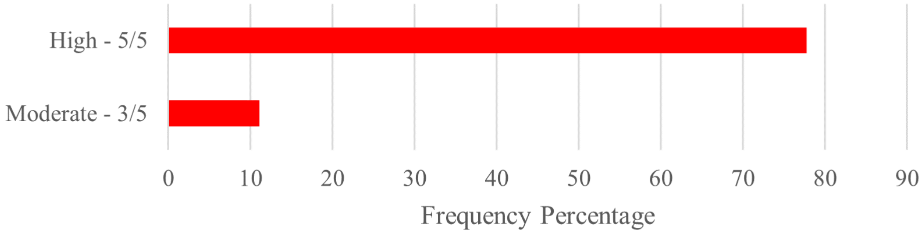


Figure 4.7: Manager respondents' perceived value of experiential learning.

The next high-order category was respondents' assessment of the University of Calgary engineering program and its laboratories. Respondents identified the specific ways in which experiential learning benefits engineering practice and professional development, presented in Figure 4.8.

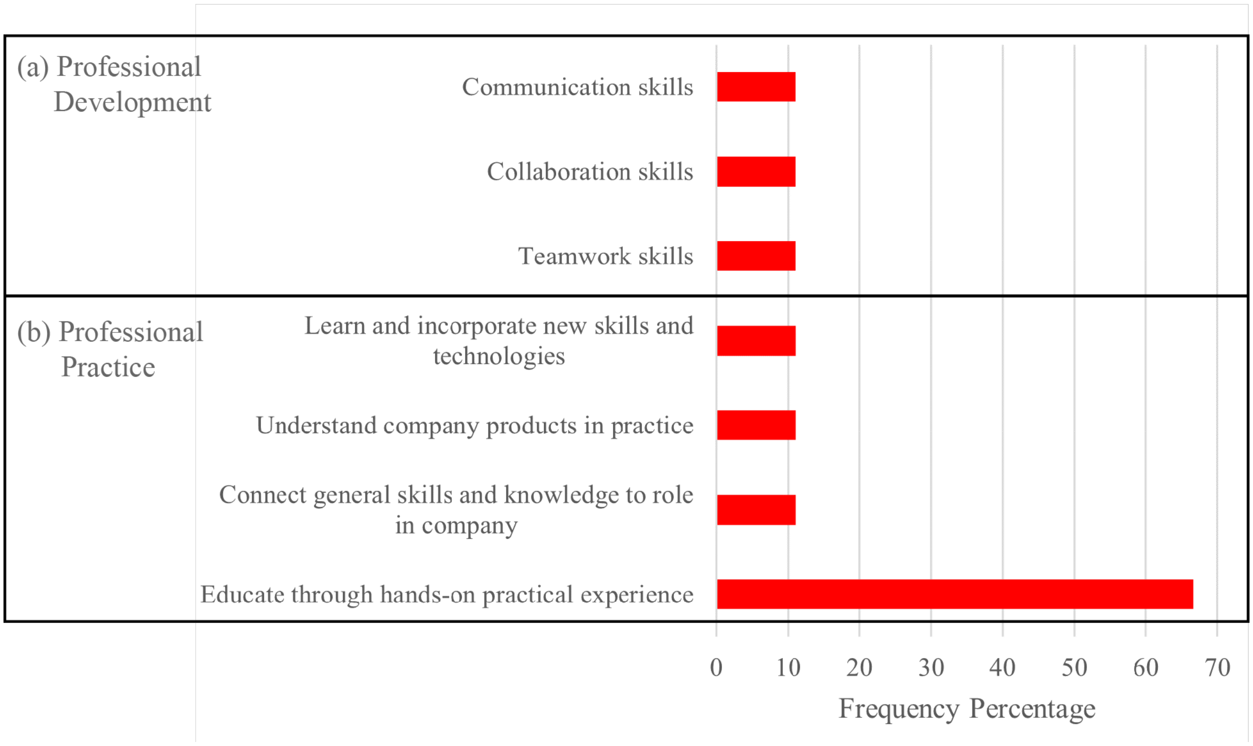


Figure 4.8: Manager respondents' perceived value of experiential learning in (a) professional development and (b) professional practice.

Respondents also evaluated how prepared recent graduates are in entering the workforce, shown in Figure 4.9. This gives an average of 3.9 on a 5-point scale, indicating that managers perceive students are somewhat prepared for employment, but that more can be done in this area.

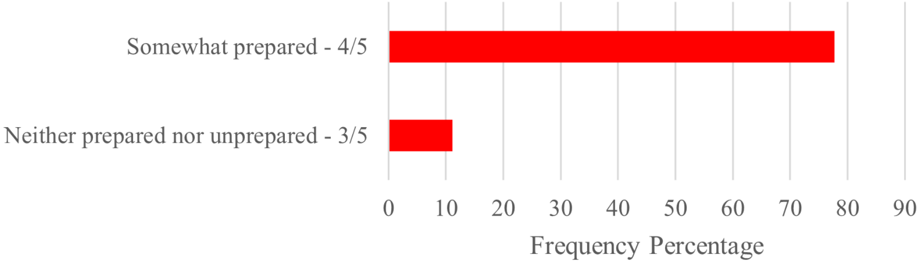


Figure 4.9: Manager respondents' evaluation of graduate preparedness.

The opinion of participants on the University of Calgary engineering program is shown in Figure 4.10. This gives an average score of 2.6 on a 5-point scale, indicating respondents had a middling opinion on the University's engineering program.

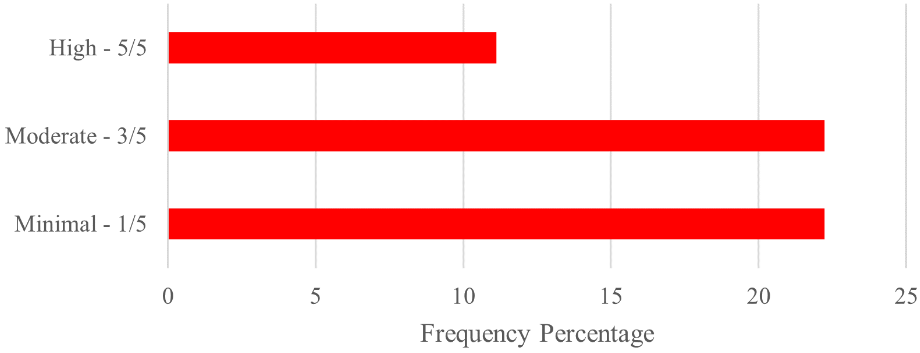


Figure 4.10: Manager respondents' opinion of the University of Calgary engineering program.

It must be noted that these grading scales lack nuance, failing to indicate how many students and graduates the managers were responsible for, or which attributes improved or detracted from their opinion of the program.

More specifically, managers evaluated what they perceive is currently done well in the program and what can be improved, shown in Figures 4.11 and 4.12, respectively. Themes in this area were found to fall into the categories of hard and soft skills.

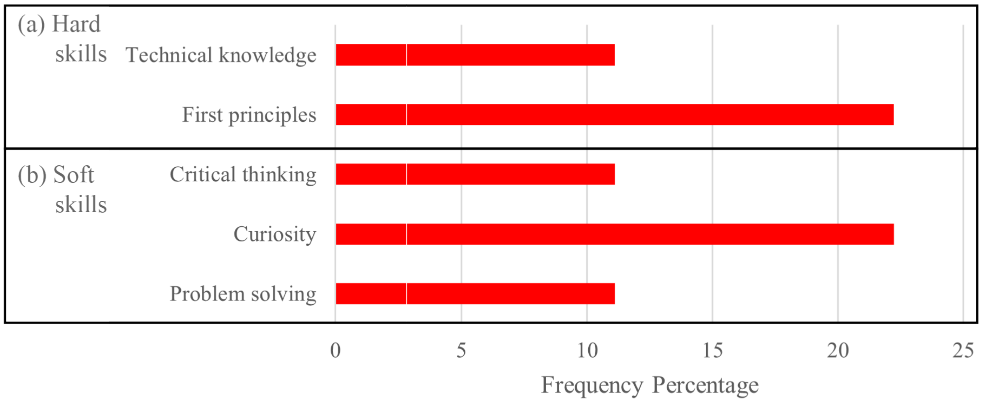


Figure 4.11: Manager respondents' opinion on what University of Calgary engineering does well in terms of (a) hard skills and (b) soft skills.

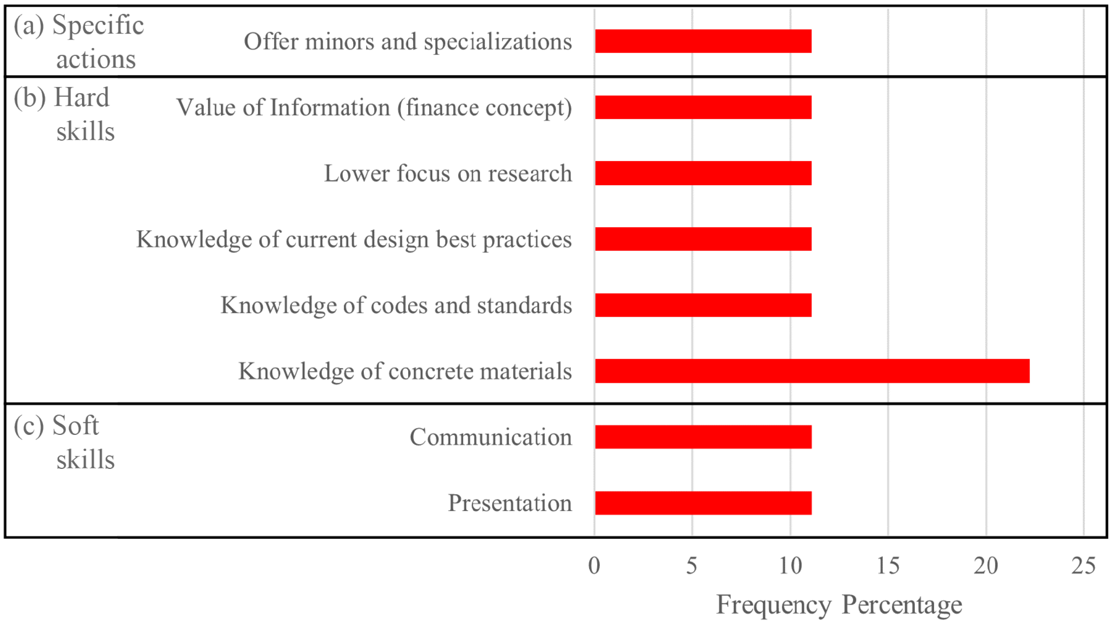


Figure 4.12: Manager respondents' opinion on what can be improved in University of Calgary engineering in terms of (a) specific actions, (b) hard skills to focus on, and (c) soft skills to focus on.

Respondents were also asked if they were aware of either the University of Calgary's Eyes High strategy, which aims to have at least one experiential learning opportunity in every undergraduate student's academic career, or the fact that the provincial government partially bases its assessment of university programs on the number and quality of available experiential learning opportunities. No respondent was aware of either strategy.

Respondents were also asked if laboratories counted as experiential learning opportunities. Of the nine responses to this question, seven said yes and two said no.

The final high-order category was connecting engineering education and practice. Managers described what would be taught in an ideal program, presented in Figure 4.13. Again, themes were organized into hard and soft skills.

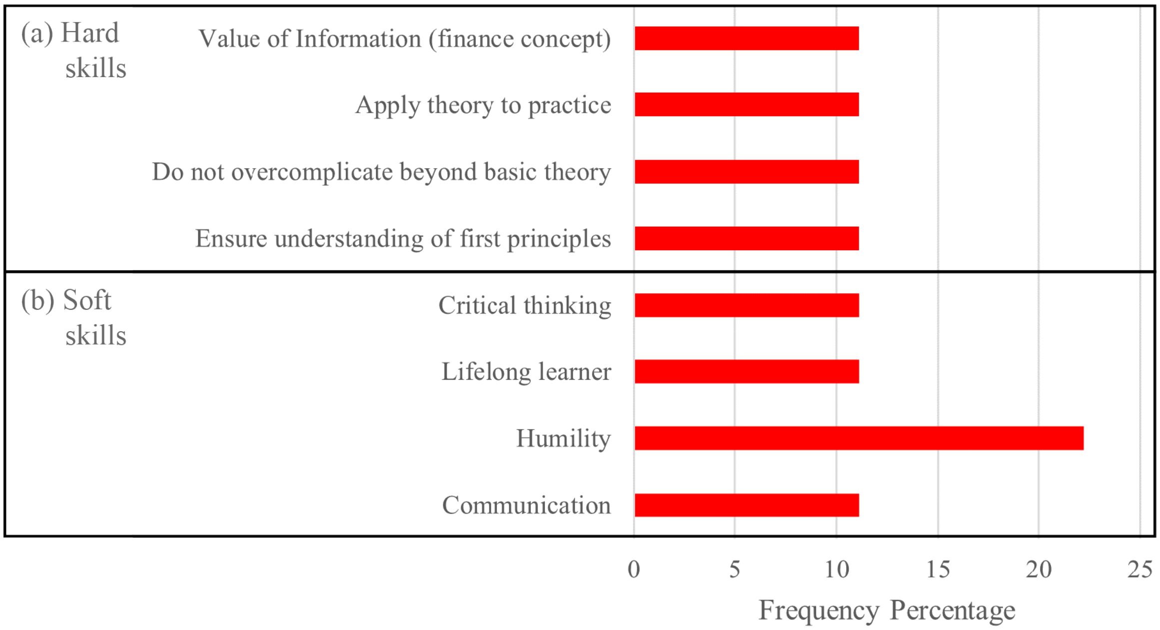


Figure 4.13: Manager respondents' ideal program attributes in terms of (a) hard skills learnt and (b) soft skills learnt.

Managers were asked if they would prefer the engineering program to focus primarily on teaching theory or practice, shown in Figure 4.14. Most preferred a focus on both, and no respondent stated the program should primarily focus on engineering practice.

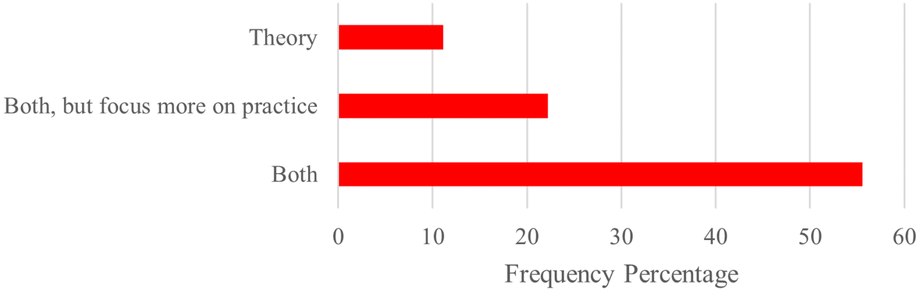


Figure 4.14: Manager respondents' preferred focus between teaching theory and practice in engineering education.

Finally, respondents listed their recommendations for improving the program, shown in Figure 4.15. Responses were organized into soft and hard skills to teach students, and specific actions that can be taken in the program. Note that the theme of "humility" draws from manager responses that state ideal graduates understand the limitations of their knowledge, work to improve and maintain their professional competencies, and accept the possibility of being wrong or factually incorrect in presentations and in written and oral communication.

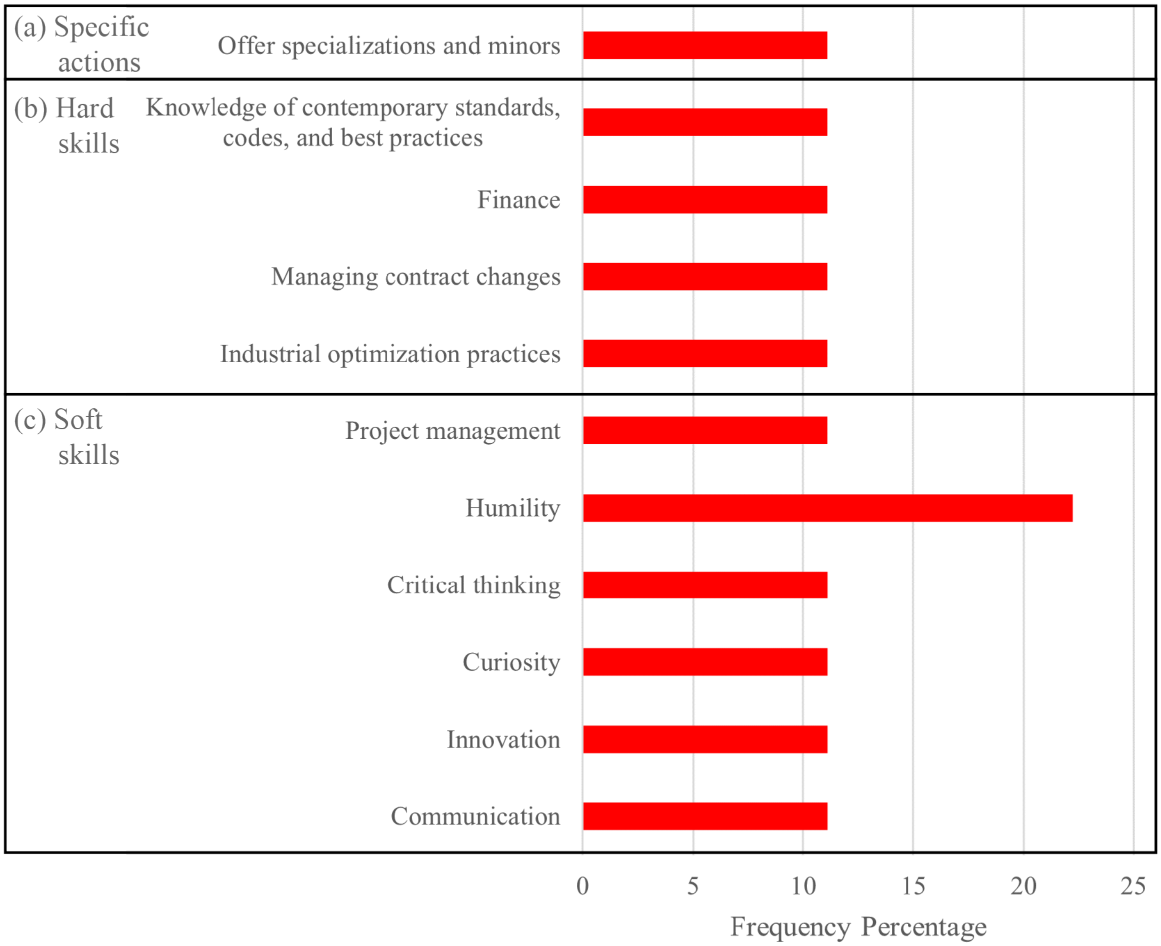


Figure 4.15: Manager respondents' recommendations for improving the University of Calgary engineering program in terms of (a) specific actions, (b) hard skills, and (c) soft skills.

Chapter 5

Analysis

The survey results will now be analyzed, with student responses analyzed in Section 5.1 and manager responses analyzed in Section 5.2. Conclusions of these analyses are summarized in Section 5.3.

5.1 Analysis of Student Survey Results

The analysis of student survey results is organized according to the qualitative coding matrix presented in Section 4.1.1. The effects of the learning laboratory actions are shown in Section 5.1.1, the perceived career benefits of engineering learning laboratories are shown in Section 5.1.2, and the perceived learning levels within these laboratories are shown in Section 5.1.3. Section 5.1.4 then integrates this analysis with the chosen educational scholarship explored in Chapter 2.

It should be noted for analysis of both survey series that select participant responses are used to support the development of conclusions. These responses have been lightly edited for readability, correcting grammar and clarifying statements that may be unclear without the broader response context. The full responses are available in Appendices A and B, where edits have been made solely for anonymization purposes.

5.1.1 The Effects of Learning Laboratory Actions

A note before analyzing the response themes relating to laboratory actions: as mentioned in Section 3.2.5, responses with a higher frequency are considered to be more strongly indicative of student sentiment than those of lower frequency. As well, response themes expressed both positively, as an action whose inclusion enhances the student learning experience, and negatively, as an action whose exclusion detracts from the student learning experience, are considered to be more strongly indicative of student sentiment than those stated solely in a positive or negative manner. This comparison also allows more nuance in the following analysis.

An example will help to illustrate this point of difference. In Figure 4.1(b), there are three themes with similar frequency, “group work”, “clear communication”, and “appropriate complexity”. The first two themes are expressed solely in a positive or negative manner, respectively, while the last theme has been expressed in both manners. This indicates that while students positively perceive their group work experiences and negatively perceive a lack of clear communication, they do not experience the inverse; students do not find individual work to detract from their learning experience, and clear communication in and of itself does not constitute a positive learning experience. However, students find their experience to be both benefited when it is of appropriate complexity, and detracted from when of inappropriate complexity.

Within this higher-order category, four lower-order categories of laboratory actions were found: the laboratory pedagogy, the laboratory experience itself, the assessment of students’ laboratory learning, and the laboratory facilitators. Each of these areas are analyzed individually in the following sections.

Pedagogy

Drawing from Figure 4.1(a), the most-requested pedagogical actions are to link the laboratory to industrial applications, to link the laboratory to the lecture material, and to separate learning outcomes between the laboratory experience and the assessment.

The student request to link the laboratory to industrial applications is also shown in Figure 4.2, which shows the laboratory career benefits perceived by students. Students are shown to value industry-relevant hard and soft skills. One student states that the laboratories in the surveyed materials science course helped them “understand how cold rolling actually works when it is done by hand vs. how it works when taught in class.” Another wrote of these laboratories, “I believe it [analyze] was an appropriate learning outcome for the laboratory and course given most material testing and strengthening processes happen at an industrial level”, making an explicit connection between the value of the laboratory and linkages to industrial processes. An additional student says of the laboratories, “This post-pandemic class of engineers is generally unaware of the more practical/industrial side of engineering, and as such an extension of knowledge that seeks to teach more about manufacturing processes is valuable.” Writing of a past negative experience, one student connects their negative impression to a lack of perceived practical applications of the competencies developed in the laboratory: “We were made to do research on our own and never taught about their [the laboratory concepts] practicality.” Writing again of a past negative experience, another student writes, “At the end of it all I had no idea why this lab was conducted, [I] had a negative impression on photoelasticity methods and thought it was never used in the real world or industry but was quickly proven wrong with a simple google search."

The mixture of responses affirming the explicit inclusion of these links as a positive action, and those who found the learning experience to be degraded when these linkages were not included, reinforces the importance of these connections. It can therefore be concluded that connecting laboratories to industrial applications improves the student learning experience, and lack of this connection harms the experience. This is an obvious conclusion. However, it is important to acknowledge once again that these observations are drawn from students' subjective experiences. It is entirely possible that these connections were indeed present in the laboratories under question, but were not perceived by the students. Therefore, this conclusion can be extended: the student learning experience in laboratories is improved when connections to industrial applications are *perceived* by students. This also supports one of the motivations for this study stated in Section 1.1, that a significant minority of past students in the surveyed materials science course did not perceive these links.

The next action requested by students from Figure 4.1(a) is to connect the laboratory to lecture material. Specifically, several student responses found their learning experience harmed because the laboratory took place *before* the relevant theoretical material had been covered in their course lectures: "The concepts that were used in the lab had been taught in class before, but were incorrectly placed in lectures as to not allow complete understanding." Another student wrote, "The labs did not seem to connect well with the course content, at least in terms of timing in the semester."

Note that these particular laboratories were designed with the expectation that students had a certain amount of preexisting knowledge from their lectures. While other laboratories may be designed to take place before lecture as a form of experiential learning, that was not the case for the surveyed students. The content of these particular laboratories do indeed relate to the course material covered in lecture. However, the mistiming of these laboratories in relation to the relevant course lectures resulted in this link not being perceived by students.

The conclusion here is clear: the student learning experience is harmed when laboratories take place before the relevant material has been covered in lecture. Note that the theme of "cover material in lecture" also appears in Figure 4.1(b) in relation to the in-person laboratory experience, supporting the prominence of this conclusion.

The last pedagogical action requested by students is to split learning outcomes between the laboratory and its assessment, with the laboratory focused on a lower level such as "apply" and the assessment aimed higher such as "justify". One student writes, "I found the best laboratory activities are where you apply your knowledge, and post-activities where you analyze, evaluate, and/or create".

This response points to a common element of learning laboratories at the University of Calgary, where the laboratory experiment is relatively simple for students to complete and the bulk of the intended learning occurs in the assessment or other post-laboratory activities. For example, the laboratory manual for the second experiment in the surveyed materials science course (see Appendix C) shows that the experiment simply required students to follow an experimental procedure, followed by a worksheet asking them to apply the laboratory concepts and experimental data to predict mechanical properties of the sample materials.

Another response, while not arguing for a split of learning levels between the laboratory and its assessment, shows the importance of intentionally designing a learning experience with available time and resources in mind. The student writes, "It's tough to apply all blooms taxonomy to a lab. Therefore, I think at the university level, each lab should just aim to complete one taxonomy branch vs all 6." This shows that students understand that laboratory time and effort is limited, and that the laboratory workload must be tailored to available resources.

It is therefore concluded that the learning experience is improved when the laboratory and assessment are intentionally designed and aligned with the learning outcomes. This relates to the earlier conclusion that linking laboratory to industrial practices improves the learning experience. Recall from Section 2.2.1 that design is a key engineering skill; therefore, connecting a laboratory to engineering design skills is expected to improve the student learning experience. This also connects with the idea, explored later in Section 5.1.3, that students prefer higher levels of the revised Bloom's taxonomy over lower ones. A design experience correlates to the "create" level of the taxonomy, and therefore design experiences can improve the learning experience by supporting the student preference for higher learning levels over lower ones.

The student responses speak to the importance of intentionally designing the laboratory experience. While the second response asking for laboratories to focus on a single level of Bloom's taxonomy points to the student not understanding that the taxonomy is hierarchical, with each subsequent level necessarily containing the previous levels within, it does indicate the need to balance the student workload with the allotted laboratory time. The theme of ensuring efficient use of time is covered in greater detail in the following section on the laboratory experience.

In summary, in terms of pedagogical learning laboratory actions, the learning experience is improved when students perceive connections to industrial applications, and when the laboratory and assessment are intentionally designed and aligned with the learning outcomes. The student learning experience is harmed when laboratories take place before the relevant material has been covered in lecture.

The Laboratory Experience

Drawing from Figure 4.1(b), the most-requested actions for the in-person concrete laboratory experience are the efficient use of time and the inclusion of a hands-on experience. "Efficient use of time" is found to consist of two related themes: “reduce time pressure”, and “reduce repetition and tedium.” Other themes are present with a frequency less than half that of these two most prominent requests. In decreasing order of frequency, these requests are for clear communication, the inclusion of group work, the inclusion of a design component, appropriate complexity of the learning experience, and adequate facilities and instructor setup.

Similar to other studies in this area (Muscat and Mollicone, 2012), one of the most prominently requested actions from students in Figure 4.1(b) is the inclusion of a hands-on experience. 12 students found this inclusion to be beneficial to their learning experience, and another 10 found their experience harmed when this component was lacking. Within the surveyed materials science course, a hands-on laboratory experience with a cold rolling process was beneficial to student learning: “It... helped aid the understanding of the concepts we were learning by giving proof through an example.” This inclusion can create a lasting impression on students; when discussing past positive laboratory experiences, one student said, “The labs I remember best are ones where a certain concept or theory was applied to something that we had to create ourselves”; another wrote, “The best laboratory I had in my educational career was creating our own battery by choosing our own cathodes and anodes. This was memorable as we got to think on our own, apply the concepts learned in class, and also receive assistance when required.” Conversely, laboratories with no hands-on experience carried negative connotations for students: “My worst experience is when all the students sit and record data as the TA performs the lab. Many labs take a couple hours and I find I do not actually learn anything from those labs”; “There were several labs performed when classes were online without an attached experiment, they felt like longer assignments.”

These responses show two nuances. First, there is a trend where students value hands-on experiences more highly than experiences requiring less participation. Second, students attribute this to hands-on experiences deepening their learning and being more memorable, similar to other studies in this area (Grantham et al., 2010; Lee et al., 2008). It is therefore concluded that a hands-on participatory laboratory enhances the student experience and learning outcomes. “Participatory” here means that all students are able to meaningfully participate, a theme which is explored later in this section in relation to the theme of group work.

The next theme from Figure 4.3(b) is of efficient use of time. Responses show has two extremes in the laboratories for the surveyed materials science course. One extreme, covered by the theme of “reduce repetition and tedium”, occurs when the laboratory takes too much time and students spend a significant portion of the laboratory waiting for equipment rather than learning. One student writes, “I’d personally prefer to see the process, understand the concepts, and finish the lab handout without having to spend several hours waiting.” The other extreme incorporates the theme of “reduce time pressure”, where a lack of time pressures students and makes them rush through the experience. A student says, “The only problem with the labs were that there was not enough time. It left students a little bit anxious as we rushed towards the end." Another says of this experience, "Towards the end [of the laboratory], we did not have a chance to complete the entire process due to time limits." A third writes, "If we had an extra lab section, it would take the time crunch off and make it [the laboratory experience] less anxiety driven".

The conclusion for the theme of reducing time pressure is clear: the student learning experience is harmed when students do not feel they have enough time to complete the assigned learning tasks.

As for the other theme of reducing repetition and tedium, in recalling past laboratories, some students found these elements to be harmful to their learning experience. Writing of a past negative experience, one student describes "...a set of extremely boring measurement labs that got students to recall extremely basic concepts about the course and explain them in excruciating detail", while another says "...we needed to simply write down the data points that were collected and then write a report and submit by next week. This was terrible [because] I was basically just a human typer no learning happened in the lab and I was fully disengaged, all I knew was that when a number was called I simply had to type it down."

In terms of reducing repetition and tedium, these responses show that students feel that when a significant portion of laboratory time does not involve a learning experience, the time is perceived as wasted and students are therefore disengaged. It can therefore be concluded that the laboratory experience is harmed when students do not perceive laboratory time as valuable to their learning.

This conclusion correlates to both the earlier conclusion in this section that a hands-on participatory experience enhances the student learning experience, and the conclusion from the previous section on pedagogical themes that the student learning experience is improved by perception of connections to professional engineering practice. A laboratory with hands-on experiences or with explicit connections to industrial applications is considered by students to be more valuable in terms of their education. It was concluded previously that improving student perception of educational value improves the laboratory learning experience. Therefore, inclusion of a hands-on experience and explicit industrial applications also improves the student learning experience by improving the perception of the laboratory's educational value, decreasing the perception of time waste.

The next response theme is clear communication. Expressed solely in a negative manner, this theme indicates that students found unclear communication to be harmful to their laboratory learning experience, while clear communication was not consciously registered by survey participants as a notable element of a positive learning experience. This therefore indicates that students expect communication to be clear. One student writes that in their current laboratories, "expectations, grading schemes, locations and ideas were poorly conveyed. Communication was very poor throughout." This response specifically targets how poor communication harmed their understanding of the expectations and grading schemes. Another says that the importance of the laboratory was not clearly communicated: “Learning how to do the hardness testing was good, but I wanted to actually understand what the collected values mean and their significance.” This relates to a previous conclusion, that perception of industrial applications improves the learning experience; this response clearly shows that communication of these connections is key. A final student writes of a past positive experience, “The facilitators gave us a clear outline of the requirements, and the final goal.” Aligning with the first quote, this shows how clear communication of expectations enhanced the learning experience.

A clear conclusion is drawn: the laboratory learning experience is harmed when communication is poor. This includes communication of the significance of the laboratory and its relation to lecture and industrial applications, communication of the laboratory requirements and processes, and communication of the assessment and grading schemes.

The next response theme is group work. Several students stated that they preferred group work specifically in relation to hands-on experiences: “The best labs I’ve participated in had hands-on experience and collaboration”; “...the best things facilitators can do are get everyone involved”; “I like being in a small group where we can all have a chance to perform a part of the lab.” Responses also exhibited a preference for small groups; one student writes, “Smaller groups were also formed so it was easier to be involved in any of the lab activities.” The surveyed students clearly prefer working in small laboratory groups where all group members have a chance to meaningfully contribute. One student says of a negative laboratory experience, “The groups were too large to work together”, and another writes of the current laboratory, “Smaller groups would have been nice as it would have been easier to work as a group and be more involved.” These responses show how large groups can inhibit student participation and decrease the amount to which they can meaningfully contribute.

It is concluded that the laboratory experience is improved when students are organized into small groups where all members can meaningfully contribute. This also relates back to the conclusion that hands-on experiences improve the learning experience; the theme of group work show that this experience must also be participatory, or designed such that all students can meaningfully contribute and engage in the hands-on experience. This also relates to the conclusions that efficient use of time and reduction of time waste improve the learning experience. Large groups inhibited participation, making time use less efficient and increasing the perception of time waste.

The next requested action is the inclusion of a design component. Many students write of enjoying design activities in their laboratories: “I have fond memories of the conceptualizing and designing in order to apply a physics principle, and I feel like it’s the reason that I remember it best”; “My favorite “Lab” ...we had to design a polymer that could be used in day to day life and to draw up a list of how much it would cost, advantages vs disadvantages and how it would work for the design purpose”; “The best experience I had was when making a battery in my high school chemistry 30 lab... We were taught basic concepts about batteries, understood them through small chemical reactions that were demonstrated, analyzed why these reactions happen and how we can manipulate them, and finally making our own battery through trial and testing".

Design activities correlate to a "create" level of learning according to the revised Bloom's taxonomy (Anderson and Krathwohl, 2001). As later explored in Section 5.1.3, students have reason to seek out this level of learning in preparation for internships, their fourth-year capstone projects, and careers following graduation. Both students and instructors value undergraduate engineering activities that employ creativity (Kazerounian and Foley, 2007), so it can be concluded that the inclusion of a design component employing an element of creative skills will benefit the student learning experience. Unlike other professions, design is integral to engineering practice (see Section 2.2.1). Therefore, the inclusion of a design component also supports the conclusion that connecting the laboratory to industrial practice improves the learning experience.

However, it is important to note that the ability of course coordinators may be limited in constructing a laboratory experience that imparts skills in design and creativity that also accomplishes the primary goals of relating theory and practice, providing practical experience, and motivating students. While a design component may benefit this last goal, course coordinators may find it detracts from the preceding goals. Therefore, the conclusion that a laboratory design component improves the learning experience comes with the caveat that it is dependant on available resources. Potential barriers to implementation are discussed further in Chapter 6.

The next theme from student responses is for laboratories to be of appropriate complexity. Students write of past negative experiences where learning tasks were perceived as either too simplistic or too complex: "...we were asked to do simplified versions of the lab at home that did not feel applicable or the same level of complexity as the analysis and reports"; "I believe that the worst level of laboratories are ones that simply require you to remember"; "If the lab experiment is too far from our current knowledge I feel discouraged and lost through the activities (i.e create)."

Clearly, it can be concluded that creating a laboratory of the appropriate complexity that challenges students and is not too simplistic or too advanced is beneficial to the student learning experience. Students have negative experiences when the laboratory is not aligned with their current level of knowledge and skill.

The final theme from Figure 4.1(b) that students find benefits their learning experience is adequate facilities and setup for the laboratory. This theme was presented solely negatively; students expect their laboratories to have adequate facilities and setup, and do not consciously register when their experience meets these expectations. However, inadequacies in this area are noticed and detract from the learning experience. One student writes, "The room was not sufficient for the topic being studied. Many students had no seating or no ability to see the TA. The space was cramped and unprofessional." Another says, "...it was difficult to reach this level [of learning, analysis] when the environment was not conducive." Several students specifically address errors in the setup for the laboratory, such as downloading software: "...a complete waste of time due to the fact that the university failed to provide the necessary software… to the students in order to complete the lab"; "...using the complicated installation software caused more frustration than learning."

These responses show that laboratory facilities can be perceived by students as inadequate when there is insufficient space or seating, or not enough equipment, for the volume of students present. As well, issues with software can pose a particular challenge for the laboratory experience.

It is therefore concluded that insufficient facilities and equipment detract from the learning experience and learning outcomes. Facilities and equipment are considered by students to be sufficient when there is enough seating and equipment for all attendees, and when the experiment is correctly set up in advance by facilitators.

These responses also related to the perception of laboratory time as wasted. The conclusion that the learning experience is harmed when time is perceived as wasted can be extended to include the fact that more time is seen as wasted when facilities and equipment are insufficient.

The theme of sufficient facilities and equipment also relates to the inclusion of a hands-on experience, which can require larger facility sizes, more equipment, and more facilitator support. Therefore, insufficient facilities and equipment can detract from the improvement in the learning experience and learning outcomes resulting from a hands-on laboratory experience.

In summary, the student learning experience is harmed when students feel they do not have enough time to complete the assigned learning tasks, when students do not perceive laboratory time as valuable to their learning, when communication is poor, and when available facilities and equipment are perceived as insufficient; insufficient facilities are also found to detract from the laboratory learning outcomes. Conversely, a hands-on participatory experience enhances the student learning experience and laboratory learning outcomes. The student learning experience is also improved by organizing the laboratory into small groups where all members can meaningfully contribute, by including a design component, and by designing laboratory activities to be neither too simple nor too complex for students' capabilities.

Assessment

Two themes appear in Figure 4.1(c) in reference to the formal graded assessment of laboratories. Students had a more positive learning experience when assessments were minimal, and a more negative experience with harsh marking of the assessment.

The reader may find these themes to be quite obvious. However, student responses offer some intriguing nuance. When requesting assessments be graded more leniently, one student writes: "My favourite labs are the ones where there is no write up because I find I focus better on the lab instead of trying to find time to do the write up as we are performing the lab". Another says, "On top of this there was no worry in needing to complete a report or answer a worksheet of questions by tomorrow, I had that slot of time to simply learn in a suitable environment without the pressure of a rubric or grade behind."

These students found their learning experience to be enhanced when they did not have to worry about their assessment during the laboratory experience. Therefore, an argument is present for enacting measures that allow students to more fully engage with the laboratory experience by reducing assessment concerns during the laboratory time slot or integrating the assessment into the laboratory experience, rather than unilaterally removing assessments altogether. As well, recall from Section 2.4.2 that, due to the high pressure in university engineering courses, students are likely to contribute less or no effort towards assessments that do not factor into course grading schemes (Edwards, 2022). Therefore, while reducing or removing grading from laboratory assessments may indeed improve the student learning experience, it likely comes at the cost of reduced student engagement and learning.

It is therefore concluded that the student learning experience and laboratory learning outcomes are enhanced when the pressure of the laboratory assessment is reduced. Student responses show that this stress is reduced by integrating the assessment with the learning task within the laboratory time slot, such as with the worksheets for the surveyed materials science laboratories, or by allowing more time between the laboratory and the assessment due date. Removing grades completely is not recommended.

Facilitator

Figure 4.1(d) shows that facilitators are highly impactful on the learning experience, with response frequencies similar to the high-frequency themes present in Figure 4.1(b). The survey results show that students desire facilitators to be professional, engaging, open and supportive, and knowledgeable in their subject area. These themes will be considered more holistically and in relation to each other than the previous areas of analysis. When taken together, these themes paint a picture of the qualities students expect in their facilitators, rather than the specific actions taken by facilitators and their impact on the learning experience. Specific actions have already been covered when discussing the pedagogy, laboratory experience, and assessment of the laboratories.

Student responses show the strong negative impact of a poor experience with a facilitator: "The TA's were also very rude, making a colleague cry by the end of the lab"; "Instead of answering my question he put me down in front of my colleagues, which as a first year student made me feel miserable"; "I stopped attending lectures as well due to the TA's that infuriated everyone." It is worth noting that strong and colourful emotional descriptors such as "miserable" or "rude", or at the other end of the spectrum, "excellent" and "wonderful", are only used by the surveyed students in reference to their laboratory facilitators. It can therefore be concluded that the laboratory learning experience is harmed when facilitators are disrespectful towards students; disrespect and rudeness are seen to constitute the theme of "unprofessionalism" seen in the responses. This is supported by other studies, which find that rudeness reduces performance and helpfulness (Porath and Erez, 2017), and makes student groups less likely to arrive at a correct solution during learning tasks (Chiu and Khoo, 2003).

The next response theme for facilitators is for them to be engaging: "...the best things facilitators can do are... make their presentations/talks exciting, and asking good questions to make students understand the material." Conversely, the learning experience is harmed when "...the facilitators are dull or seem they are not interested in guiding us through the lab." It is therefore concluded that the learning experience is enhanced when facilitators are perceived as engaging and interested in the laboratory and teaching.

The final two themes are that facilitators be open and supportive, and that they be knowledgeable. It is a reasonable expectation from students that their facilitators be knowledgeable in the theoretical material relating to the given laboratory; after all, the Cambridge dictionary defines a facilitator as "someone who helps a person or organization do something more easily or find the answer to a problem, by discussing things and suggesting ways of doing things" (Cambridge University Press and Assessment, 2023). Relevant knowledge makes the facilitator a more useful resource to the student, able to answer more questions and provide more depth and context to students; the individual is therefore better able to facilitate the laboratory experience. As well, when discussing professionalism, it was found that rudeness or similar disrespectful behaviour on the part of facilitators harmed the learning experience; this behaviour appears to be the inverse of the request that facilitators be honest and supportive. The impact of this disrespectful behaviour is seen in student responses when discussing negative facilitator experiences: "They were consistently neglectful of their duties and brushed any student off that was confused." This response clearly shows how students expect to use their facilitators as sources of knowledge in the laboratory, and for their interactions to be respectful.

It is therefore concluded that the laboratory experience is harmed when facilitators are perceived to be disrespectful, unknowledgeable or not open or supportive.

5.1.2 Perceived Career Benefits of Engineering Laboratories

Figure 4.2 shows the relationship between undergraduate engineering laboratories and careers in industry as perceived by students. Students see the laboratories as benefiting their careers in teaching industry practices and knowledge, hard skills, soft skills, and group work. These themes are listed in order of decreasing perceived relevance; however, their inclusion in student responses indicate that all these themes are perceived as relevant. Also note that here, hard skills refer to specific technical skills and knowledge that are only applicable in a specific employment context, such as how to interpret the results of a tensile test, while soft skills refer to general skills and knowledge that are transferable between employment and education contexts, such as teamwork or written communication skills.

The themes of “industry practices and knowledge” and “hard skills” appear similar at first glance. However, it should be noted that an undergraduate degree in engineering does not necessarily mean a given student will enter the engineering industry in an engineering capacity. Students may continue along an academic route through a master’s or Ph.D, leading to a career in education; students may enter a career related to engineering such as writing grant applications for an academic institution, or engage in other Science, Technology, Engineering and Mathematics (STEM) disciplines. The author himself is engaged in graduate education focusing on engineering education, and would therefore classify the skills and knowledge he gained in undergraduate as more “hard skills” than “industry knowledge.”

It is important to keep in mind that engineering students have a wide variety of career pathways to choose from. That being said, these two themes lead to a clear conclusion: that students primarily see their laboratories as an environment to learn skills and knowledge that will be later applied in their careers.

Soft skills are also seen as a useful benefit of laboratory work. The surveyed students expressed a clear preference for group work, with some identifying that this allows them to develop group and teamwork skills: “I think all labs in university create better soft skills in group work.” Group work is an avenue to develop group and teamwork skills. Many laboratories are assessed through a lab report, which employs students’ technical writing and communication skills.

Therefore, students also expect laboratories to impart soft skills, primarily group work as seen in the frequency of that response theme. Recall the conclusion from the pedagogy portion of Section 5.1.1 that the student learning experience is improved when connections to industrial practice are perceived. It can be understood from analysis of Figure 4.2 that the connections students value are industry-applicable hard and soft skills.

5.1.3 Perceived Learning Levels of Engineering Laboratories

Figure 4.3 show that students can positively perceive learning levels in their laboratories that correspond to all classifications in Bloom’s taxonomy except for Recall, the simplest tier of the hierarchy.

However, issues arise when this level is not aligned with the current skill level of the student cohort, shown in Figure 4.3(a) and (c). This correlates to the conclusion from Section 5.1.1 that the learning experience is harmed when learning levels are not perceived to be of appropriate complexity. If the learning level is exceeded by students' abilities, the laboratory activities are perceived as unengaging, repetitive, and tedious. Recall the previous quotes from Section 5.1.1 showing the negative laboratory experience resulting from inappropriate complexity. A student says of laboratories perceived to be too simplistic, "I believe that the worst level of laboratories are ones that simply require you to remember." An additional student says of laboratories perceived as too complex, "If the lab experiment is too far from our current knowledge I feel discouraged and lost through the activities (i.e create)".

This imbalance between the effects of exceedingly high and exceedingly low learning levels is to be expected given the context of this study. The surveyed students are enrolled in a third-year undergraduate engineering materials science course. These students are highly accomplished. Consider the mechanical and manufacturing engineering program provided by the University of Calgary: high school students must have a minimum grade point average or GPA of 3.3 for their application to be competitive (BeMo, 2023), and, once admitted, must achieve a minimum grade of C- in each course to be given credit (University of Calgary, n.d.-a). The surveyed students have experienced four academic semesters consisting of highly challenging courses across a range of engineering subjects, and have taken dozens of engineering laboratories requiring skills in understanding the technical content of their courses and applying this knowledge to analysis of the laboratory phenomena. They have also completed projects and courses introducing them to the rudiments of the design process in preparation for internships and for their fourth-year design capstone projects.

Given this context, it is understandable that asking students to "recall" information in their laboratories, as per Bloom's taxonomy, is a simplistic activity that does not develop new skills or competencies in students. It is also understandable that, in preparing for internships and capstone projects, students are seeking out a challenge that engages them in the design process, which corresponds to the "create" learning level of Bloom's taxonomy.

It should also be noted from Figure 4.3 that more students had a negative laboratory experience due to overly simplistic tasks than overly complex ones. It can therefore be concluded that, in deciding on the level of learning in a particular laboratory, a level exceeding student skills is substantially less harmful to the learning experience than the inverse situation. However, neither situation is preferable for students.

5.1.4 Integration of Selected Educational Scholarship

The following sections analyze the student survey results using the selected educational scholarship. These are situated cognition theory, from Section 2.2.1; constructivism, from Section 2.2.2; experiential learning theory, from Section 2.2.3; and self-determination theory, from Section 2.2.4. The theoretical framework of the zone of proximal development, from Section 2.3.4 is also utilized.

Situated Cognition Theory

Situated cognition theory provides an important perspective on the conclusions that the student laboratory learning experience is improved when connections are made to industrial applications and by the inclusion of a design component, and harmed when laboratory time is not perceived as valuable. Recall from Section 2.2.1 that situated cognition theory proposes that all learning and knowledge is situated within context and cannot be understood without it. This section also concluded that engineering education is contextualized by the professional practice of engineering. Students enrol in the program expecting it to lead to a career in engineering, so when a theory or skill in a course is perceived by students as relevant to professional engineering practice, they value it more highly. In general, the perceived relevance or salience of a given experience directly correlates to participant engagement (McCay-Peet et al., 2012).

In accordance with situated cognition theory, consider the factors contextualizing the experience of the average engineering student. It is important to remember that undergraduate engineering is a challenging and time-consuming endeavour. At the University of Calgary, engineering students are learning challenging technical topics in up to six full-time courses (University of Calgary, 2023), with each of these potentially containing assignments, midterms, final exams, and group term projects in addition to laboratories. Beyond this, many students find part-time employment; others have family and friends with unique needs the student must take time to support; many may be taking extra-curricular activities or participate in student design teams to round out their undergraduate experience; and finally, every student is a human being who needs downtime and social contact. The point is that these are stressed students with many competing demands on their time beyond the immediate laboratory experience, which contextualizes their engagement or disengagement in the laboratories. Given the high workload of these students and the direct relationship between perceived relevance of a learning activity and engagement in it (McCay-Peet et al., 2012), it is understandable that engagement can be lowered when a given laboratory is not perceived as valuable to their education. The demands of this current environment can also force students to triage their effort and engagement; realistically, they are unable to fully engage and devote themselves to every single learning task in every semester in a given course, and must decide for themselves where to focus their effort.

Therefore, industrial connections improve the student laboratory experience because it is these very connections that make the entire undergraduate engineering program valuable to the student. The lack of these connections contribute to the perception of the laboratories as time wasted, a perception that is heightened when contextualized by a highly demanding and time-consuming academic program.

Furthermore, an important part of engineering practice is design. This is recognized in the construction of the University of Calgary undergraduate engineering program, which includes a mandatory fourth-year capstone design course as a culmination of the degree (University of Calgary, 2023). The Canadian Engineering Accreditation Board, responsible for accrediting post-secondary engineering programs in Canada, says, “It is recognized that the process, skills, and competencies associated with design are integral to the skills associated with engineering and that the activity of design is central to the practice of engineering” (Engineers Canada, 2019).

Therefore, design skills are perceived by students as valuable, and their inclusion in laboratory learning tasks can improve the student experience and learning outcomes by improving the salience of the laboratory’s connection to professional engineering practice. It should be noted that design activities, correlating to the highest ‘Create’ level of the revised Bloom’s taxonomy, are necessarily more difficult and time-consuming than comparatively simpler levels such as ‘Analyze’. Available time, resources, and student competencies must therefore be available for inclusion of a design component, which is explored further in in the following sections on constructivism, constructive alignment, and the zone of proximal development.

Constructivism

Constructivism offers insights to several conclusions. It was previously shown that the student laboratory learning experience is improved when the laboratory and assessment are intentionally designed and aligned with learning outcomes and when assessment pressure within the laboratory is reduced. It was also shown that the learning experience is harmed when laboratories are positioned before the relevant lecture, when students feel they have insufficient time to complete the laboratory and when facilities and equipment are perceived as inefficient.

Recall from Section 2.2.2 that the core tenet of constructivism is that learning is the process of constructing meaning through experience. Students enter an experience with preexisting knowledge, skills, and notions, which may be correct or incorrect. The learning experience provides new knowledge that students integrate into their knowledge base. Since learning is always influenced by this prior knowledge (Cobern, 1993), when new knowledge contradicts this base, students must either reject the new learning or rearrange their knowledge base to allow for the new learning.

Recall the conclusion that the learning experience is harmed when laboratories take place before the lecture intended to support the laboratory. From a constructivist perspective, the combination of lectures and laboratories work to integrate the imparted skills and knowledge into students’ existing knowledge bases. However, if this existing knowledge base is minimal or lacking sufficient resolution, such as when laboratories are placed before the relevant lecture rather than after, then the student’s understanding will not be significantly advanced by the laboratory. This is because the nature of students’ knowledge determines what is recalled, what hypotheses are generated, and what students therefore identify as learning issues (Hendry et al., 1999). The surveyed students also did not have sufficient time after the laboratory to gain this missing knowledge, integrate it into their knowledge bases, and demonstrate their understanding on their assessment; the laboratory worksheet was due only twenty-four hours after the laboratory, and students must also use this time to complete deliverables for other engineering courses, fulfill basic needs for food and sleep, and engage in downtime to rest, relax, and prepare for the next day. If the assessment was instead a laboratory report due a week after the laboratory, then students would have the time to attain this missing knowledge.

Therefore, the harm of positioning laboratories before lectures, in the case where laboratory design assumes a certain amount of preexisting knowledge from lecture on the part of the student, results from students having an insufficient knowledge base into which to integrate the laboratory learning.

Furthermore, when students feel they do not have enough time to complete the laboratory, or that the available facilities and equipment are insufficient, they have insufficient time and resources to complete the tasks intended to integrate the new learning into their existing knowledge base, harming the learning process.

Constructivism supports the previous conclusion that the learning experience is improved when industrial applications and connections to professional practice are perceived by students. A constructivist perspective states that students enter the laboratory with their own preconceived notions on how the experience relates to professional engineering practice. Unless the connection to industrial applications is clearly and explicitly communicated to students, their understanding of this connection remains essentially unchanged. If a student's understanding is incorrect, it will remain incorrect.

Constructivism also shows how reducing unintentional assessment pressure during the laboratory experience can improve the student learning experience and learning outcomes. The laboratory may be designed such that the assessment takes place a certain amount of time after the laboratory experiment. In this case, if the assessment is due within a short time of the laboratory, student focus may be split between the assessment and the laboratory learning activity. This distracts students from the process of integrating the laboratory learning with their existing knowledge bases, which then detracts from the learning outcomes (Barry et al., 2015).

All these conclusions reinforce the point that alignment of the laboratory and its assessment with the learning outcomes improves the learning experience, and can be extended to also improving the learning outcomes by allowing greater integration with students' knowledge bases. If the laboratory is designed to follow a lecture but takes place beforehand, the laboratory is no longer fully aligned with the learning outcomes, as its design assumes a context that is no longer valid. The same case occurs when laboratory time, facilities, or equipment are insufficient.

This conclusion bears a clear connection to the concept of constructive alignment, and is therefore further developed in Section 6.2.3.

Experiential Learning Theory

Experiential learning theory offers insights to the conclusion that a hands-on participatory experience enhances the student learning experience and learning outcomes, as well as the conclusion that the student learning experience is enhanced by small group sizes. This theory also offers insight into how students may consider experiential hands-on learning in laboratories to be more relevant to their education, and that the lack of this contributes to the perception of laboratory time as wasted.

Recall from Section 2.2.3 that the core of this theory is that learning is done through experience. While Kolb's experiential learning theory has seen criticism, the framework of his cycle consisting of a concrete experience, reflective observation, abstract conceptualization, and active experimentation has been shown to deepen learning (Grantham et al., 2010) and improve student performance (Lee et al., 2008).

The conclusions drawn from student responses stated at the opening to this section can be synthesized using experiential learning theory. A hands-on participatory experience constitutes a concrete experience in Kolb's cycle. Small group sizes can enhance this experience: by arranging the laboratory for small groups where every member can perform a hands-on task that is necessary for successful completion of the laboratory, all students are able to have a concrete hands-on experience. This also allows for all students to have the full intended laboratory experience that constructs their knowledge, as discussed in the preceding analysis section.

The experiential learning cycle calls for further stages of reflection, conceptualization, and experimentation. It is concluded than the inclusion of these components enhances the learning experience and deepens learning, enhancing learning outcomes. Recall from Section 5.1.1 that making time use more efficient and reducing time pressure improves the student learning experience. Experiential learning theory shows that time pressure may detract from the student learning experience because students do not have sufficent time to engage in all four modes of the learning cycle.

The cycle is flexible, and all four stages do not need to occur within the laboratory experiment time, as seen in applications of the cycle (Chan, 2012). Worksheets and reports offer the opportunity for reflection and conceptualization, and answering assessment questions, particularly more open-ended ones that correspond to the higher levels of the revised Bloom's taxonomy, can provide room for active experimentation. For example, a materials science laboratory investigating nanoscale surface roughness can offer room for active experimentation by asking questions comparing real roughness values found in the laboratory experiment to those predicted by theoretical models. This comparison allows students to see how well their knowledge base, developed in the experiment and through conceptualization, matches to reality, allowing them to refine their knowledge. This also aligns with the tenets of constructivism explored previously in Section 2.2.2.

As well, note that the inclusion of a design component can also provide active experimentation. As previously discussed in the analysis section on situated cognition theory, design skills form part of the professional engineering context that drives student participation and engagement in the engineering degree program. Design is an open-ended process, requiring that designers experiment, create and prototype models, gather feedback, and redesign (Razzouk and Shute, 2012). This aligns with the definition from Section 2.2.3 that active experimentation is the process of applying one's knowledge to make decisions and solve problems. Design can therefore be described as a process of active experimentation, and it is concluded that the inclusion of a design component supports hands-on participatory experiences developed using Kolb's experiential learning cycle.

It should also be noted that many responses conflate wasted laboratory time with experiences that are less hands-on. Students write of the surveyed laboratories: "Since it took us a while and required essentially no contribution, it felt like a lot of time was wasted after the initial presentation of the lab"; "...the primary goal of engineering laboratories should be to gain a hands on and intuitive sense of the phenomena being explored in the laboratory"; "It would have helped if we could also have annealed the sample ourselves. Not being able to use the oven reduced our experience with the overall process". One says of a positive experience, "I like being in a small group where we can all have a chance to perform a part of the lab." Writing of a negative experience, a student says that, "The worst laboratory experience was during online school, all of it. Getting no hands on experience, watching youtube videos, and writing long lab reports didn't cover any of Bloom's taxonomy. I just forgot everything as soon as I submitted my work." These responses show that the surveyed students consider hands-on laboratory learning to be more relevant to their education and improves student perception of learning outcomes, improving both their ability to achieve these outcomes and their perceived validity. Therefore, it is concluded that the inclusion of a hands-on laboratory experience enhances the student learning experience because students perceive hands-on learning as more relevant to their education and as more efficacious in achieving the stated learning outcomes.

Self-Determination Theory

Self-determination theory (see Section 2.2.4) is applicable to several conclusions from the student surveys. Recall that the essence of self-determination theory is that motivation requires three psychological needs be met: autonomy, or the sense that one willingly chooses and endorses their actions; competency, or the sense of mastery and effectiveness in a given experience; and relatedness, or the sense of belonging to and being accepted by a larger group.

This theory provides insights into the conclusions that the student learning experience is harmed when laboratories take place before the relevant lectures, when students do not perceive laboratory time as valuable to their learning, when laboratory time, facilities and equipment are perceived as insufficient, when communication is poor, and when facilitators are rude, unknowledgeable, or not open and engaging. It was also concluded that the student learning experience is enhanced when connections to industrial practices are perceived by students, when the laboratory is designed around small group sizes, when the laboratory includes a design component, when the laboratory includes a hands-on exprience, and when the experience is aligned with student capabilities.

Consider the first conclusion, that the student learning experience is harmed when laboratories take place before the relevant material has been covered in lecture. From a self-determination theory perspective, the reason for this harm is that students do not have sufficient competency in the theoretical focus of the laboratory and do not endorse the laboratory's placement before the relevant lecture material has been covered, harming their motivation.

The same harm to student competencies can be seen as occurring when the laboratory is not aligned with student capabilities. If students are expected to have a certain skill but don't, they will not be able to fully engage in the laboratory and experience the intended learning. It is therefore concluded that the learning experience is harmed when students do not have the expected competencies, and that developing these competencies prior to the laboratory therefore enhances the student learning experience.

The concept of aligning laboratory activities with student competencies is further discussed in the analysis section on the zone of proximal development. It should be noted that students in a given course are expected to retain skills and knowledge from previous required courses, which is implicit to the structure of the engineering program at the University of Calgary (University of Calgary, 2023). These competencies are therefore the responsibility of the student to retain, not for the course coordinator and laboratory facilitators to reteach.

Consider the conclusions that the student learning experience is harmed when students do not perceive the time spent in the laboratory as valuable, and that the student laboratory learning experience is improved when connections are made to industrial applications. It was found in the analysis section on situated cognition theory that it is these very connections that make the laboratory experience perceived as valuable by students. It was also found that students have limited time and effort to expend on laboratories.

The question remains as to how to improve the perception of laboratories as valuable beyond the broad conclusion of including industrial connections; self-determination theory offers help in this regard. In particular, improving the perception of a laboratory's educational value moves students from extrinsic motivation (see Section 2.4.1), only valuing the laboratory because it is a graded part of the course, to intrinsic motivation, valuing the laboratory because it supports their broader goal of attaining an engineering degree that supports a future professional engineering degree.

Consider the psychological need for autonomy, or the sense of choosing and endorsing one's actions. From a macro perspective, students endorse their enrolment in the undergraduate engineering program. There may be familial or societal pressures that drove the decision, but these students have decided to attempt, and hopefully complete, an undergraduate engineering degree. From the micro perspective, students who feel a laboratory is wasting their time do not endorse their participation in that laboratory. Note the academic context: the surveyed materials science course is mandatory (University of Calgary, 2023), framing the course as an essential part of gaining an engineering degree; given how the degree is required for engagement in the engineering industry (Engineers Canada, n.d.-a), the course is therefore presented as an essential part of professional engineering practice. When connections to practice are not perceived, the student is more likely to experience either external motivation, only completing the laboratory because it is necessary for the course grade required to continue in the engineering degree program, or complete amotivation and disengagement. The developed competencies are not perceived as relevant or valuable to the student's broader engagement in the engineering degree program. This also relates to the conclusion that, while reducing assessment pressure enhances the learning experience, removing graded assessments is likely to decrease student engagement with the learning task. Grades explicitly connect engagement with the learning task to the overall course grade the controls student admission to subsequent courses, years of study, and ultimately graduation from the program. Therefore, grades act to extrinsically motivate students when they do not possess intrinsic motivation for the learning task, as they connect the task to the broader program the student is engaged in.

The question of competency and autonomy also applies to the conclusion that the learning experience is harmed when students feel that the available time, facilities, and equipment are insufficient to complete the laboratory learning tasks. This was found in the analysis section on constructivism to be due to students not being able to fully integrate the laboratory learning into their current knowledge bases. Viewed using self-determination theory, this barrier to learning limits the degree to which students can develop the intended competencies, harming their psychological need for competency. This also harms their need for autonomy, as student engage in the laboratory to develop career-relevant competencies. When these competencies are not developed to the extent promised by the course outline and learning outcomes, student engagement in the laboratory is not endorsed. Recall that this also aligns with an experiential learning theory perspective: students do not have time to engage in the full experiential learning cycle and therefore do not fully develop their competencies.

Therefore, time pressure or insufficient facilities and equipment can reduce student engagement because the expected competencies are not fully developed. The question of how best to develop this competency is explored later in the section on the zone of proximal development.

This perspective also supports the inclusion of a design component. As stated previously in the analysis section on situated cognition theory, design is part of the professional engineering practice that contextualizes the learning laboratories. Therefore, the inclusion of a design component aids in developing student design competencies that they perceive as relevant to their choice of degree program, endorsing their need for autonomy.

The detrimental effect of poor communication on the student learning experience can also be understood using self-determination theory. Poor communication harms the student need for competency. The intention of the laboratory is to develop competency in the specified learning outcomes. Communication from facilitators can be understood as enabling the competency and autonomy needs that result in motivation. Exhibiting competence in a laboratory environment means meeting the expectations of the facilitator; when students understand these expectations, they are in a better position to demonstrate their competency and have sufficient information to decide and endorse their particular course of action in the laboratory. When elements of the laboratory, including the experimental process, the intended learning outcomes, or the assessment and its grading scheme, are poorly communicated, students do not have a full understanding of how to develop and demonstrate the intended competencies. This confusion detracts from their motivation in the laboratory, especially in terms of the assessment. The assessment is how students demonstrate their competency, and is often factored into the final grade that controls student advancement through the engineering degree program. If the student does not understand how to demonstrate competency due to poor communication, then they are likely to be less motivated in the experience.

Therefore, it is concluded that poor communication limits the student ability to develop and display the expected laboratory competencies, harming their learning experience and the learning outcomes.

Consider now the conclusion that the learning experience is harmed by unknowledgeable facilitators. This can also be understood as harming the student need for competency. When facilitators are unable to answer questions from students, they are no longer a resource through which students can find errors in their knowledge bases and improve their understanding, harming the development of their competency. Therefore, unknowledgeable facilitators harm the development of student competencies, detracting from the learning experience and learning outcomes.

Moving on to the conclusion that unengaging facilitators harm the student learning experience, the question remains as to what constitutes an engaging facilitator. Student responses are understandably vague on the specifics of this point, as these are subjective and emotional recollections of past events rather than objective first-hand retellings.

Engagement with an experience necessarily involves motivation for that experience, which in turn requires the student to feel autonomous, choosing the experience of their own free will and endorsing their choice of action; competent, with the ability to complete at least part of the experience with their existing skills and knowledge; and related, being part of their broader laboratory and educational cohort. As the intention of the laboratory experience is to develop competency in the relevant theoretical area, it is not expected that students enter the experience completely competent in the given activity; if this was so, the laboratory would serve no purpose. As well, facilitators do not have control over the level of competency that students enter the laboratory with, and their control over the curriculum or laboratory learning objectives is limited at best.

However, while facilitators cannot affect the competency students enter the laboratory with, they can take actions to improve the learning within the laboratory and enhance the development of student competency. This has been previously explored throughout this section. Areas in which the facilitator has control are in connecting the laboratory to industrial practice and by clearly communicating with students. By connecting the laboratory to broader course and career goals, the learning tasks are connected to the student's intrinsic motivation for engaging in and completing the degree program. It can therefore be concluded that facilitators can improve the laboratory experience by being more engaging, which can be accomplished by clearly communicating with students and by connecting the laboratory to industrial practices.

Moving to the final element of facilitator behaviour, rude facilitators can be seen as harming the student need for relatedness, or the sense of belonging to a larger group. Many student responses spoke of being targeted or singled out, which would separate them from the broader student cohort and harm their need for relatedness. Consider this response: "I once asked a question to clear something up but the TA did not maintain a positive and approachable environment. Instead of answering my question, he put me down in front of my peers which as a first year student made me feel miserable." Recall that the student surveys were administered to a third-year course; this recollection has stayed with the student from first year, showing the strong negative impact. Another student decided that attending lectures in the surveyed course was not worth the perceived frustration caused by the presence of rude facilitators: "I stopped attending lectures as well due to the TA's that infuriated everyone and overall made this course not a pleasant experience."

A critical theory perspective (see Section 2.1.3) can also aid in understanding the negative impact of rude facilitators on the student experience through harming the need for relatedness. Traditionally, the classroom power dynamic is firmly weighted towards teachers (Cothran and Ennis, 1997). Laboratory facilitators may also mark the laboratory assessments, so students may fear reprisal on their course marks if they protest a facilitator's behaviour; facilitators may be graduate students or hired technicians who are necessarily more entrenched in the university administration and therefore hold more power in that realm; facilitators may work more closely with the course coordinator in a professional capacity, which may also carry personal relationships such as friendship, giving the facilitator an advantage when discussing issues with the course coordinator. Students are therefore operating from a position of limited power when responding to laboratory facilitators, enhancing the negative effect of rude facilitators on student relatedness.

Conversely, this means that facilitators can also enhance the student learning experience by aiding their need for relatedness. This brings in the conclusion that when facilitators are open and supportive, they can enhance the learning experience by enabling the student need for relatedness. It is therefore concluded that openness and support from facilitators enhances student engagement through relatedness, and that the converse behaviour of rudeness harms this engagement.

Moving now to a more positive conclusion, it was found that small group sizes enhance the student learning experience by allowing all students to meaningfully participate in the laboratory activities. This supports the development of student competencies, as all students are able to experience the full laboratory activity as intended. As discussed in the analysis section on situated cognition theory, this more fully enables the student learning process. One study surveyed university students and found that relatedness, or the sense of belonging to a larger group, to be the most important self-reported psychological need in their schoolwork (Trenshaw et al., 2016). Group work can therefore also be a tool to fulfill this need by providing students with a small group with which to relate through the laboratory activities. It is therefore concluded that small group sizes enhance the learning experience because all students are able to fully participate and meaningfully develop the intended competencies.

Zone of Proximal Development

The zone of proximal development offer a great deal of insight into the conclusion that the laboratory experience and learning outcomes are enhanced when they are aligned with student capabilities. Recall from Section 2.3.4 that students can be considered to have three areas of competency for learning tasks. The first is where student competency is insufficient to make any progress on the learning task, even with assistance. The second is where students are completely competent, requiring no assistance to complete the learning task. The third lies between these two, where students are able to attempt the task but still need assistance for successful completion. Aligning learning tasks with this area, called the zone of proximal development, is found to result in greater mastery than when the task is aligned with one of the other two areas (Baker et al., 2020). Learning outcomes designed using this framework are also found to be more effective (Sideeg, 2016).

The harm of positioning a learning outcome below or above the students' skill level can be seen in the competency and autonomy components of self-determination theory. In the former case where learning levels are too low, falling below the student skill level as described by the zone of proximal development, students are not developing new competencies but rather retreading skills and knowledge they have already developed. The intended purpose of the surveyed materials science course, or indeed any course at any post-secondary institution, is to teach and develop skills and knowledge that are relevant to the students' desired activities following completion of the program; in this case, employment in an engineering career. It can also be assumed that students exhibit some degree of autonomy in selecting their post-secondary program; various societal and familial pressures may have influenced their decision to enrol, but it can be assumed that they endorse their participation in the program to some degree. When a laboratory is intended to develop competencies that students have already obtained, the laboratory is no longer contributing to developing the competencies students want to obtain through their degree. The laboratory therefore does not align with the goals of the students; the student does not endorse their participation in the laboratory, simply doing it because it is a course requirement. As a result, the psychological need for autonomy is not fulfilled, and the student is disengaged from the learning activity. This contributes to the perception of laboratory time as wasted. Recall again that engineering students are juggling priorities between potentially six demanding technical courses (see Section 2.2.1); relearning something they are already competent in is therefore likely to reduce engagement and motivation.

At the other end of the spectrum of difficulty, learning activities that exceed student competency to such a degree that they are unable to complete the activity regardless of the level of instructor assistance fail to satisfy the psychological need for competency. The student feels unable to successfully complete the learning activity and is therefore unmotivated, as shown by student responses from Section 5.1.1. However, as mentioned previously in Section 5.1.3, engineering students, particularly in the latter half of their program, are quite accomplished and seek to develop the skills and competencies that they will employ in their internships, capstone projects, and careers. Given that engineering programs are structured sequentially, with upper-year courses building on the skills and knowledge introduced in lower-year courses, it is unlikely that an instructor will present students with a learning activity using skills completely unfamiliar to them.

It is therefore concluded that alignment of the laboratory experience with students' zones of proximal development enhances learning outcomes and the learning experience; if it is too complex and lacking sufficient support, students are discouraged, and if it is too simplistic, students are bored and disengaged. In both cases, students are less motivated because the laboratory does not develop the competencies they endorsed their laboratory participation for.

Much has now been said here about how learning levels should align with students' zones of proximal development. However, this leads to an important question: how to identify these zones. While recommendations in this vein will be developed in Chapter 6, future work on how best to identify these zones is recommended.

5.2 Analysis of Manager Survey Results

The manager results will now be analyzed. The context of survey respondents is presented in Section 5.2.1, and analysis of their assessment of the University of Calgary's engineering program is displayed in Section 5.2.2.

Before entering the analysis, the severe limitations of this section should be mentioned. The manager surveys only had ten participants. Participants were recruited from a list of engineering employers the University of Calgary's engineering internship program has worked with. To ease participation requirements, survey respondents were not followed up with after their responses were submitted. Many respondents also gave feedback tailored to the general University of Calgary engineering program rather than the mechanical engineering department or the surveyed materials science course. The end result is that the survey lacked scientific rigour, failing to specify the definition of experiential learning, to verify the specific relationship of the respondent with the surveyed materials science course, and the specifics of the manager's experience supervising interns and recent graduates, such as the number of students, the duration of their employment or internship, and the details of their employment responsibilities.

Given this context, manager responses are used to highlight certain aspects of the student survey respondents and shed more light on the industry context. They are not analyzed independently, and primarily aid in unveiling the skills and knowledge this particular group of ten managers deem important for engineering employment.

5.2.1 Participant Context

Before analyzing the results of the engineering industry manager surveys, the relationship of respondents to the University of Calgary engineering program and its laboratories should be stated. As seen in Figure 4.4, just under half of respondents are employed in the oil and gas sector. Another 22% are employed in geotechnical engineering, a field related to oil and gas. The remaining third of respondents are evenly split between industrial engineering, civil engineering, materials science, and facility management. Noting that student responses came from a materials science course in the Department of Mechanical and Manufacturing Engineering at the University of Calgary, which is primarily interested with the relationship between the microstructure and mechanical properties of steels and other metals, it can be seen that not every respondent works in an industry that utilizes the technical knowledge imparted in this course and its laboratories. Materials science and oil and gas are the most likely fields to utilize materials science knowledge that is specific to mechanical engineering, and industrial engineering may employ this knowledge depending on specific applications. Geotechnical engineering, which is concerned with the behaviour of soils under load, and civil engineering, which has a much greater focus on concrete as the primary engineering material, have the least application of materials science focused on mechanical engineering. This contextualizes the respondents as generally being employed in areas that utilize materials science knowledge, but are not directly focused on it.

However, it is important to note that this conclusion is drawn from analysis and inference of the survey results and is not directly stated in participant responses. This indicates that, for potential future iterations of this study, survey questions should be more explicit and direct in asking for relevant information.

The next contextual element is the degree of relevant supervisory experience. Recall from Section 3.2.1 that managers with a stake in undergraduate engineering are defined as those who manage recent graduates of the University of Calgary engineering program. This allowed the surveys to focus on members of industry with the most direct experience managing students who had undertaken the materials science laboratories; graduates are specified as 'recent' to avoid responses referring to students who graduated more than five years before their employment under the responding manager, as a longer time frame would obfuscate recollections of the laboratory experience. With that in mind, Figure 4.5 shows the degree of relevant supervisory experience of the responding managers. Rated on a five-point scale, respondents had an average of 3.3, indicating the average supervisory experience was slightly greater than moderate.

Respondents also described their understanding and degree of appreciation of experiential learning theory in training engineers, shown in Figure 4.7 and 4.6, respectively. Rated on a five-point scale, their averages in this area were 3.3 and 4.8, respectively. This indicates that the average manager understands the basics of the theory, if not its complexities. However, the latter score indicates the average manager greatly appreciates the role of experience in training engineers.

5.2.2 Assessment of the University of Calgary Engineering Program

The second high-order category for the manager surveys was respondents' assessment of the University of Calgary engineering program and its laboratories.

Given the small survey size and limited applicability of these survey results, they will not be analyzed in depth, only providing insight towards student responses.

Respondents first identified the specific role that experiential learning plays in training engineers, shown in Figure 4.8. The only theme correlating to more than a single respondent was to educate through a hands-on experience, supporting its prominence in student responses in Figure 4.1(b). This also aligns with the conclusion from the portion of Section 5.1.4 on the zone of proximal development, that students primarily see hands-on career-relevant experiences as the benefit of the engineering learning laboratories.

One respondent identified the value in seeing how real-world experiences differ from the theory taught in classrooms: “The theory and knowledge is the foundation, but reality and the “practical” doesn’t always follow the theory neatly”. Another writes, “In our workplace experiential learning is the hands-on practical experience workers get in how we do things in our industry and company. It shows them how to complete their day-to-day work independent of the technical skills or background they enter our company with. Some will be company specific and some will be industry best practices that they could learn elsewhere.” When asked about balancing practice and theory, another response states, “Theory in practice makes good engineers”. These quotes align with other studies that found a participatory experience deepens learning by connecting it to real-world applications (Chan, 2012; Muscat and Mollicone, 2012).

Given that both undergraduate engineering students and the managers expecting to employ them have clearly stated that they prefer learning through hands-on participatory experiences and that these experiences deepen and enhance their education, it can be safely recommended that the laboratory experience include a hands-on participatory component.

One of the previous responses also shows that the respondents do not conflate “practical” and “company-specific” skills: “In our workplace experiential learning is the hands-on practical experience workers get in how we do things in our industry and company. It shows them how to complete their day-to-day work independent of the technical skills or background they enter our company with. Some will be company specific and some will be industry best practices that they could learn elsewhere.” Another respondent writes, “Company specific skills should not be a concern. Engaging industry to suggest general discipline-specific job skills would be the ideal path forward.” Another states, “You need to be well-rounded.” It is therefore important for engineering education to teach foundational skills and knowledge that are applicable and transferrable across many specific technical fields. This also indicates a potential area in which to follow up this work: engaging industry to identify the general discipline skills that would best improve graduate employability.

It should also be noted that respondents, while desiring a greater focus on practical applications, recognize the value of learning theory and first principles: “Much of the value of University learning is to ensure that graduates have a firm understanding of the theory and problem-solving methods that can be applied in real-world applications. Too much emphasis on experiential learning may take away from ensuring firm understanding of first principles.” Another says, “Theory and knowledge are where universities should focus. As long as entry level jobs remain, new engineers are able to gain more practical experience after graduation.”

The final high-order category was the connection between engineering education and practice. While the previous category focused on the existing engineering program at the University of Calgary, this category is oriented around the details of what managers consider the ideal undergraduate program.

Unsurprisingly, a portion of the attributes of the ideal engineering program described in Figure 4.13 are restated from previous results analyzing the current program. New themes in hard skills that appear in this figure are applying theory to practice and ensuring an understanding of first principles, aligning with the general position of the respondents in increasing the program focus on practical applications. Interestingly, new soft skills present in Figure 4.13 are lifelong learning and humility, the latter of which is the most prominent theme in this figure. A respondent states the following as a positive attribute to develop in students: “Not afraid to ask questions or admit not knowing.” Another says, “Individuals should take it upon themselves to recognize specific gaps in their skill profile and work to fill them.” Interrelated, these two themes of humility and lifelong learning indicate a desire for an engineering graduate who is more aware of their limitations and works to mitigate them than the current crop of engineering students. This supports the notion that engineers are expected to maintain their professional competencies (Engineers Canada, n.d.-b).

This point is expanded on in Figure 4.14, which shows respondents’ preferred focus between teaching theory and teaching practice. Only 11%, or a single response, expressed a desire to focus on theory. 55% wanted a focus on both, while the remaining 22% wanted both, but desires a greater focus on practice than currently exists. This aligns with the previous points of analysis regarding reducing the laboratory focus on research and increasing the focus on industry-relevant information.

5.3 Analysis Conclusions

The conclusions of this analysis will now be summarized.

The most prominent conclusion is that the student laboratory learning experience is enhanced when learning tasks are hands-on and participatory. Students view hands-on practical experiences as more educationally relevant, aligning with managers’ perceptions that engineering education should offer these kinds of experiences. Construction of the hands-on experience using Kolb’s experiential learning cycle is found to improve student performance and deepen learning. Note that the entire cycle does not need to be contained solely within the learning tasks, but can also be integrated into the laboratory assessment and other post-laboratory activities. These improvements to the experience are further enhanced by designing the laboratory for small group sizes where all members can contribute. This allows all students to engage in the hands-on experience and develop their competencies as intended.

The next most prominent conclusion is that the student learning experience is harmed when students do not perceive the laboratory time as educationally valuable; students have many competing demands and will disregard experiences that lack educational value. Laboratories are perceived as having more educational value when students perceive a connection between the laboratory and industrial applications, as it is these connections that motivate students to engage in and complete their engineering degree. As design components are also highly relevant to their upcoming capstone design projects and engineering careers, the inclusion of a design component can further improve the student learning experience. Besides hard skills that are relevant to specific industries, students also value soft skills that are perceived as relevant to employment. In general, alignment of the laboratory with broader student course, degree, and career goals, as contextualized by professional engineering practice, enhances the student learning experience and learning outcomes.

The final prominent conclusion is that the laboratory learning experience is harmed when communication is poor. This applies to all elements of the laboratory from start to finish. Students require clear communication to fully develop and demonstrate their competencies as required by the laboratory.

These three conclusions relate to major portions of the analysis and remaining conclusions, forming the guiding principles for developing recommendations. Further conclusions are found to support these principles.

In terms of improving the perceived relevance of a laboratory, the learning experience and learning outcomes are found to be improved by aligning the laboratory with students' zones of proximal development; overly complex or simplistic laboratories do not meaningfully develop student competencies and are therefore perceived as having little educational value. It was noted that students are expected to retain certain competencies from prerequisite courses, and that it is therefore not the responsibility of instructors to reteach this information provided this requirement is clearly communicated to students.

The laboratory learning experience is also found to be enhanced when the assessment pressure is sufficiently low enough to not distract students during the laboratory learning tasks, improving integration of the laboratory learning into their knowledge bases.

In the case where laboratory design anticipates that students will have preexisting knowledge from their lectures, the student learning experience and learning outcomes are harmed when laboratories instead take place before the relevant lectures. The student learning experience is also harmed when the allocated laboratory time or available facilities and equipment are perceived as insufficient. All these components are part of the learning experience, and deficiencies in them therefore detract from the student experience and from the efficacy of learning outcomes in developing student competencies.

A particular case of poor communication harming the learning experience is when facilitators are rude or unknowledgeable, reducing their effectiveness in developing student competencies and causing lasting negative impressions. Students have limited power to respond to rudeness, so it is important for course coordinators to ensure openness and support on the part of facilitators, which better satisfies the student need for relatedness and therefore improves their engagement.

Chapter 6

Recommendations for Improving Undergraduate Engineering Laboratories

Now that survey responses have been fully analyzed and integrated with the reviewed educational scholarship, recommendations for implementing them in the engineering learning laboratory can be presented. The limitations of these recommendations is first discussed in Section 6.1; the recommendations are then developed in Section 6.2.

6.1 Limitations of Recommendations

The intent of this study is to develop a methodological framework for applying established educational scholarship to improve learning outcomes in undergraduate engineering laboratories. Given that the study was initially motivated by end-of-semester student survey results in a third-year materials science course, it was decided to limit the research scope to analyzing this particular course.

This study is therefore limited to providing a framework improving learning outcomes specifically in undergraduate mechanical and manufacturing engineering materials science courses at the University. Expanding to other courses and other engineering disciplines will require accompanying studies in those courses and disciplines. As well, this study took place in and is tailored to the Canadian engineering education context; further studies are needed to determine if findings are applicable to post-secondary engineering education outside of Canada and North America. This study is also limited by the number of participants.

Survey results may represent student difficulties with the course in question during the semester the study was conducted, and results may not necessarily reflect the experience of students in other courses, under other professors, or future students experiencing the same course under the same professor. Follow-up studies are therefore recommended to ensure these themes are relevant to the broader Canadian undergraduate engineering student body; this is discussed further in Section 7.3.

6.2 The New Learning Laboratory Methodological Framework

The general conclusions resulting from analysis of the survey results and integration with educational scholarship have been summarized in Section 5.3. The specific actions to take that improve learning outcomes and the laboratory learning experience can now be detailed.

The new laboratory framework centres around three principles: inclusion of a hands-on participatory experience; clear, explicit, and respectful communication between the laboratory facilitators and the students; and constructive alignment of the learning outcomes, the learning activities, and the assessment of laboratories, which is found to address many of the analysis conclusions. All other conclusions on the student learning experience are found to fall under the umbrella of one or more of these principles. These three principles are covered in Sections 6.2.1, 6.2.2, and 6.2.3, respectively.

6.2.1 Including a Hands-On Participatory Experience

It is recommended to structure a significant portion of the laboratory learning activity as a hands-on participatory experience. This is defined as a laboratory where every student takes an action that is necessary for successful completion of the laboratory, and which develops the competencies outlined in the laboratory learning outcomes. A laboratory where the majority of student participation takes the form of writing down data points while the facilitator conducts the experiment is to be avoided. This example is specifically cited by many student survey participants as a common experience which students find unengaging and tedious, and which results in little to no learning the student finds meaningful. More detail on engaging students by avoiding tedium is available in Section 6.2.3.

Continuing on, a participatory hands-on experience is recommended to be included for several reasons. Surveyed students expressed a marked preference for hands-on experiences, far outstripping all other response themes. Surveyed managers have expressed a desire for engineering education to place a greater focus on practical applications, skills, and knowledge. Learning is deepened when students perceive an assessment as authentic, meaning that the assessment corresponds to workplace tasks and requirements (Gulikers et al., 2008). A practical experience that is authentic to the context of professional engineer will therefore be better perceived and more deeply engaged in by students. Finally, a hands-on practical experience has been found in numerous studies to deepen learning, improving learning outcomes, and improve the learning experience (Chan, 2012; Muscat and Mollicone, 2012; Grantham et al., 2010; Lee et al., 2008).

In developing a hands-on participatory experience, it is recommended to utilize Kolb's experiential learning cycle. While the core tenets of experiential learning theory are notably lacking in evidence, as discussed in Section 2.2.3, the cycle itself has significant literary support showing its efficacy in improving learning outcomes and the learning experience (Chan, 2012; Muscat and Mollicone, 2012). To reiterate, students should have a hands-on experience that sequentially engages Kolb's four learning modes: undertaking the concrete experience, reflectively observing the experience, undertaking abstract conceptualization to integrate this learning into their existing body of knowledge, and active experimentation of their new knowledge framework. It is important to acknowledge that these modes can occur across the entirety of the laboratory experience, from the pre-laboratory all the way to receiving the marked assessment. The course coordinator does not have to attempt to implement all four modes within the laboratory time slot.

The reader may note that this does not advance an understanding of how, specifically, to develop a participatory and hands-on learning laboratory experience. This is to allow flexibility and innovation from course coordinators in designing laboratories. Several recommendations, borne from observing Kolb's experiential learning cycle and its applications, can aid in this laboratory design. First, while the cycle commonly presents the concrete experience as the first mode of learning, the laboratory can start with any mode from the cycle. Some instructors may find it better to start with abstract conceptualization, exploring the student cohort's preexisting understanding before the laboratory experience. Others may find a reflective activity helps bring preexisting knowledge and skills to the forefront of students' minds. Active experimentation may help in first exploring the studied phenomena before introducing the established theory.

Another observation is the importance of critical reflection, highlighted previously in Section 2.3.2. Common in experiential learning theories, critical reflection is the practice of engaging in focused examination of an experience so as to deepen learning from it. It is therefore recommended to include a guided reflection element in the hands-on experience. This can be an additional component to the laboratory, such as a follow-up discussion in the next lecture after the laboratory. It can also be integrated into the overall laboratory experience; if intentionally designed, a laboratory report can function as a critical reflection, for example. The reflection does not have to be this formal; a simple conversation can fill the purpose. The intent is to have students revisit the experience of the learning activity, reinforcing their learning through repetition. It is recommended to structure this reflection using Ash and Clayton's Describe, Examine, Articulate Learning or DEAL model, covered in Section 2.3.2, as it has seen substantial use and has been verified through a wide variety of studies at varying education and employment levels (Ash and Clayton, 2009; Eyler and Giles, 1999; Yan et al., 2019; Croft et al., 2013; Brooks et al., 2010; Bettencourt, 2015; Conrad and Hedin, 1990).

Finally, note that a hands-on experience does not need to exactly mimic real-world applications. The concept of unit cells in crystallography, the fundamental atomic arrangements whose repetition forms the crystal lattice of many common metallic engineering materials, can be taught through atomic simulations or atomic force microscopy that shows a real image of the actual atoms. However, a much simpler, less expensive, and more common activity is to use styrofoam balls and toothpicks, measuring the atomic radii using common and inexpensive callipers. While greatly simplified, the stick-and-ball model still allows for student participation and experimentation, and can effectively communicate the desired concepts.

Ensuring Adequate Facilities

A notable barrier to the implementation of a participatory hands-on laboratory experience is the limitations of facilities and equipment. University-level engineering programs are subject to ever-rising volumes of students, who must be housed and educated in limited facilities (University of Calgary, n.d.-a). In addition to the scheduling issues noted previously in Section 6.2.2, several surveyed students noted that their laboratories had insufficient facilities; there was not sufficient seating or enough experimental apparatuses for the number of students in attendance. Some experimental equipment may require additional training for students, such as safety training for using a metal lathe in a manufacturing processes laboratory. Finally, the apparatuses utilized in engineering learning laboratories have become increasingly complex and computerized (Feisel and Peterson, 2002). While this has improved the quality of experimental results in learning laboratories and may better imitate real-world industrial processes, experimental machinery has also become more expensive as a result and can require specialized technicians, who can cost more and may be employed by the manufacturer rather than as a technician at the university. Repairing or replacing laboratory equipment can be extremely expensive and require the services of a technician with limited availability, potentially taking weeks or months of downtime before the machine is brought back online. In short, universities may be understandably reticent in allowing students to actively experiment in laboratories when mistakes can result in highly expensive repairs that take an extended period of time to complete, limiting the amount of equipment available in the laboratory and potentially requiring modification to the course schedule.

Addressing these barriers is worthy of a study in and of itself. However, some recommendations can help. When designing a course, a coordinator should take stock of the available facilities, including the amount of equipment available, its condition, required training before use, and occupancy limits. The laboratory experience can then be tailored to the available resources. To balance the use of realistic but prohibitively expensive equipment with a participatory hands-on experience, consider using simpler equipment or methods to impart laboratory concepts, or combining a simpler experiment conducted by students with a more complex one conducted by the facilitator, and using the comparison as a teaching method. For example, in using the previously-described ball-and-stick method to teach unit cells in materials science, a follow-up activity could be the construction of a computer simulation that more accurately simulates real atomic behaviour. Comparisons between the models would teach students the strengths and weaknesses of each. Again, there is no one-size-fits-all approach in education, but utilizing these recommendations can generate a laboratory learning experience that is perceived more positively by students and results in deeper learning.

Group Size

The ideal group size should be discussed. The surveyed students exhibited a marked preference for small group sizes, citing its value in developing teamwork skills and allowing for collaboration. Some students noted the disruptive effect of large group sizes: "The groups were too large to reasonably work together on something that would have probably been more effective with 2 students, simply due to the size of the equipment we were working with." Others specifically mentioned that large group sizes can prohibit access to the learning activity, going against the principle of hands-on participatory experiences discussed earlier: "The best things facilitators can do are get everyone involved (have less people in a group so everyone can do something)"; "Smaller groups were also formed so it was easier to be involved in any of the lab activities"; "I like being in a small group where we can all have a chance to perform a part of the lab." Only one surveyed student expressed a desire for completing laboratories individually, which does not develop skills in teamwork, collaboration, and communication.

Small group sizes help enable the recommendation for a hands-on participatory experience. While a laboratory may be designed to be hands-on, if group sizes are so large that not every member is able to fully participate in the learning tasks, then not every student has a hands-on experience; it is for this reason that the experience is recommended to be participatory. Small groups allow all members to meaningfully participate.

Therefore, it is recommended to design laboratories for small group sizes. The exact size depends on the duration, depth, and complexity of the laboratory, the amount of available equipment, and the size of the student cohort, so a specific group size is not recommended. Note here that laboratory duration is meant to encompass laboratories taking multiple sessions to complete, or a series of laboratories that build off of one another. These extended experiences have more components and are more complex, and may be better suited to larger group sizes.

The group should be small enough that all members can meaningfully contribute and conduct unique tasks, but not so small that the number of groups exceeds available equipment or that students are overwhelmed by the amount of work required in the laboratory. A specific group size is dependent on these factors, so a specific number of participants is not recommended to allow for flexibility in course design. Another method for accommodating a large number of groups is to have multiple stations with unique laboratory tasks that students rotate through, allowing for more groups with a limited amount of equipment.

In summary, it is recommended to design a significant portion of the laboratory learning activities as hands-on participatory experiences. Using Kolb's experiential learning cycle as a framework and Ash and Clayton's Describe, Examine, Articulate Learning or DEAL model for critical reflection can aid in constructing the laboratory and deepening learning through critical reflection. Small group sizes allow everyone to meaningfully participate in the experience. Barriers to implementing a hands-on experience, such as prohibitively expensive equipment or limited availability of sufficiently large laboratory spaces, must be considered and accommodated for when designing the laboratory experience.

6.2.2 Communication

Communication must be clear, explicit, and respectful. This is applicable to all elements of the laboratory, and indeed to education as a whole. However, communication is of particular importance in the following areas: the general outline and requirements of the laboratory; the connection of the laboratory to industrial applications and to what students can reasonably expect in their careers following graduation; and the nature and value of soft skills developed by the laboratory.

The outline of a laboratory at the University of Calgary is generally contained in two documents: the course outline, which details the course schedule, requirements, learning outcomes, and assessment strategy, and the laboratory manual, which includes the purpose of the laboratory in the form of learning outcomes, a step-by-step outline of the experimental process and the actions students are expected to take, and the details of the laboratory assessment. In keeping with the principle of clear communication, these two documents should clearly and explicitly detail the laboratory process, the importance of the laboratory for the course, and how the laboratory relates to industrial or research applications. The course outline is available to students at the start of the semester, and laboratory manuals are made available to students prior to the start of the laboratory. These documents are therefore the first point of contact between the course coordinator and the student on the laboratory, and should be comprehensive in detailing what to expect in the experience.

Note that research is a career path some students will follow, and so research applications are a viable focus or connection for an engineering laboratory. As well, Engineers Canada states that engineers must work to maintain their competency, which requires engaging with published research to stay up to date on the current state of their field. Skills in research are therefore applicable to all engineering students regardless of their desired career path.

The laboratory should be clearly and explicitly connected to the course it is situated in, to the overall engineering degree the student is undertaking, and to future career applications. These connections improve engagement and motivation by explicitly linking the current laboratory to the overall profession the student is taking the degree, and by extension the laboratory, to be employed in. Recommendations on what connections should be made are detailed in Section 6.2.3.

Take an example: an engineering student at the University of Calgary may not be engaged with the third-year materials science course, having already found an interest in fluid dynamics. The laboratory can be connected to the overarching mechanical engineering degree, for example by reminding the student that no discipline exists in a vacuum and that, as endorsed by the Canadian Engineering Accreditation Board in their post-secondary program accreditation criteria, it is still important for a mechanical engineer who practices in fluid mechanics to be knowledgeable about materials science. For example, if the student goes on to work in developing new dams to generate electricity, it is important to know the mechanical properties of materials used in the piping, superstructure, and mechanical equipment. As well, a student enrolled in the surveyed course can expect to shortly start a 12- to 16-month internship, which may change their opinion on fluid dynamics, and in which they may need to apply materials science knowledge.

These connections between the laboratory and the degree and future career are not guaranteed to result in an engaged and motivated student. However, they can result in greater salience, or perceived importance, of the laboratory for the student's degree and career, which improves perception of the developed competency and the overall laboratory learning experience.

The final area to communicate is the soft skills developed by the laboratory. While understandably of lower perceived value than hard skills in a professional program, soft skills are still valuable to have in the students' academic and professional careers. Teaching these soft skills is detailed later in this analysis; the communication of them is highlighted here, as developing soft skills is not in and of itself guaranteed to improve the program learning outcomes in terms of employability or to improve the student learning experience through connecting the laboratory to industrial applications if students do not perceive the connections. The importance of these skills in students' future careers must be *clearly* and *explicitly* communicated to students so that they are aware that the skills were taught and that they are of career value. A small note: other studies (Riemer, 2007; Keane and Gibson, 1999; Missingham, 2006; Jensen, 2000) have also noted the desire from industry for engineering graduates to possess more soft skills, particularly in teamwork and in communication. Surveyed students also saw the benefits of these soft skills, particularly in teamwork (see Section 5.1.2). Expressing this to students, that soft skills are specifically a trait sought after by employers, can improve the salience of the highlighted skills in improving career outcomes.

Pre-Laboratory Communication

A note must be made that the prerequisite knowledge and skills required for the laboratory must be communicated to students before they can engage in the laboratory experience. While this may seem an obvious conclusion, it is important to highlight this given this study's context at the University of Calgary. The University's engineering program has a high volume of students, welcoming over 1100 first-year students for the Fall 2022 academic semester (McFarland, n.d.) and hosting several thousand more in higher years of study, in addition to graduate programs and research by professors. This results in a high number of students undertaking courses with accompanying laboratories, with course coordinators competing over the limited space in which to conduct these laboratories. This can result in laboratories taking place before the relevant material has been taught in lecture.

It is recommended to avoid this as much as possible. This experience is disorienting to students as shown in their responses: "The concepts that were used in the lab had been taught in class before, [but] were incorrectly [placed] in lectures as [to] not allow complete understanding"; "The labs did not seem to connect well with the course content, at least in terms of timing in the semester."

In cases where placing the laboratory after the requisite lecture is not possible, such as due to the facility limitations listed above, then another route of communication must be included. This can take several forms. Lab manuals and pre-laboratory work sheets or videos are a common tool at the University to impart necessary or relevant laboratory information to participates outside of the lecture environment. Laboratories commonly include an orientation at the start where a facilitator explains the experiment about to be conducted. This can be expanded to explain the relevant material, and may be a useful inclusion even when the material has already been covered in lecture, as repetition has strong evidentiary basis in helping to reinforce and deepen the relevant learning (Ebbinghaus, 1885). One survey respondent writes of this, "The most positive experience I have had in a lab was when the TA's took an extra 10 minutes to explain everything that was going on." However, it is important to note that this recommendation is for when laboratories were designed to follow a lecture imparting relevant theoretical material, but limitations cause the laboratory to instead occur before the relevant lecture. Ensuring the correct order is greatly preferred; when the order is incorrect, the recommended measures minimize the disruption to the learning experience rather than maximizing it.

This framework is intended to be widely applicable in engineering education contexts, and a specific pathway of communication will not be recommended so as to preserve flexibility in course design. What is important is that the skills and knowledge required for the laboratory are imparted to students before the laboratory takes place.

A note should be made on respectful communication, which was highlighted at the start of this section. Respectful communication here is defined as being honest, open, and polite. This recommendation focuses on the laboratory facilitators who directly interact with students during the laboratory experience. While respectful communication is important as a course coordinator, coordinator communication extends outside of the laboratory space to other course elements such as final exams, projects, and the lectures; improvements to course coordinator communication are therefore considered to be best considered from a course- or institution-wide perspective and is therefore outside of the scope of these laboratory recommendations. As well, course coordinators at the University of Calgary are generally, although not universally, post-doctoral researchers; the post of teaching professor at the University specifically requires distinguished achievements in professional learning and development, as well as research and scholarship (University of Calgary General Faculties Counsel, 2021). Therefore, course coordinators at the University of Calgary can be generally assumed to have more experience communicating professionally and are subject to more rigorous feedback and assessment mechanisms, such as end-of-course surveys, than the average laboratory facilitator.

Identifying Student Competencies

The later section on constructive alignment recommends directing learning levels towards a student cohort's zone of proximal development. While students are expected to retain competency in learning outcomes from previous courses, in the case where a course develops new competencies, it is recommended to engage directly with the students in dialogue to determine their level of competency. For discussing these new competencies, engagement should happen at the start of the semester, allowing the most time possible to make any necessary alterations to the laboratories if extra review or teaching of knowledge and skills is needed beforehand. This necessarily requires factoring in flexibility to course design to potentially accommodate any student issues. Having an extra laboratory slot, or a week with no lessons planned, builds this flexibility into the course schedule. However, no approach is one-size-fits all, so it is left to the course coordinator to decide how best to build in this flexibility. Communication in this area should align with other recommendations from this section, being clear, explicit, and respectful.

Professionalism in Facilitators

It was found in Section 5.1.1 that unprofessional facilitators can have a large impact on the student learning experience. This theme resulted in the strongest emotional response from surveyed students, even when several years had passed since the laboratory experience in question, and it is concluded that unprofessional facilitators have a strong disengaging effect on students. This unprofessionalism was found to primarily constitute rudeness, the opposite of which was found to be openness and supportiveness. Surveyed students mention positive actions in this area: “Facilitators made the greatest difference in whether or not a lab was fulfilling to the student, the openness of first year TA’s and willingness to share their experiences is something that is not replicated by upper year lab facilitators overall”; “The most positive experience I have had in a lab was when the TA’s took an extra 10 minutes to explain everything that was going on. Not only that, they held “a question period” towards the end of the lab and were very supportive”. Sharing of experiences, taking extra time to explain the laboratory, and providing a question period to correct misunderstandings aid the perception of openness and support.

The question is now, how to foster these qualities in facilitators, or hire facilitators who demonstrate these qualities? The relationship of the course coordinator to the laboratory facilitators should be mentioned. At the University of Calgary, laboratory facilitators are generally either graduate students or technicians hired by the University. In the former case, a contract exists governing the relationship between facilitator and course coordinator. The amount of hours the student can work for the coordinator is strictly defined. The ability of the course coordinator to require training that fosters the aforementioned qualities is therefore limited, as it will take away from the limited time available for course and laboratory duties. Therefore, implementation of professionalism in facilitators may be best approached from an institution-wide perspective, factoring this requirement into hiring contracts and the training of teaching assistants. For example, graduate teaching assistants at the University of Calgary are required to attend a training course that prepares them for their duties. This course could be extended to impart the elements of professionalism mentioned above. As well, sufficient knowledge in the theory and practice involved in the laboratory can be included as a condition of the facilitator’s hiring. The theme of unprofessionalism drew from student survey responses on both their current and past laboratories, indicating that this problem extends beyond the surveyed materials science course, warranting a faculty- or institution-wide approach. However, this lies far outside the scope of this research endeavour.

In summary, the learning experience and learning outcomes of a laboratory are improved by clear, explicit, and respectful communication. As the first point of contact, the course outline and laboratory manual should clearly detail what students can expect from the laboratory in terms of process, learning outcomes, and assessment. There should be clear and explicit communication of how the laboratory connects to the course, the engineering degree, and engineering practice in industry in terms of both hard and soft skills. Ensure that the requisite knowledge and skills are taught to students before they engage in the laboratory. As well, facilitators enable all elements of the laboratory; ensuring their professionalism is an important part of clear laboratory communication.

6.2.3 Constructive Alignment of Learning Outcomes, Learning Activities, and Laboratory Assessments

The theoretical framework of constructive alignment can address several conclusions on the student laboratory learning experience. Specifically, it offers solutions to enhancing the learning experience by intentionally designing the laboratory and assessment and aligning them with the learning outcomes. Constructive alignment also potentially addresses the conclusions that the student learning experience is harmed by poor communication and insufficient facilities, equipment, and laboratory time, and that the experience and learning outcomes are enhanced by reducing assessment pressure during laboratory learning tasks.

Recall from Section 2.3.3 that a constructively aligned course is one where the learning outcomes, the learning task, and the assessment are designed to mutually support each other. This framework aids teachers in bridging the gap between the intended learning and the methods used to accomplish it (Biggs, 1996) , and use of this framework is found to improve student success rates (Khumalo, 2018). Success rates, or the rate at which students graduate from the program, are dependent upon students remaining in the program and achieving the assigned learning outcomes. In improving the success rate, constructive alignment also necessarily improves the retention rate and the learning outcomes.

This framework can also address how poor communication and insufficient time, facilities, and equipment harm the learning experience. Poor communication affects all three elements of the laboratory. Regardless of if the design of the laboratory follows constructive alignment, the laboratory as experienced by students will not be constructively aligned if the learning outcomes, the specifics of the learning task, or the specifics of the assessment and grading scheme are not clearly communicated to students. As shown in the portion of Section 5.1.4 on self-determination theory, this poor communication inhibits the development and display of student competencies. Since this alignment is dependent upon its perception by students, it can be concluded that explicitly communicating the elements of the constructively aligned laboratory to students enhances their learning experience and learning outcomes. Insufficient time, facilities, or equipment result in a misalignment of the learning task.

This can also be extended to the assessment of the laboratory. Surveyed students stated that their learning experience and outcomes were enhanced when assessment pressure was reduced, allowing them to more fully engage in the learning tasks. In the case that assessments take place outside of the laboratory time slot, it was found that allowing more time aided in reducing assessment pressure. Constructive alignment shows that this pressure can also be reduced by aligning the assessment with the laboratory activity. Take the example of a worksheet. If the worksheet questions directly follow from the laboratory learning tasks and are designed to be completed during the laboratory time, the assessment itself becomes part of the learning task and aids in developing student competencies. This can also be applied to laboratory reports, or indeed any laboratory assessment: constructive alignment with the learning tasks is anticipated to aid in developing student understanding, as this is the core underlying tenet of constructive alignment.

It is therefore concluded that the student experience and laboratory learning outcomes are enhanced when the learning outcomes, the laboratory activity, and the assessment thereof are constructively aligned with each other. Constructive alignment is therefore used in the following sections to develop recommendations on aligning the laboratory components with each other.

Learning Outcomes

As previously stated, learning outcomes describe the expected competencies students will develop through the learning experience. Learning outcomes define the value the learning experience adds to the student's education.

Constructively aligned learning outcomes should be specific actions the student will take. To improve student engagement and motivation, these learning outcomes should be clearly communicated as per Section 6.2.2, and should also be aligned with the broader course, degree, and career objectives of the general student cohort. These methods improve student motivation by relating the specific laboratory, which the student may be uninterested in, to the broader degree program, which the student is motivated to complete. In terms of self-determination theory, these methods connect the developing competencies to a student's choice to engage in the laboratory, satisfying their need for autonomy and improving motivation.

To clearly communicate learning outcomes that are constructively aligned with the laboratory learning activity and assessment, it is recommended to use the verb-content-context or VCC model. Developed at the University of Waterloo (University of Waterloo, n.d.), learning outcomes utilizing VCC start with the specific action or verb the student will accomplish, the content of that action, and the context the action takes place in. A useful source for these action verbs is the revised Bloom's taxonomy (Anderson and Krathwohl, 2001). As well, verbs from the taxonomy correlate to specific learning levels, which will allow the course designer to tailor the learning outcomes to the specific level of learning desired.

An example utilizing the learning outcomes of the surveyed materials science course will illustrate the VCC model. The original learning outcome for the course's series of laboratories was "to learn and gain experience in metal processing methods (thermomechanical processing) for improving the mechanical performance of metals". Using the model, the verb is "to learn and gain experience", the content is "metal processing methods (thermomechanical processing)", and the context is "improving the mechanical performance of metals".

While the content and context are appropriate, as they both identify the content of the laboratories and its broader context in the materials science course, “learn and gain experience” is an overly-broad action for students to take; any amount of learning or experience gained, however minimal, will satisfy this requirement. “Analyze and explain” are better verbs to use here. “Analyze” identifies that students are exploring the relationship between processing methods and mechanical performance, while “explain” provides a route for students to express their understanding of the analysis in a way that can be assessed. Slightly reworded for grammar, the learning outcome is now “to analyze and explain how metal processing methods (thermomechanical processing) improve the mechanical performance of metals.”

The second recommendation for constructively aligning learning outcomes is to ensure they are aligned with the broader course, degree, and career objectives of the general student cohort. Specifically for engineering learning laboratories, note that surveyed students desire hard skills and industry knowledge that are applicable to their post-graduation careers. Surveyed managers expressed the hard skills they desire in engineering graduates: understanding how the theories from lecture work in practice, emphasizing how well the underlying assumptions and principles hold up when applied to a real-world situation, and regulatory knowledge such as codes, standards, and best practices. It is recommended to connect the laboratory to the discipline-specific exemplars of these hard skills.

When students do not perceive these connections and become disengaged from the laboratory experience, there is a disconnect between their motivation to complete an engineering degree and their amotivation for completing a laboratory that is a necessary component. This disconnect can be repaired through the identification type of motivation, where learners are extrinsically motivated to complete a goal because they identify its importance for a broader, intrinsically motivated goal. In this case, the laboratory is a necessary component of the broader undergraduate degree the student hopes to obtain. Therefore, laboratory time can be better perceived as time well spent when connections are made to students’ broader goals in their degree.

Take the surveyed materials science course: the knowledge and concepts learned are most valuable to students if they intend to enter a career in materials science. Therefore, connecting the laboratories to real-world materials science applications, and highlighting that the laboratory directly contributes to competencies in this area, justifies the student’s participation in the laboratory and fulfills their need for autonomy. As the laboratory directly relates to the student’s desired career path, they are more likely to experience intrinsic motivation.

Many other students may not know what career they would like to pursue following graduation, or may have chosen a different area such as thermodynamics or fluid mechanics. In this case, the point can be made that the principles and theories of materials science are still important across a wide array of engineering applications; if they weren’t, materials science would not be a mandatory component of all Canadian undergraduate engineering programs (Engineers Canada, n.d.-a). The student may not be intrinsically motivated within the materials science laboratories, but can identify that the experience is still valuable to their broader intrinsic goal of completing the engineering program.

As well, it is important to understand that each student is unique in their motivations and goals. Focusing on maximizing the learning outcomes for each individual student may result in an unwieldy course and require more facilitator time and effort than is practically available in the university environment, while keeping the same learning outcomes year over year ignores the needs of the specific student cohort taking the course and risks minimizing learning outcomes. It is therefore recommended to tailor the learning outcomes to the general cohort rather than a specific student. Other supports, such as office hours or tutoring, can be highlighted to this student to aid them.

Learning is maximized when the learning experience sits in the zone of proximal development for each student (Vygotsky, 1978), a concept which is covered in more depth in Section 2.3.4. Seen through the lens of self-determination theory, described in Section 2.2.4, a learning experience falling below or exceeding a student's zone of proximal development harm their motivation by not fulfilling the student's need for autonomy: they are engaged in the learning experience to advance their knowledge and further their education in their selected degree, but the laboratory learning experience is failing to meet their needs and does not validate their endorsement of the experience. Learning levels should therefore target the student cohort's zone of proximal development.

There are several ways to identify this zone for students. Higher-level courses at the University of Calgary often have prerequisite courses, which the student must complete before enrolling in their desired course. In assigning students a passing grade, the University is saying the student has achieved the course's stated learning outcomes, and students are expected to retain their competency. Therefore, reviewing prerequisite course outlines will help identify the level of competency students are entering the course with. This can also be used to look forward, identifying which courses the current course is a prerequisite for and using those course outlines to decide the competencies that should be developed through the current course and laboratories.

This will identify the pre-existing competencies students are expected to have, but a course may introduce and develop new competencies that were not covered in prerequisite courses. In these areas, every student cohort is unique and will have variable levels of competency when entering the course. It is therefore recommended to directly engage students in dialogue on these new competencies, which was explored previously in Section 6.2.2.

A final note on identifying the zone of proximal development for a particular student cohort: engineering as a discipline is a pastiche of numerous scientific and mathematical disciplines such as thermodynamics and linear algebra, which themselves are composed of subtopics and varying fields of inquiry. Students enter a course with differing skill levels in different competencies, and a high level of competency in one does not guarantee competency in another. It is important to acknowledge that students have varying competencies and skill levels, and the course coordinator should seek to align the learning experience with the zones of proximal development in these smaller topics and skills. In short, the zone of proximal development for students cannot be identified solely in the area of the course, materials science in the case of the surveyed course; these zones must be identified for the relevant knowledge and skills that make up the course, such as identifying grain sizes and boundaries, or analyzing the relationship between grains and mechanical properties.

Learning Activities

Developing a constructively-aligned learning experience is relatively simple: ensure that the learning tasks require students to take the actions described by the learning outcomes, in such a way that the assessment will directly assess the learning task and the developed competencies.

Take the newly-developed learning outcome from the previous section as an example: "to analyze and explain how metal processing methods (thermomechanical processing) improve the mechanical performance of metals." Students are expected to analyze and explain, and so the laboratory learning tasks should contain elements of analysis and explanation. Possible methods are using a worksheet students complete throughout the laboratory that explicitly asks analysis and explanation questions, or having periodic check-ins with the laboratory facilitator explaining their analysis. This list is not exhaustive, and no specific pathway is recommended to allow flexibility and innovation in course design.

Since this learning outcome was developed from the laboratory manual, rather than the typical inverse method that starts with the learning outcome, the content of that particular laboratory necessarily involves the content of the learning outcome, resulting in a constructively aligned laboratory experience. The students will indeed engage in materials selection, several metal processing methods, crystallographic analysis, and mechanical property testing, as shown in the lab manual in Appendix C, and analyze how these processes affect mechanical properties.

It was noted in the preceding section that the learning outcomes should relate to the broader course and industrial context. Graduate student facilitators may be in a unique position in connecting the laboratory to broader professional practice, as many may be engaged in research in the laboratory area (University of Calgary, n.d.-b). Sharing their own research can improve engagement by showing the connections and by showing the researcher's enthusiasm for the subject area; after all, enthusiasm can be contagious (MacDonald, 1995), enhancing student engagement.

Assessment

The final piece of constructive alignment, the assessment of the learning activity, is perhaps the most important given the contemporary Canadian and North American post-secondary focus on quantitative grades. Studies have found that assessments are the most prominent signals to students on how to approach a given course (Nightingale et al., 2007). The constructive alignment process provides the necessary reflection when developing assignments to ensure they directly assess the competencies described in the learning outcomes. A constructively aligned assessment directly assesses the competencies described in the learning outcomes and developed through the learning experience. The assessment is tailored and specific, and should continue to develop the desired competencies.

Note that laboratory assessments at the University of Calgary are often incorporated into the overall course grading scheme (University of Calgary, 2023), and final marks in a course dictate whether students can enroll in subsequent courses. Insufficient marks can result in the student retaking the course, increasing the time and effort required for the program and potentially delaying their graduation and entry into the workforce. This shows that student stress regarding laboratory assessments is connected to the overall course grading scheme, and highlights a previous conclusion that student engagement and effort for a given assessment are often dependent on it being graded (Edwards, 2022).

Consider once again the newly-developed learning outcome for the surveyed material science course, "to analyze and explain how metal processing methods (thermomechanical processing) improve the mechanical performance of metals." Laboratory assessments must therefore directly assess the students' abilities in analyzing and explaining the relationship of the selected processing methods to a sample's mechanical properties. Assessments that directly test the student's ability to explain the structure-property relationship are oral or written assessments; note that this example shows how constructively aligned assessments directly relate to the actions verbs used in the learning outcomes. Assessments that meet the learning outcome developed above could be a presentation, a worksheet involving written questions, a formal laboratory report, or other methods. Again, a specific assessment method is not recommended to allow for course instructor flexibility and innovation. Note that assessments can be a learning task in and of themselves; writing a laboratory report can develop skills in technical writing and communication, for example.

It should be mentioned here that analysis of student survey responses show that students more fully engage in the laboratory experience when the pressure of assessments is reduced when students are working on the learning activities. The remainder of this section will outline recommendations for reducing assessment pressure.

The primary recommendation is to separate the learning activity and its assessment by a period of time dependant on the specific needs of the course coordinator and student cohort. Summative graded assessments should not take place within the laboratory itself, as students focus on doing well on their assessment rather than the laboratory activities. Using formative assessments instead, such as an informal conversation between the students and the facilitator, will help the facilitator to understand and develop student knowledge without adding undue pressure that distracts them from the learning tasks. When the assessment exerts less pressure on students during the laboratory activities, they are more focused on the task at hand. The amount of time separating these components depends on the amount of student effort required for the assessment. A worksheet may be submitted directly after the laboratory; however, since this risks splitting student focus during the laboratory, the worksheet should be integrated into the laboratory experience, aiding students in developing their understanding. A laboratory report, on the other hand, may require significant time and effort on the part of the student, and a substantial amount of time, one to two weeks, should pass between the laboratory itself and the due date for the report. Once again, a specific assessment or timeframe is not recommended to allow for instructor flexibility and innovation. The timeframe will also be dependant on the course and program context; University of Calgary engineering students are generally engaged in a full course load consisting of between four and seven courses (University of Calgary, 2023), all of which may have laboratories, assignments, projects, and examinations. These competing student obligations and the limited time they have available to devote to any given assessment or learning task should be considered when setting laboratory assessment deadlines.

The second recommendation in reducing assessment pressure is to consider whether the assessment is summative or formative. Covered in more depth in Section 2.4.2, this is a distinction between summative assessments intended to evaluate student competencies and formative assessments that aid the student and instructor in developing these competencies. A summative laboratory assessment is primarily intended to evaluate whether students satisfactorily completed the laboratory activity and developed the expected competencies, while a formative laboratory assessment will provide feedback to students that they can use to improve in future learning experiences. At the University of Calgary, laboratories fulfil both functions, but are primarily formative in that they aid in developing competencies that are summatively assessed in a final exam or project. This assessment type focuses more on feedback than grading. The specific laboratory assessment type is left to the course coordinator; it is simply recommended to consider the distinction and employ points of analysis in developing the laboratory assessment.

Tedium

One barrier to constructive alignment is the conclusion that the learning experience is harmed when students perceive elements of the laboratory as tedious or repetitive. This is most applicable to laboratories where students are recording data while a facilitator conducts the experiment. As mentioned in Section 6.2.1, this form of laboratory is to be avoided as much as possible.

Using self-determination theory (Ryan and Deci, 1985), it was proposed in Section 5.1.1 that students find the laboratory tedious or repetitive when the laboratory does not meaningfully develop their competencies, resulting in a student who endorses their participation in the overall degree but not the specific laboratory or course. Expressed as a deficiency in the student's psychological need for autonomy, this shows that laboratories are perceived as meaningful and useful to one's education when the laboratory meaningfully develops the student's competency.

This carries two implications: that the laboratory must develop competency and should therefore be situated within the student cohort's zone of proximal development, and that the laboratory must be connected to the broader degree program and career outcomes that the student is enrolled in. A laboratory that does not meaningfully advance the student's competencies, or develops competencies the student does not perceive as relevant to their overall degree program, are more likely to disengage and demotivate students.

A small side note: students may encounter activities they perceive as tedious in their careers, and managers and course coordinators may value skills in productively managing this common experience. For example, using a tensile testing involves preparing the sample and setting up the machine, then waiting for an extended period of time while the sample is stretched to failure. Likewise, data collection and recording, while considered a "dry" or disengaging activity, is an important part of laboratory experimentation. Developing skills around productively managing the tedium can be imparted through a learning laboratory experience, and so including components perceived as tedious by students may still hold educational value. However, if this is to be included, it should be a deliberate component of the laboratory, and its inclusion should be explained to students. A learning experience does not have to be entirely pleasant to be valuable, and indeed much learning comes through the uncomfortable experience of failure, but deliberately unpleasant or uncomfortable components should be intentionally included rather than incidentally, and their inclusion and value should be clearly and explicitly communicated to students.

Teaching Soft Skills

It was previously mentioned that the laboratory should be aligned with the broader degree and professional engineering context; soft skills form part of this context. Manager and student surveys revealed the soft skills that these two groups value in employment and desire to develop in engineering learning laboratories. Both groups desired skills in teamwork, collaboration, and communication, which lend themselves towards a laboratory experience designed for group work. Therefore, it is recommended to design laboratories to be completed by groups of students, rather than individually.

However, more can be done to develop these skills. Intentionally including the development of these skills does not guarantee that student uptake and comprehension will be improved. However, intentionally including them forms the basis for improving the learning experience, using the stated learning outcomes as a basis; the lack of clear learning outcomes has historically been an obstacle to improving an educational program (Feisel and Peterson, 2002). In addition to designing the laboratory for group work, it is recommended to include these desired soft skills as a learning outcome and explicitly mention to students that developing these skills is a valuable part of their education, as they are a common part of engineering practice and desired by many engineering employers. The laboratory experience should be designed so as to require group work, collaboration, and communication.

For example, a laboratory designed for groups of three people should require all three students to perform different tasks, as opposed to having the students conduct the same task three times. The assessment should also require contribution from all three students. A good example is a laboratory report; tailoring the required length and the due date to the group size ensures that all three members must contribute, rather than having a single member do the work. Laboratory reports and worksheets can also require analyses drawing from multiple laboratory tasks, requiring students to work together and supply knowledge from the different tasks they each conducted.

It is very important to note here that specific soft skills drawn from the manager surveys are not included here due to the low response rate; many of the skills from these surveys occur only in a single response. While industrial applications are a key part of the context of engineering education, the desires of a single manager should not dictate large-scale course redevelopments.

In summary, the learning outcomes, learning activity, and assessment of a laboratory should be constructively aligned with each other and with the broader course, degree, and career of students. Learning outcomes should be specific, aimed towards the discipline-specific hard and soft skills that engineering graduates are expected to have, tailored to the zone of proximal development of the particular student cohort currently enrolled, and utilize the verb-content-context model. The learning activity and laboratory assessment should directly follow from the learning outcomes. The learning experience is further enhanced by reducing assessment pressure during completion of the learning activity, accomplished by allowing time between the activity and assessment and designing the assessment as formative or summative to better tailor the assessment to student and instructor needs. Reduction of tedium supports this use of constructive alignment.

Chapter 7

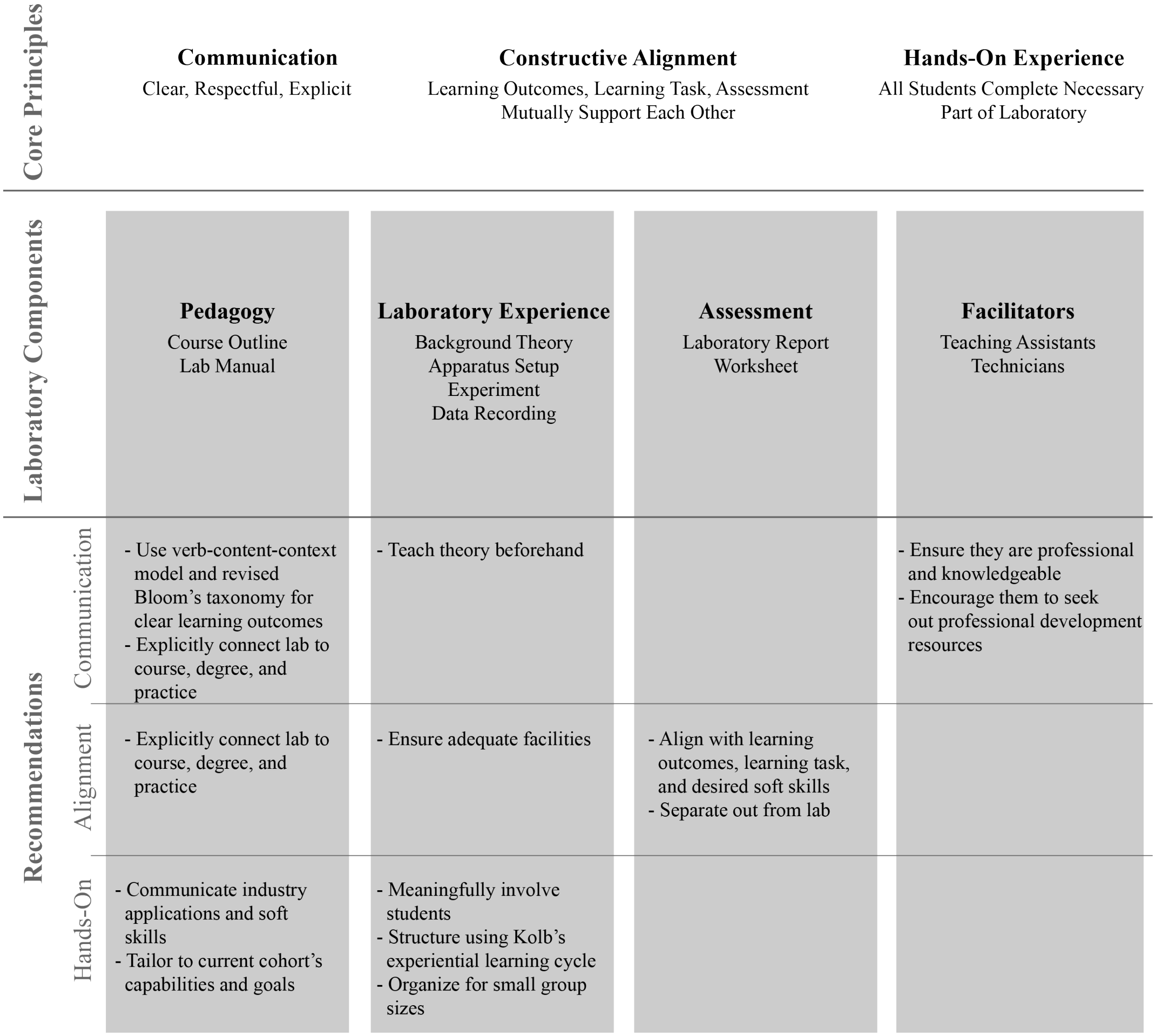
Conclusion

This chapter first summarizes the final set of recommendations in Section 7.1. The research process is summarized in Section 7.2, and future developments are recommended in Section 7.3. Finally, concluding remarks are provided in Section 7.4.

7.1 Final Recommendations

The research question was, how can established educational scholarship be applied to undergraduate engineering laboratories in order to improve student perception of the learning experience?

The research endeavour has resulted in a set of recommendations for improving student perception of the learning experience in undergraduate engineering laboratories, forming the recommended new learning laboratory methodology. This new methodology is presented in condensed form in Figure 7.1.



Core Principles

Communication
Clear, Respectful, Explicit

Constructive Alignment
Learning Outcomes, Learning Task, Assessment Mutually Support Each Other

Hands-On Experience
All Students Complete Necessary Part of Laboratory

Laboratory Components	**Pedagogy** Course Outline Lab Manual	**Laboratory Experience** Background Theory Apparatus Setup Experiment Data Recording	**Assessment** Laboratory Report Worksheet	**Facilitators** Teaching Assistants Technicians
Recommendations – Communication	- Use verb-content-context model and revised Bloom's taxonomy for clear learning outcomes - Explicitly connect lab to course, degree, and practice	- Teach theory beforehand		- Ensure they are professional and knowledgeable - Encourage them to seek out professional development resources
Alignment	- Explicitly connect lab to course, degree, and practice	- Ensure adequate facilities	- Align with learning outcomes, learning task, and desired soft skills - Separate out from lab	
Hands-On	- Communicate industry applications and soft skills - Tailor to current cohort's capabilities and goals	- Meaningfully involve students - Structure using Kolb's experiential learning cycle - Organize for small group sizes		

Figure 7.1: The new laboratory learning methodology.

7.2 Summary and Reflection of the Research Process

The first step of the research process was gathering the background knowledge that contextualizes the research endeavour. Literature from the provincial government's Ministry of Advanced Education and the University of Calgary, both key stakeholders in undergraduate engineering laboratories, was found and used to identify the needs and desires of these stakeholders in relation to the laboratories. Current engineering students and members of the Albertan engineering industry who can expect to hire them following graduation were also identified as key stakeholders. Information on these stakeholders' needs and desires were limited, indicating a need to gather further data. This step also highlighted the importance of gathering such contextual information before beginning the core of the research endeavour, as gathering it through a formal research effort such as the utilized qualitative surveys requires substantial time and effort that would detract from the manager and student surveys.

The next step was to conduct a literature review to identify the established educational scholarship that would be applied in the study. Situated cognition theory and constructivism were utilized as the combined research paradigms, leading to self-determination theory being used as the primary theory of learning for this research. Experiential learning theory is also utilized due to the contemporary provincial, industrial, and institutional focus on including experiential learning opportunities in undergraduate educational programming.

However, due to concerns around its evidentiary basis, only the framework of Kolb's experiential learning cycle is utilized to any significant degree in this study. This element of the study identified two factors to consider in future research endeavours. First, while the bulk of the literature review was conducted before development and administration of the study methodology and methods, review was conducted to some degree throughout the entire duration of the study. This indicates that the literature review is a flexible and open-ended process. Second, feedback was provided later in the study timeline that indicated certain theories and frameworks were subject to extensive contemporary criticism on their lack of evidence, which altered their use in the study. This indicates a need to search out multiple perspectives on reviewed literature and to take a critical approach, seeking to identify and accommodate potential flaws.

Additional frameworks used in this study were the revised Bloom's taxonomy, the Describe, Examine, Articulate Learning or DEAL cycle, the concepts of formative and summative assessments and of intrinsic and extrinsic motivations, constructive alignment, and the zone of proximal development. This process illuminated the importance of a structured research effort that takes the research question and progressively identifies the paradigm, theories, frameworks, methodologies, and finally methods to be utilized in the study. Taking this approach was found to ensure that each of these study elements was holistically supported by and integrated into the body of the research effort.

The literature review identified a knowledge gap, the needs and desires of current engineering students and engineering industry managers, who are the two primary stakeholders. To gather data on these stakeholders' needs and desires in relation to undergraduate engineering laboratories, qualitative reflective surveys were developed using the DEAL cycle and the revised Bloom's taxonomy. Potential manager participants were drawn from a list of companies the University of Calgary has previously worked with for hiring engineering students for their upper-year internships. Student participants were recruited from a mandatory third-year materials science course in the Department of Mechanical and Manufacturing Engineering.

This step provided experience with the ethics approval process at the University of Calgary, which also highlights another element of knowledge gained from this study: the importance of providing adequate scheduling, lead times, and buffer time in research. The ethics board required six weeks between submittal of the application and the start of the research effort, requiring planning ahead of time to accommodate the study schedule. As well, throughout the study, portions of this work were released to reviewers, and adequate time had to be scheduled to allow for feedback to be developed, received, and incorporated into the study.

Qualitative content analysis was selected as the study methodology. Survey data was broken down into a set of themes developed from survey responses and the reviewed literature, organized under headings and subheadings. The frequency percentage of each theme was used in conjunction with select quotes and reviewed literature to analyze the surveys and produce the set of recommendations provided in Section 7.2. This step highlighted the importance of feedback. The qualitative coding process is complex and subjective, and receiving feedback and consulting additional coders greatly strengthened confidence in the analysis and developed recommendations.

7.3 Future Developments

This study has uncovered two potential areas of research that can follow up this research endeavour. Potential work on improving the proposed methodology will be presented, followed by research gaps uncovered during the study.

7.3.1 Improving the Proposed Methodology

To cement the validity and evidentiary basis of the developed recommendations, several study areas have been highlighted for future development and research.

The primary recommendation for future work in this area is to address the study limitations and verify that the developed recommendations do indeed result in improved learning outcomes in undergraduate engineering laboratories. As previously mentioned, the results of this study are subject to several significant limitations.

The recommendations have not yet been applied to a course as of the time of writing. Further studies are required to ensure that the proposed methodology does indeed improve learning outcomes in undergraduate engineering laboratories.

The recommendations were developed based on surveys of engineering managers and undergraduate engineering students currently enrolled in a mandatory third-year materials science course. Further series of surveys should be administered to both groups to identify which themes are consistent across different classrooms and engineering employers, and which themes are unique to the individuals surveyed in this particular research endeavour. This will in turn aid in identifying any proposed recommendations that are relevant only to the surveyed managers and students, and bolster the evidentiary basis for themes found to occur across multiple iterations of this study.

The goal of the study was to develop a methodology that can be applied to any undergraduate engineering laboratory, regardless of location, level, or discipline. However, only a voluntary subset of a single student cohort in a single upper-year mechanical engineering course was surveyed. Future work can bolster and refine the proposed recommendations by investigating their applicability across varying years of study, in different engineering disciplines, and across multiple courses.

Demographic information was not factored into the development of the proposed recommendations. There is therefore a research gap in investigating how the proposed recommendations affect learning outcomes for different demographic groups. The impact on domestic students as opposed to international, on those who identify as visible minorities, on individuals with mental or physical disabilities, and on diverse individuals along the gender and sexual identity spectra; these areas are ripe for investigation.

As a professional program explicitly aimed towards producing graduates ready to be hired in the Canadian engineering profession, learning outcomes in undergraduate engineering are closely linked to career outcomes. Therefore, in investigating how the proposed methodology improves learning outcomes, the effect on student employability should also be investigated. The University of Calgary and many other engineering education institutions include professional internships as part of the degree program. It is proposed that, in investigating the effect of the proposed methodology on student employability, outcomes in student internships and in their professional careers following graduation from the program should be investigated. The engineering industry should also be engaged to develop a better understanding of what employers are looking for in recent engineering graduates.

This study utilizes the zone of proximal development. While it was concluded in Section 5.1.4 that targeting these zones improves learning, and it was recommended in Section 6.2.3 to uncover these zones by analyzing learning outcomes in prerequisite courses and by engaging students in dialogue, a formal mechanism for finding these zones was not developed. It is therefore recommended that future work investigate how best to identify the zones of proximal development for a given student cohort.

7.3.2 Research Gaps

Several research gaps were identified.

The efficacy of course coordinators' actions in implementing several of the developed recommendations is limited by external factors. These areas are appropriate for full-scale studies in and of themselves, and should be investigated in the future to develop alternate pathways that result in more efficacious course development.

It was recommended to avoid placing laboratories before the requisite lecture and, if this is unavoidable, to include another pathway with which to impart the required skills and knowledge. Neither option addresses the core issue of large class sizes and limited laboratory space availability that results in laboratories taking place before the relevant lectures. Tackling this challenge is an open research gap in engineering education.

In recommending professionalism in laboratory facilitators, it was noted that the relationship between graduate students and course coordinators may be controlled by a contract or agreement, such as is the case at the University of Calgary. Investigating how to develop professional teaching skills while respecting this relationship and avoiding undo hardship on facilitators who may also be students themselves is a potential area of research.

Experiential learning theory was utilized in this study due to calls from local industry, the provincial government, and University administration for more experiential learning opportunities to be included in undergraduate curricula. However, this theory of learning and several others were found to be subject to significant criticism. While applications of Kolb's experiential learning cycle have been found to improve learning outcomes in educational programming, the core tenets of the theory itself have not been subject to rigorous scientific research. It is therefore unknown whether the improvement in learning outcomes witnessed in applications of this and other theories improve learning outcomes are an intentional result that can be attributed to the core tenets of the theory, or are incidental results. There is therefore a need for a theory of learning with a strong evidentiary basis in rigorous scientific research. Until this evidence-based theory of learning is developed, it will be difficult to intentionally improve learning outcomes in educational programming.

7.4 Concluding Remarks

Engineering education is the process of taking students with an interest in applying mathematical and scientific principles to solve problems, and turning them into employment-ready graduates who are prepared to become full members of the engineering profession after accruing the requisite professional experience. Laboratories serve a key role in this process, relating the theory taught in lectures to engineering practice, imparting a practical experience in a largely theoretical degree, and motivating students.

As with all integral components of any educational endeavour, laboratories should employ evidence-based practices that have been scientifically proven to bolster the learning experience and enhance learning outcomes. By drawing on established educational literature and engaging directly with key stakeholders, the new learning laboratory methodological framework has the potential to accomplish these goals. Clear communication, inclusion of a hands-on experience, and professionalism in facilitators have been demonstrated by the surveyed students and managers to be factors that greatly affect the engineering laboratory experience and learning outcomes. Further research and development in this area can refine the proposed methodology and further improve learning outcomes for all engineering students.

Bibliography

American Museum of Natural History. (n.d.). *What is a theory?* [Retrieved May 4, 2023]. https://www.amnh.org/exhibitions/darwin/evolution-today/what-is-a-theory

Anderson, L., & Krathwohl, D. (2001). *A taxonomy for learning, teaching, and assessing: A revision of bloom's taxonomy of educational objectives*. New York: Longman.

Ash, S., & Clayton, P. (2009). Generating, deepening, and documenting learning: The power of critical reflection in applied learning. *Journal of Applied Learning in Higher Education*, *1*(1), 25–48.

Baker, R., Ma, W., Zhao, Y., Wang, S., & Ma, Z. (2020). The results of implementing zone of proximal development on learning outcomes.

Bandura, A., & Walters, R. (1977). *Social learning theory* (Vol. 1). Prentice Hall: Englewood Cliffs.

Barry, S., Murphy, K., & Drew, S. (2015). From deconstructive misalignment to constructive alignment: Exploring student uses of mobile technologies in university classrooms. *Computers Education*, *81*, 202–210. https://doi.org/https://doi.org/10.1016/j.compedu.2014.10.014

BeMo. (2023). *University of calgary: How to get accepted in 2023* [Retrieved March 20, 2023]. https://bemoacademicconsulting.com/blog/how-to-get-into-university%5C%20of-calgary

Berger, P., & Luckmann, T. (1966). *The social construction of reality: A treatise in the sociology of knowledge*. Doubleday & Company: New York.

Bettencourt, M. (2015). Supporting student learning outcomes through service learning. *Foreign Language Annals*, *48*(3), 473–490.

Biggs, J. (1996). Enhancing teaching through constructive alignment. *Higher Education*, *32*, 347–364.

Blanshard, B. (2022). *Rationalism* [Retrieved August 18, 2022]. https://www.britannica.com/topic/rationalism/History-of-rationalism

Bloom, B. (1956). *Taxonomy of educational objectives - the classification of educational goals*. New York: David McKay.

Brickhouse, N. (2001). Embodying science: A feminist perspective on learning. *Journal of Research in Science Teaching*, *38*(3), 282–295.

Britto, R., & Usman, M. (2015). Bloom's taxonomy in software engineering education: A systematic mapping study.

Brock University. (2017). How to write learning outcomes.

Brooks, E., Harris, C., & Clayton, P. (2010). Deepening applied learning: An enhanced case study approach using critical reflection. *Journal of Applied Learning in Higher Education*, *2*(55-76).

Brown, J., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, *18*(1), 32–42.

Cambridge University Press and Assessment. (2023). *Meaning of facilitator in english* [Retrieved June 10, 2023]. https://dictionary.cambridge.org/dictionary/english/facilitator

Case, J., & Jawitz, J. (2004). Using situated cognition in researching student experience of the workplace. *Journal of Research in Science Teaching*, *41*(5), 415–431.

Chan, C. (2012). Exploring an experiential learning project through kolb's learning theory using a qualitative research method. *European Journal of Engineering Education*, *37*(4), 405–415.

Chickering, A. (1977). *Experience and learning. an introduction to experiential learning.* Change Magazine Press.

Chiu, M., & Khoo, L. (2003). Rudeness and status effects during group problem solving: Do they bias evaluations and reduce the likelihood of correct solutions? *Journal of Educational Psychology*, *93*, 506–523. https://doi.org/https://doi.org/10.1037/0022-0663.95.3.506

Chomsky, N. (1959). Review of skinner's verbal behaviour. In M. M. Jakobovits L.A (Ed.), *Readings in the psychology of language* (pp. 26–58). Prentice Hall.

Cobern, W. (1993). Constructivism. *Journal of Educational and Psychological Consultation*, *4*(1), 105–112.

Comesana, J. (2019). *Skepticism* [Retrieved August 18, 2022]. https://plato.stanford.edu/entries/skepticism/

Conrad, D., & Hedin, D. (1990). Learning from service: Experience is the best teacher - or is it? In e. a. Kendall J. (Ed.), *Combining service and learning. i* (pp. 87–98). National Society for Internships; Experiential Education.

Cothran, D., & Ennis, C. (1997). Students' and teachers' perceptions of conflict and power. *Teaching and Teacher Education*, *13*(5), 541–553. https://doi.org/https://doi.org/10.1016/S0742-051X(97)85542-4

Croft, E., Winkelman, P., Boisvert, A., & Patten, K. (2013). Global engineering leadership - design and implementation of local and international service learning curriculum for senior engineering students.

Deci, E., & Ryan, R. (1985). *Intrinsic motivation and self-determination in human behaviour.* New York: Springer.

Dewey, J. (1938). *Experience and education.* New York: Simon; Schuster.

Dixson, D., & Worrell, F. (2016). Formative and summative assessment in the classroom. *Theory into Practice*, *55*(2), 153–159.

Durning, S., & Artino, A. (2011). Situativity theory: A perspective on how participants and the envionment can interact: Amee guide no. 52. *Medical Teacher*, *33*(3), 188–199.

Ebbinghaus, H. (1885). *Über das gedächtnis: Untersuchungen zur experimentellen psychologie*. Duncker & Humblot.

Edwards, S. (2022). One and done, or a bundle and stumble? an exploration of assessment methods in undergraduate science curricula. *Acta Educationis Generalis*, *12*(3), 47–61. https://doi.org/10.2478/atd-2022-0023

Eliot, T. (1943). *Four quartets*. Harcourt.

Elo, S., & Kyngas, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, *62*(1), 107–115.

Engineers Canada. (n.d.-a). *Accreditation board* [Retrieved June 6, 2023]. https://engineerscanada.ca/accreditation/accreditation-board

Engineers Canada. (n.d.-b). *Overview of the licensing process* [Retrieved March 29, 2023]. https://engineerscanada.ca/become-an-engineer/overview-of-licensing-process

Engineers Canada. (2016). *Public guideline on the code of ethics* [Retrieved August 22, 2022]. https://engineerscanada.ca/publications/public-guideline-on-the-code-of-ethics

Engineers Canada. (2019). *The engineering design task force report*.

Eyler, J., & Giles, D. (1999). *Where's the learning in service-learning?* Jossey-Bass.

Fair Play Talks. (2020). *Ospe plans to end engineering's systemic bias & exclusion culture* [Retrieved March 21, 2023]. https://www.fairplaytalks.com/2020/11/27/ospe-announces-plan-to-end-engineerings-systemic-bias-culture-of-exclusion/

Feisel, L., & Peterson, G. (2002). A colloquy on learning objectives for engineering education laboratories.

for Disease Control, C., & Prevention. (2022). *The syphilis study at tuskegee timeline* [Retrieved March 21, 2023]. https://www.cdc.gov/tuskegee/timeline.htm

Forehand, M. (2012). Bloom's taxonomy. In M. Orey (Ed.), *Emerging perspectives on learning, teaching, and technology* (pp. 41–47). Creative Commons.

French, J. (2021). *Some alberta post-secondary institutions left relatively unscathed while u of a funds slashed, new data shows* [Retrieved May 17, 2022]. https://www.cbc.ca/news/canada/edmonton/some-alberta-post-secondary-institutions-left-relatively-unscathed-while-u-of-a-funds-slashed-new-data-shows-1.6081029

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. Basic Books: New York.

Glazer, N. (2014). Formative plus summative assessment in large undergraduate courses: Why both? *International Journal of Teaching and Learning in Higher Education*, *26*(2), 276–286.

Goel, S., & Sharda, N. (2004). What do engineers want? examining engineering education through bloom's taxonomy.

Government of Alberta. (2021). *Budget 2021: Ministry business plan: Advanced education* [Retrieved July 21, 2021]. https://open.alberta.ca/dataset/1a50e092-9b23-4f7c-93a9-a13e9264c1ed/resource/4b5d78b6-eb2f-45cb-921c-d9d5fdc5200d/download/ae-advanced-education-business-plan-2021-2024.pdf

Grantham, K., Okudan, G., Simpson, T., & Ashour, O. (2010). A study on situated cognition: Product dissection's effect on redesign activities.

Gulikers, J., Kester, L., Kirschner, P., & Bastiaens, T. (2008). The effect of practical experience on perceptions of assessment authenticity, study approach, and learning outcomes. *Learning and Instruction*, *18*, 172–186.

Hadjerrouit, S. (2005). Constructivism as guiding philosophy for software engineering education. *inroads - The SIGCSE Bulletin*, *37*(4).

Hendry, G. D., Frommer, M., & Walker, R. A. (1999). Constructivism and problem-based learning. *Journal of further and higher education*, *23*(3), 369–371.

Hofweber, T. (2021). *Logic and ontology* [Retrieved August 18, 2022]. https://plato.stanford.edu/entries/logic-ontology/

International Board of Education. (n.d.). *Most influential theories of learning* [Retrieved October 28, 2022]. http://www.ibe.unesco.org/en/geqaf/annexes/technical-notes/most-influential-theories-learning

Jensen, H. (2000). Strategic planning for the education process in the next century*. *Global Journal of Engineering Education*, *4*, 35–42.

Kaipainen, E., Braun, R., & Arseneault, R. (2020). *Experiential learning plan for the university of calgary (2020-25)*. Taylor Institute for Teaching; Learning.

Kazerounian, K., & Foley, S. (2007). Barriers to creativity in engineering education: A study of instructors and students perceptions. *Journal of Mechanical Design*, *129*, 761–768.

Keane, A., & Gibson, I. (1999). Communication trends in engineering firms: Implications for undergraduate engineering courses*. *International Journal of Engineering Education*, *15*, 115–121.

Khumalo, S. (2018). Improving student success rate in open distance learning settings through the principle of constructive alignment. In M. Sinecen (Ed.), *Trends in e-learning* (pp. 31–45). Intech Open.

Kirschner, P., Sweller, J., & Clark, R. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*, 75–86. https://doi.org/10.1207/s15326985ep4102_1

Kolb, D. (1984). The process of experiential learning. In D. Kolb (Ed.), *Experiential learning: Experience as the source of learning and development* (pp. 20–38). Prentice-Hall.

Kolb, D., & Kolb, A. (2013). *The kolb learning style inventory 4.0: Guide to theory, psychometrics, research & applications*. Experience-Based Learning Systems.

Kraft, R. J. (1990). Experiential learning. In J. Miles & S. Priest (Eds.), *Adventure education* (pp. 181–186). Venture.

Lee, J., McCullouch, B., & Chang, L. (2008). Macrolevel and microlevel frameworks of experiential learning theory in construction engineering education. *Journal of Professional Issues in Engineering Education and Practice*, *134*(2), 158–164.

Lewin, K. (1946). Action research and minority problems. *Journal of Social Issues*, *2*(4), 34–36.

Lindstrom, G., Taylor, L., & Weleschuk, A. (2017). *Guiding principles for assessment of students' learning*. Taylor Institute for Teaching; Learning.

Love, T. (1999). Engineering design education: Some implications of a post-positivist theory of design cognition. In N. Juster (Ed.), *The continuum of design education* (pp. 33–42). Praxis Education & Edith Cowan University.

MacDonald, D. (1995). Enthusiasm is contagious. *Canadian Veterinary Journal*, *36*, 408–409.

Macionis, J., & Gerber, L. (2010). *Sociology*. Pearson Education Canada.

Mayberry, M. (1998). Reproductive and resistant pedagogies: The comparative roles of collaborative learning and feminist pedagogy in science education. *Journal of Research in Science Teaching*, *25*(4).

McCay-Peet, L., Lalmas, M., & Navalpakkam, V. (2012). On saliency, affect and focused attention. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 541–550. https://doi.org/10.1145/2207676.2207751

McFarland, J. (n.d.). *Schulich school of engineering welcomes largest class of first-year students* [Retrieved May 23, 2023]. https://schulich.ucalgary.ca/news/schulich-school-engineering-welcomes-largest-class-first-year-students

McGuire, S. (2015). *Teach students how to learn*. Stylus Publishing.

Miettinen, R. (2000). The concept of experiential learning and john dewey's theory of reflective thought and action. *International Journal of Lifelong Education*, *19*, 54–72. https://doi.org/10.1080/026013700293458

Missingham, D. (2006). The integration of professional communication skills into engineering education engineering education. *EDU-COM 2006 International Conference*, 346–357. https://ro.ecu.edu.au/ceducom

Moreno, L., Gonzalez, C., Castilla, I., Gonzalez, E., & Sigut, J. (2007). Applying a constructivist and collaborative methodological approach in engineering education. *Computers and Education*, *49*(3), 891–915.

Murphy, M. P. (2021). Belief without evidence? a policy research note on universal design for learning. *Policy Futures in Education*, *19*, 7–12. https://doi.org/10.1177/1478210320940206

Muscat, M., & Mollicone, P. (2012). Using kolb's learning cycle to enhance the teaching and learning of mechanics of materials. *International Journal of Mechanical Engineering Education*, *40*(1), 66–78.

Najibi, A. (2020). *Racial discrimination in face recognition technology* [Retrieved March 21, 2023]. https://sitn.hms.harvard.edu/flash/2020/racial-discrimination-in-face-recognition-technology/

Nickerson, C. (2022). *Understanding critical theory* [Retrieved August 18, 2022]. https://www.simplypsychology.org/critical-theory.html

Nightingale, S., Carew, A., & Fung, J. (2007). *Application of constructive alignment principles to engineering education: Have we really changed?* Australian Association for Environmental Engineering.

Pearson, M., & Smith, D. (1985). Debriefing in experience-based learning. In D. Boud, R. Keough, & D. Walker (Eds.), *Reflection: Turning experience into learning* (pp. 69–84). Routledge-Falmer.

Pham, L. (2018). *A review of key paradigms: Positivism, interpretivism and critical inquiry* [Retrieved August 18, 2022]. https://www.researchgate.net/publication/324486854_A_Review_of_key_paradigms_positivism_interpretivism_and_critical_inquiry

Piaget, J. (1952). *The origins of intelligence in children* [(M. Cook, Trans.)]. W.W. Norton & Co.

Porath, C., & Erez, A. (2017). Does rudeness really matter? the effects of rudeness on task performance and helpfulness. *Academy of Management Journal*, *50*. https://doi.org/https://doi.org/10.5465/amj.2007.20159919

Psillos, A., & Curd, M. (2010). *The routledge companion to philosophy of science*. Routledge.

Razzouk, R., & Shute, V. (2012). What is design thinking and why is it important? *Review of Educational Research*, *82*, 330–348. https://doi.org/10.3102/0034654312457429

ResearchGate. (n.d.). *Experiential learning: Experience as the source of learning and development* [Retrieved June 30, 2022]. https://www.researchgate.net/publication/235701029_Experiential_Learning_Experience_As_The_Source_Of_Learning_And_Development

Richard, J. (2016). *Writing learning outcomes: Principles, considerations, and examples*. Maritime Provinces Higher Education Commission.

Riemer, M. (2007). Communication skills for the 21st century engineer. *Global Journal of Engineering Education*, *11*, 89–100.

Rogers, J. (2020). *The interpretivist lens - what design study as a method of inquiry can teach us* [Retrieved August 18, 2022]. https://vdl.sci.utah.edu/blog/2020/10/30/interpret-lens/

Romero, P., Rojas, K., & Romero, C. (2013). Postpositivism, positivist and engineering. *International Journal of Engineering Research and Development*, *9*(1), 5–6.

Rose, D., Harbour, W., Johnston, C., Samantha G Daley, S., & Abarbanell, L. (2006). Universal design for learning in postsecondary education: Reflections on principles and their application. *Journal of Postsecondary Education and Disability*, *19*, 135–151.

Roth, W., & McGinn, M. (1997). Deinstitutionalizing school science: Implications of a strong view of situated cognition. *Research in Science Education*, *27*(4), 497–513.

Ryan, R., & Deci, E. (1985). Cognitive evaluation theory: Perceived causality and perceived competence. In R. Ryan & E. Deci (Eds.), *Intrinsic motivation and self-determination in human behaviour* (pp. 43–85). Springer.

Ryan, R., & Deci, E. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology*, (25), 54–67.

Seaman, J. (2008). Experience, reflect, critique: The end of the "learning cycles" era. *Journal of Experiential Education*, *31*, 3–18.

Seneor, A., & Mezzanotte, M. (2022). *Open source data science: How to reduce bias in ai* [Retrieved March 21, 2023]. https://www.weforum.org/agenda/2022/10/open-source-data-science-bias-more-ethical-ai-technology/

Sideeg, A. (2016). Bloom's taxonomy, backward design, and vygotsky's zone of proximal development in crafting learning outcomes. *International Journal of Linguistics*, *8*, 158. https://doi.org/10.5296/ijl.v8i2.9252

Skinner, B. (1976). *About behaviorism*. Random House.

Stanton, T. (1990). Liberal arts, experiential learning and public service: Necessary ingredients for socially responsible undergraduate education. In J. Kendall (Ed.), *Combining service and learning. i* (pp. 175–189). National Society for Internships; Experiential Education.

Stice, J. (1987). Using kolb's learning cycle to improve student learning. *Engineering Education*, *77*(5), 291–296.

Stolk, J., Jacobs, J., Girard, C., & Pudvan, L. (2018). Learners' needs satisfaction, classroom climate, and situational motivations: Evaluating self-determination theory in an engineering context.

Taylor Institute for Teaching and Learning. (2023). *Teaching and learning research and scholarship* [Retrieved June 15, 2023]. https://taylorinstitute.ucalgary.ca/resources/scholarship-teaching-learning

Trenshaw, K., Revelo, R., Earl, K., & Herman, G. (2016). Using self determination theory principles to promote engineering students' intrinsic motivation to learn. *International Journal of Engineering Education*, *32*(3(A)), 1194–1207.

University of British Columbia. (n.d.). *Writing learning outcomes* [Retrieved June 9, 2023]. https://ets.educ.ubc.ca/old-learning-design/elements-of-design/writing-learning-outcomes/

University of Calgary. (n.d.-a). *Academic performance, review, and student standing* [Retrieved March 20, 2023]. https://www.ucalgary.ca/pubs/calendar/current/en-3-4.html

University of Calgary. (n.d.-b). *Understanding graduate studies* [Retrieved June 9, 2023]. https://grad.ucalgary.ca/future-students/understanding-graduate-studies

University of Calgary. (n.d.-c). *Universal student ratings of instruction* [Retrieved June 5, 2023]. https://www.ucalgary.ca/provost/teaching-learning/student-surveys/usri

University of Calgary. (2023). *4.8 mechanical engineering* [Retrieved May 26, 2023]. https://www.ucalgary.ca/pubs/calendar/current/en-4-8.html

University of Calgary General Faculties Counsel. (2021). *Gfc academic staff criteria & processes handbook* [Retrieved May 25, 2023]. https://www.ucalgary.ca/hr/sites/default/files/teams/239/gfc-academic-staff-criteria-and-processes-handbook-final.pdf

University of Waterloo. (n.d.). *Writing intended learning outcomes* [Retrieved March 22, 2023]. https://uwaterloo.ca/centre-for-teaching-excellence/catalogs/tip-sheets/writing-intended-learning-outcomes

Vanderbilt University Center for Teaching. (n.d.). *Bloom's taxonomy* [Retrieved June 1, 2022]. https://cft.vanderbilt.edu/guides-sub-pages/blooms-taxonomy/

Vygotsky, L. (1978). The role of play in development. In R. Parker-Rees & J. Willan (Eds.), *Early years education: Histories and traditions* (pp. 199–211). Taylor & Francis.

Waterhouse, L. (2006). Multiple intelligences, the mozart effect, and emotional intelligence: A critical review. *Educational Psychologist*, *41*(4), 207–225.

Wenger, E., McDermott, R., & Snyder, W. (2002). *Cultivating communities of practice*. Harvard Business School Publishing: Massachusetts.

Wichmann, T. (1980). Babies and bath water: Two experiential heresies. *Journal of Experiential Education*, *3*, 6–12.

Yan, Y., Anna, M., & Jack, H. (2019). Engagement in practice: An engineering service-learning course in collaboration with an art 2d design course to serve young people on the autism spectrum using the touchboard.

Zimbardo, P. (n.d.). *The stanford prison experiment* [Retrieved March 21, 2023]. https://www.prisonexp.org/

Appendix A - Student Surveys

Surveys were released to current mechanical and manufacturing engineering students enrolled in a mandatory third-year materials science course. 21 students participated, resulting in a total of 87 responses. These responses have been anonymized before distribution, with identifying information such as names, course codes, and specific dates and locations of laboratories have been removed and replaced with generic identifiers in square brackets. Two teaching assistants were identified in responses and have been labelled as "TA A" and "TA B"; a laboratory technician also assisted and is denoted as "Lab Tech C".

Question 1 was, "Please enter your first and last name. This will allow us to identify responses from participants who have declined to share their responses with their professor and remove them before the results are disseminated. Your name will not be linked to your responses and surveys will be anonymized before distribution." Responses to this question are not provided here, as after anonymization, no information relevant to this study is retained.

Question 2 was, "Please objectively describe your experience in your recent Laboratory 2 in [surveyed materials science course]. When and where did this laboratory take place? Who facilitated or led the laboratory? What experiment did you conduct in this laboratory? How was this laboratory assessed?" The responses to this question are as follows:

1. "Lab 2 took place in [location] and was facilitated by TA's [TA A] and [TA B]. The experiment being conducted was "Cold Rolling, Sectioning and Heat Treatment". The lab was assessed by group and individual participation and a short, relatively uninspired, question sheet to be submitted at a later time."

2. "Lab 2 took place in [location] about halfway through the semester. The TA's were leading this laboratory... The laboratory was assessed based on the worksheet completed and how well all questions were answered. However, we were given time in the lab period to finish the worksheet and opportunities were given to ask questions."

3. "Lab 2 was conducted [in location], led by [Lab Tech C], [TA A] and [TA B]. The experiment conducted

(during the weeks of [date]) was cold rolling while also discussing hot rolling techniques related to materials engineering. The lab report was assessed in a 1 page activity report due 24 hours after the exam"

4. "Lab #2 was in [location] and we were cold rolling brass strips of metal. The TAs ran the lab with the assistance of the Lab/machine shop technician. First we measured the starting dimensions before cold rolling and measured the same dimensions after cold rolling. During the rolling process we took note of the difference between the rollers. This lab was assessed by a short write up with prompted questions either reflecting on what we learned or using the data collected."

5. "Laboratory 2 took place on [date] in [location]. It was led by two TAs and a Lab Technician. In this lab, we were tasked with cold rolling a metal sample to use it for future labs in the same course. The assessment was a lab handout to complete and submit before noon the next day, and participation marks. Objectively, the lab was ok, however since I was in the first group to ever perform the lab, the process took much longer than anticipated (trying to figure out how to manipulate the experiment as a result of technical difficulties)."

6. "Lab 2 took place in [location] on [date]. Our TAs [TA A] and [TA B] lead the lab and [Lab Tech C] was the lab tech. I this lab, we did cold rolling on a 70/30 brass plate. To assess the lab, we did post-lab questions."

7. "Laboratory 2 was decent, but could have been better. Cold-rolling and its method was showcased. The TA's were good at explaining what the lab was about and its concepts. The laboratory was assessed through a quick lab writeup. If it was the... TA pair, (not sure of their names), it would have not been a good experience as they did not want to teach. They were consistently neglectful of their duties and brushed any student off that was confused."

8. "I did the lab [2] on [date] in [location], led by [Lab Tech C]. In the lab, we cold rolled a bar of brass, and had to answer a few questions. The lab was assessed through the short questions."

9. "Lab [2] occurred on [date] in [location] Lab was facilitated by our great lab tech [Lab Tech C] and the TAs leading it were [TA A] and [TA B]. We cold rolled brass in this lab using a roll machine and was assessed by a group submission report for which only a couple of questions had to be answered, we asked if we could answer as a group and submit those same answers for grading and were told that was fine but marks were deducted later on."

10. "The last lab [4] that I did for [surveyed materials science course] took place in [location] the week

after reading week. This lab was led by one of the TAs of the course and a lab technician. In this lab, we performed tensile tests and hardness tests on different cold worked and annealed brass samples. This laboratory will be assessed based on 3 conceptual questions related to the data and lab concepts, and the recording of the tensile and hardness data."

11. "The second lab of the course took place in [location]. It took place on [date]. It was led by TA's [TA A] and [TA B]. The laboratory was about cold-rolling and how to perform it on a sample of 70/30 brass. We were split into 2 groups and each group go their turn to cold roll their own sample of brass. It was assessed via a lab report which consisted of answering the short answer questions provided in the manual, which required us to read values off of given charts based on the percent cold work our material had undergone. We were also asked summarization questions from the info slide presented at the beginning of the lab section."

12. "This lab [2] took place in [location]. It was facilitated by two TA's and one tech. The experiment conducted involved cold rolling and what should have been annealation had the equipment arrived on time. This laboratory was assessed based on our responses to 4 short answer questions."

13. "This lab [2] took place in [location] on [date] , with [TA A] and [TA B]. We used the press to cold roll a brass speciman. Our assesment was answering these short questions: "Give a short "scientific" summary of the lab, and what you learnt today. 2. From the literature, what is the yield strength of 70/30 brass? 3. From Figs. 4a and b, Callister & Rethwisch 10e, estimate the yield strength, tensile strength, and ductility of 50% CW 70/30 brass. Fig. B.4: Effect of percentage cold work on (a) yield strength, (b) tensile strength, and (c) ductility of selected metals.""

14. "Lab 2 in [surveyed materials science course] consisted of students learning about the cold rolling process. The lab was led by 2 TA's and a member of the makerspace staff. Students cold-rolled the provided samples of Brass 30/70 using a newly installed rolling machine. The lab was assessed using a lab report which was submitted online."

15. "[Location] - Cold Rolling expt [Lab 2]"

Question 3 was, "A common tool to classify learning outcomes is Bloom's taxonomy, which classifies educational goals from the most basic to the most complex. These outcomes are: a. Remember: recall facts and basic concepts. b. Understand: explain ideas or concepts. c. Apply: use information in new situations. d. Analyze: draw connections among ideas. e. Evaluate: justify a stand or decision. f. Create: produce new or original work. Given these definitions, please indicate which level of learning you were asked to apply in this laboratory. Do you find this to be an appropriate learning outcome for the laboratory and course? Are there actions the facilitator could take to enhance the level of learning? Are there actions being taken that reduce your level of learning?" The responses to this question are as follows:

1. "Understand and apply."
2. "We were required to Analyze and Evaluate the effects of cold rolling, sectioning and heat treatment on the mechanical properties of specific alloys. In order to do this we were expected to Remember, Understand and Apply previous information from lectures to this alternative topic. Overall the topic, that being Alloy cold rolling, sectioning and heat treatment, did not differ significantly from practices described in lecture."
3. "We were asked to Analyze in this lab. For the lab, this was appropriate because it was our first introduction to cold rolling, so the furthest it should go experimentally is applying theoretical concepts from the info presentation to cold roll our own sample and then analyze it using given data charts to understand how cold rolling actually works when it is done by hand vs. how it works when taught in class. It would have helped if we could also have annealed the sample ourselves. Not being able to use the oven reduced our experience with the overall process."
4. "We achieved the "create" level of learning as we were taught new concepts and formulas about cold rolling then we analyzed and justified why they occurred, and were able to attempt the process ourselves."
5. "Throughout the whole lab process we used all from a-e. I personally think this was perfect for the course it felt very related and helped aid the understanding of the concepts we were learning by giving us proof though an example. If there was more time available it would have been nice to be a part of the process between the rolling and making the pucks preferably without a write up. I think that the lab write ups being short helped focus the actual ideas that we were meant to be seeing so no there is nothing to reduce the level of learning."
6. "This lab was mostly focused on "understanding." The questions being asked of mostly came down to having a decent understanding of the processes being performed on the brass and being able to recount these processes back to the person assessing us. I believe that this is reasonable, as in my opinion the primary goal of engineering laboratories should be to gain a hands on and intuitive sense of the phenomena being explored in the laboratory. I believe that bogging down these sorts of activities in tedium poorly defined requirements can significantly decrease the level and quality of learning, and

the absence of these sorts of bloat meant that this lab was a positive experience. Perhaps a more application based question could have been asked of us to increase our level of learning in this lab, however overall I would consider this lab to be a positive experience.”

7. “The level of learning that we were doing in the lab was c,d and e. The labs were fun when learning the course material because they connected very well to the concepts learned in class. Yes, this is an appropriate learning outcome for the laboratory and course because we had a chance to apply, analyze and evaluate the concepts used in a new situation. There were no actions being taken that reduce level of learning. The only problem with the labs were that there was not enough time. It left students a little bit anxious as we rushed towards the end.”

8. “The learning outcomes are nicely specific and targeted, but when it comes to reaching those targets its hard to get in the mindset as it is not really stimulating in the sense of problem solving and outside the box thinking it definitely allows me to recall taught content in lectures and apply that knowledge but that is where it stops. Not sure why this is the case honestly but it would be nice if the lab encouraged connection of ideas to solve a new problem.”

9. “In this lab, we did level c, apply. We used methods learned in class that would change the material properties. It was an appropriate learning outcome, however we were unable to heat treat it because of safety precautions.”

10. “I would say that the learning outcomes were either c and d for this lab. I think this is an appropriate level for this lab, as it is very similar to what we are being asked to do during tests and other class assessments.”

11. “I would say that a, b, and c were the learning outcomes of this lab. Maybe also f since we got to have some hands on experience. I think the learning outcomes were fair and made sense for this lab. To improve the labs I would say that they need to have experienced TA’s that don’t rely on the makerspace staff. The makerspace staff were basically babysitting the TA’s.”

12. “I found the lab to be interesting and something I haven’t done before, which means that I can still remember it. It was primarily an analysis based lab. I find it to be an appropriate learning outcome. Since it took us a while and required essentially no contribution, it felt like a lot of time was wasted after the initial presentation of the lab. To enhance it, again, I’d personally prefer to see the process, understand the concepts, and finish the lab handout without having to spend several hours waiting.”

13. “I believe that the lab was at a d level. This seems to be an appropriate level for this course because it

possibly optimizes the workload to learning ratio. I think any going to a higher level such as creating is unreasonable, and requires much more time and knowledge than is possible within a semester."

14. "For this lab, a level 'b' was achieved. The concepts that were used in the lab had been taught in class before, but were incorrectly placed in lectures as not allow complete understanding, retreading these topics helped build more suitable knowledge. As engaging as this retreading of material was, the lab did not achieve any higher result than this; students were simply handed a sample and told to pass it through a machine, no application of knowledge was required to complete this task."

15. "Analyze. I believe it was an appropriate learning outcome for the laboratory and course given most material testing and strengthening processes happen at an industrial level. Cold rolling, however, can be conducted at room temperature therefore, it was the best heat treating process to be analyzed during the lab. There wasn't many actions the facilitator could've done to enhance his lab however, for other labs using the complicated installation software caused more frustration than learning."

Question 4 was, "Thinking back to laboratories you've taken in the past, whether at the high school or university level, what was the best or most positive experience you have had in a laboratory? Using Bloom's taxonomy, what level of learning were you asked to apply? What actions did facilitators take to make this a memorable experience?" The responses to this question were as follows:

1. "The best lab experience took place in [1st-year general chemistry course] and [1st-year behaviour of matter course]. Facilitators made the greatest difference in whether or not a lab was fulfilling to the student, the openness of first year TA's and willingness to share their experiences is something that is not replicated by upper year lab facilitators overall. This is not to be confused with coddling the student, rather it is the sharing of knowledge that is much better in these two course's labs. Upper year lab facilitators are much more interested in testing you rather than ensuring you learn about the process being studied. The result is a disconnect from theory and reality. This could be because the lab time provided is not sufficient. [Behaviour of matter course] is memorable due to the topic being studied, that being the effect of pressure and temperature on the phase of matter."

2. "The most positive experience I have had in a lab was when the TA's took an extra 10 minutes to explain everything that was going on. Not only that, they held "a question period" towards the end of the lab and were very supportive. The learning outcomes asked to apply in labs are C, D, E."

3. "The best Educational labs I've have have used of all six. This can be hard however as it causes a lot of work to be done- stressing the student. Therefore, I think it's important to only have small applications of each blooms taxonomy for the lab to be most successful."

4. “I think most of the labs I have done in university are pretty good. I like being in a small group where we can all have a chance to perform a part of the lab is useful. My favourite labs are the ones where there is no write up because I find I focus better on the lab instead of trying to find time to do the write up as we are performing the lab. Most labs I have done do not go past the d level. By providing a lab environment where all the students have to focus on is actually performing the lab I actually remember and understand what is being done better.”

5. “The labs I remember best are ones where a certain concept or theory was applied to something that we had to create ourselves. An example of this was the egg drop, I have fond memories of the conceptualizing and designing in order to apply a physics principle, and I feel like it’s the reason that I remember it best. The facilitators gave us a clear outline of the requirements, and the final goal.”

6. “The best laboratories are the most hands-on ones. I found the best laboratory activities are where you apply your knowledge , and post-activities where you analyze, evaluate, and/or create. To make it a memorable experience, the best things facilitators can do are get everyone involved (have less people in a group so everyone can do something), make their presentations/talks exciting, and asking good questions to make students understand the material.”

7. “The best laboratory I had in my educational career was creating our own battery by choosing our own cathodes and anodes. This was memorable as we got to think on our own, apply the concepts learned in class, and also receive assistance when required. This lab covered the entirety of Bloom’s taxonomy. We also had a competitive style where the best battery created would get a prize. Our battery won (I think) at replicating the volts of a car battery with 5 amps. Very fun! University labs are very dry compared to that. They expect you to know everything, get ridiculed when you don’t know, boring lab reports with little-to-no hands on experience, and harsh marking.”

8. “There are not any previous labs that stand out to me, but I think that analyzing and possibly evaluate have been the best for me.”

9. “My favorite “Lab” was that of [2nd-year materials science course], it wasn’t exactly a Lab though as the tutorials and Labs were combined and collectively called “Tutorials”. During one of these “Labs” we had to design a polymer that could be used in day to day life and to draw up a list of how much it would cost, advantages vs disadvantages and how it would work for the design purpose. We were given a list of “ingredients” that could be used in the synthesis of the polymer and we had to choose wisely to create it as the TA would then go and make it himself and give it to us in the next “Lab” to run tests on the sample polymer to see if we achieved our goal. This was an amazing lab as it involved direct

collaboration with a team and research beyond lecture material, the lecture material simply served as a baseline for us and further information had to be found in order to make a suitable polymer, this was to be done in the scheduled time and had no report to complete, the entire grading was simply off participation and attendance in the "lab". If you were there, got your name on the booklet and helped out your team you got 100% on said lab. This was an awesome experience as it was practical, and challenging so I was able to critically think like an engineer. On top of this there was no worry in needing to complete a report or answer a worksheet of questions by tomorrow, I had that slot of time to simply learn in a suitable environment without the pressure of a rubric or grade behind."

10. "The best laboratory experience that I have had was with one of my second year biomedical engineering courses, [2nd-year introduction to biomedical engineering course]. In this course, the labs were very involved and all members of the lab groups were able to substantially contribute. In this lab section, I would say that the lab ranged from levels d through f, as different lab activities/questions required different levels of learning application. The facilitators made sure that the lab times were used effectively, with activities happening for the entire lab period and there were no excessive wait times due to a lack of equipment. Smaller groups were also formed so it was easier to be involved in any of the lab activities."

11. "The best experience I had was when making a battery in my high school chemistry 30 lab. This is because the lab went all the way to the Create part of bloom's taxonomy. We were taught basic concepts about batteries, understood them through small chemical reactions that were demonstrated, analyzed why these reactions happen and how we can manipulate them, and finally making our own battery through trial and testing. Being able to go into the lab at any time to work extensively was very enjoyable and made the learning experience memorable."

12. "The most positive experience I have had in a laboratory was in the [3rd-year manufacturing course] laboratory this term. This lab focused solely on the hands on aspects of laboratories, and the learning was entirely localized within the established laboratory time slot, meaning there was no necessary or tedious work being tacked on that would add needless stress to the lives of students. It is a bit difficult to apply a learning level to this experience, however I would likely say that this lab would fall under the level of "apply" as we were required to apply our book learning and the explanations provided to us from the techs to create a new machined workpiece."

13. "The best labs I've participated in had hands-on experience and collaboration. In those labs we were able to apply the knowledge and create things on our own. The facilitators gave us a strong background

and set up applicable experiments."

14. "The labs for [2nd-year materials science course] allowed students to achieve a level 'f' of understanding. This was accomplished by giving students 'building blocks' of various polymers, then requesting a polymer in return that had certain material properties. This process integrated the most powerful STEM teaching tool: design. By getting students to design a polymer, the lab actively ensured that students understood the core principles behind why polymers form, and how their structure impacts their properties. Had the lab simply given students a polymer and asked why it had certain material properties, it would have achieved at best a level 'c'."

15. "create, analyze and apply- make you do it after a short demonstration and get you to answer question as an attempt to engage."

Question 5 was, "Thinking back to laboratories you've taken in the past, whether at the high school or university level, what was the worst or most negative experience you have had in a laboratory? Using Bloom's taxonomy, what level of learning were you asked to apply? What actions did facilitators take to make this a negative experience?". The responses to this question were as follows:

1. "The worst lab I've ever taken was [surveyed materials science course] Lab 3, located in [location]. The room was not sufficient for the topic being studied. Many students had no seating or no ability to see the TA. The space was cramped and unprofessional. The TA's were also very rude, making a colleague cry by the end of the lab. Overall very disappointing with not enough communication prelab to prepare the students. Additionally lab 1 of surveyed materials science course] was a complete waste of time due to the fact that the university failed to provide the necessary software (ANSYS Granta Edupack) to the students in order to complete the lab."

2. "The most negative experience I have had in a lab is being put down for asking a certain question. I once asked a question to clear something up but the TA did not maintain a positive and approachable environment. Instead of answering my question, he put me down in front of my peers which as a first year student made me feel miserable."

3. "Like for the response above, I can't recall one single lab that was the most negative but I can say that labs that have a strict timeline for completion (due by the end of the lab) have caused me a lot more stress and therefore giving me a negative experience compared to others due one week to two weeks after the lab. It's tough to apply all blooms taxonomy to a lab. Therefore, I think at the university level, each lab should just aim to complete one taxonomy branch vs all 6."

4. “My worst experience is when all the students sit and record data as the TA performs the lab. Many labs take a couple hours and I find I do not actually learn anything from those labs. Usually a lab like this would only ask us to understand the concepts.”

5. “I believe that the worst level of laboratories are ones that simply require you to remember. There were several labs performed when classes were online without an attached experiment, they felt like longer assignments. Facilitators also weren’t too keen on responding when asked for help.”

6. “Some negative experiences is when the facilitators are dull or seem they are not interested in guiding us through the lab. Also, if the lab experiment is too far from our current knowledge I feel discouraged and lost through the activities (i.e create).”

7. “The worst laboratory experience was during online school, all of it. Getting no hands on experience, watching youtube videos, and writing long lab reports didn’t cover any of Bloom’s taxonomy. I just forgot everything as soon as I submitted my work. But the other worst lab experience was with the two TA’s that didn’t do anything. They kept saying, “This is easy, you should know how to do this,” being on their phones, and being overall incompetent by not knowing a simple materials question (one they are currently a masters student and a doctorate student in).”

8. “Recently I had a lab where the setup was very inaccurate, and the TA ended up simply reading off a dataset to us. I found this to be a complete waste of time, and it did not benefit my learning at all. The level of the lab was apply.”

9. “My worst lab was one from [3rd-year mechanics of deformable solids course], it was a photoelasticity lab where the entire lab was conducted by the TA, we needed to simply write down the data points that were collected and the write a report and submit by next week. This was terrible cause I was basically just a human typer no learning happened in the lab and I was fully disengaged, all I knew was that when a number was called I simply had to type it down. I truly had no idea what the lab was even about till I got to the report like 5 days later and even then concepts were very unclear and the TA’s when reached to by email were not much help. The results obtained absurd levels error reaching up to 1000% and we were later told that this was simply normal. At the end of it all I had no idea why this lab was conducted had a negative impression on photoelasticity methods and thought it was never used in the real world or industry but was quickly proven wrong with a simple google search. That Lab felt more of like an English assignment than a STEM Lab. None of the concepts mentioned in Bloom’s taxonomy were covered and I walked away with a vague understanding of the concepts.”

10. “The most negative experience I’ve had in a lab setting was with a signals and instrumentation lab, where circuits had to be built to accomplish different functions. The intended level of learning would have been c. However, not enough instructions were given in this lab to make it easy to follow along, and the TAs (facilitators) had not read the lab documents prior to the lab. Finally, the groups were too large to reasonably work together on something that would have probably been more effective with 2 students, simply due to the size of the equipment we were working with.”

11. “The worst lab was definitely [2nd-year acoustics, optics and radiation course] laboratories that I took in second year when we were expected to analyze flux through basic questionnaires. This only went as far as Understand on bloom’s taxonomy because we were made to do research on our own and never taught about their practicality. Facilitators being reluctant to answer questions made it an even more negative experience.”

12. “The most negative experience I have had with a laboratory was the [2nd-year fluid mechanics course] laboratories. I found that the expectations were poorly defined, the grading was harsh, and the format was quite stressful. The level of learning we were asked to apply was probably analyzation, which is not a problem in of itself, however it was difficult to reach this level when the environment was not conducive.”

13. “The worst lab experience I’ve had is where we were asked to do simplified versions of the lab at home that did not feel applicable or the same level of complexity as the analysis and reports.”

14. “[2nd-year thermodynamics course] had 2 distinct types of labs, the first was a set of extremely boring measurement labs that got students to recall extremely basic concepts about the course and explain them in excruciating detail, thus achieving a level ’a’.”

15. “Just tell what to do and be in a rush to complete.”

Question 6 was, “Did this most recent [surveyed materials science course] laboratory impart skills and knowledge that you believe are useful in your academic and professional career? These benefits do not need to be “hard” skills such as a particular piece of materials science knowledge, they can also be “soft” skills such as skills in group work or in report writing.”. The responses to this question were as follows:

1. “The last lab of [surveyed materials science course] was by far the most valuable, I do believe experience with different hardness and tensile tests are important, however I do not know how important these skills will be in industry as opposed to research.”

2. "Yes. The last lab that was done for the course was counting grains. This was a very important concept throughout the entire course. Not only that, this was a concept that was tested on the final exam and one of the midterms. Another benefit of these labs was how easy it was to connect with TA's and peers. Since the environment in the lab was positive and approachable, it made the experience very fun."

3. "I think all labs in university create better soft skills in group work. I also really liked the large group sizes of [surveyed materials science course] as it allowed for more collaboration and growth in teamwork skills used. labs have been my favorite part of my university education thus far as I love working with my peers and meeting new people, (extroverted personality comes out :) [sic])"

4. "I think that this lab format helped academically as it gave a very simple example of an actual concept used in material science."

5. "The labs performed in [surveyed materials science course] were interesting and useful in my opinion. They primarily developed hard skills. They would be better in general if they didn't consume as much time (especially for people in the first group of the lab)."

6. "Personally, I believe working in group projects is a very important skill to know. In this class, I got to work with people that I've never worked with before with different personalities. It is good practice to know how to work with a variety of people! Additionally, I learned to cold roll but that was all outside of lecture material that I learned for my academic career."

7. "The most recent laboratory as the hardness testing lab. It was alright but instead of understanding, there was a lot of useless repetition and just do a, b, c and you're done. Learning how to do the hardness testing was good, but I wanted to actually understand what the collected values mean and their significance."

8. "The labs throughout the semester gave me a way to visualize some of the concepts within the course. It was valuable to me because it helped me remember some of the effects of processes on materials,. I also enjoyed seeing how the processing was done, and even getting to do some of it."

9. "I have neutral feelings for this lab; on the one hand I learned the importance of and how to operate hardness test machines and their importance in industry but at the same time it was usually a lot of hanging out with the group having a person go up one by one and operate the machine and obtain readings, there was a lot of downtime where we kind of just stood around not really engaged, and the tensile test was as expected from the last couple labs that were done, just waiting around for data. It

wasn't bad as I did learn about tech and tests used in industry but I wasn't fully engaged in the lab either."

10. "I can't really think of any skills as most of the laboratories were spent filling out the worksheets and waiting for the machines to become available."

11. "Yes, I do believe the material analysis process helped me understand how materials are actually chosen and analyzed in the industry and I will be utilizing lessons learned here in my career. Being able to use ANSYS Granta especially is a tradeable skill that I value."

12. "This lab imparted a degree of hard skills in the cold rolling process and provided some conceptual insight into the process of annealation. It did not provide any soft skills as there was no report and we completed the lab individually, however I do not find this to be a bad thing, and in fact find it to be quite refreshing."

13. "Yes, it have me hard skills including using a rolling mill and analyzing cold work charts and soft skills including group work and report writing."

14. "The lab did teach students about the process of cold rolling which is a legitimate manufacturing process. This post-pandemic class of engineers is generally unaware of the more practical/industrial side of engineering, and as such an extension of knowledge that seeks to teach more about manufacturing processes is valuable."

15. "Yes, working in groups, reviewing literature and being as accurate as possible."

Question 7 was, "Please consider the survey you have just completed. If you have any observations or comments on the [surveyed materials science course] laboratories or engineering laboratories in general that was not covered in these questions, please provide them here." The responses to this question were as follows:

1. "Overall [surveyed materials science course] labs expectations, grading schemes, locations and ideas were poorly conveyed. Communication was very poor throughout and with exception of the last lab, Lab 4 (Hardness Testing), there was always an issue to distract from the topic. Ex) Software not provided, oven for heat treating not working thus causing the absence of heat treatment from the lab, unprofessional workspaces and overall, a disorganized lab process due to large amounts of students causing half of the lab time to be spent sitting around doing nothing. I should have brought homework from other courses, I wasted roughly an hour waiting for my turn, and my groups turn, to view the experiment in every lab."

2. "The only suggestion I have going forward is perhaps giving more lab time to the counting grains lab [Lab 4]. Towards the end, we did not have a chance to complete the entire process due to time limits. If we had an extra lab section, it would take the time crunch off and make it less anxiety driven."
3. "None."
4. "For this lab smaller groups would have been nice as it would have been easier to work as a group and be more involved. But I was also told there was time and material constraints. Overall I am very happy with this lab."
5. "The other concern I had with these labs was the handout deadline of noon the next day. The handouts are straight forward and can easily be completed within the time frame given that you don't have other assignments or studying to do. I think it would be better if the deadline was at least increased to midnight the next day."
6. "The ENME laboratories started with presentations from the TAs. I believe this could have been a pre-lab assignment or something you had to read before the lab time. The presentations felt long and dragged on."
7. "Please make sure to get better TA's. A student should not have to feel like they want to scream with their face on their pillow after leaving a lab due to ignorant TA's. We are here to learn, not to argue with TA's. That is mostly why I felt like I stopped having an interest with the materials class. I stopped attending lectures as well due to the TA's that infuriated everyone and overall made this course not a pleasant experience."
8. "Communication between the TA's could be better when it comes to setting up the labs teaching the concepts and grading as well. I could read off the PowerPoints at home if I wanted to, not very engaging and I felt as though whether or not you paid attention to the power point in the beginning had little impact as the lab progressed."
9. "The labs did not seem to connect well with the course content, at least in terms of timing in the semester. Furthermore, they were heavily focused on processing methods despite the course covering a lot more than processing of materials, and the lab activities themselves were not very involved or engaging."
10. "I think it would be helpful to spread the laboratories out to not have so much content in them. Knowing about cold rolling and machine analysis before going to the lab would be a much better and more efficient way to run the course because you don't have a bunch of confused students asking

questions about what to do. This would be done through modifying lectures to include relevant lab info before the labs actually take place."

11. "The main observation I would have is to focus on the hands on aspect of the laboratories and to avoid providing students busywork as was the case in labs 3 and 4, where repetitive and menial analysis is required when our understanding could be assessed just as well performing the analysis on only one sample whereupon the rest of the data would be processed and provided to us for analysis."

12. "One suggestion I would have for the [surveyed materials science course] team would be to alter the current labs to instead have students design a process by which a required part can be made. For example, students could be given the requirement to create a part with particular shape, yield, and ductility requirements. Then told that they can use cold-rolling, laser cutting, and annealing to make a part that matches these requirements. Students would have to create a procedure by which they could achieve the particular properties, then carry it out to see if the procedure had the desired effect. Having to design a process would require sometime and may best be completed in groups but would allow for the complete understanding of both methods as it would be impossible to design a process without full understanding of both methods."

Appendix B - Manager Surveys

Manager surveys were administered between June 2022 and April 2023. Surveys were released to managers employed at engineering companies in Alberta and with experience supervising recent graduates of the University of Calgary engineering program, defined as students who had graduated in the past five years. A total of ten managers responded. Not every manager answered every question, so there are not ten responses to each question. The responses have been anonymized, with identifying information replaced with generic identifiers in square brackets.

Question 1 was, “Please state your name and employer.” Responses are not included for purposes of anonymization.

Question 2 was, “Please briefly describe what your company does.” The responses to this question are as follows:

1. “Corporate Real Estate Facility Management Services/Engineering/Energy Management.”
2. “Oil and Gas.”
3. “Geotechnical Engineering/construction.”
4. “Industrial automation, electrical engineering & project management.”
5. “Oilfield services.”
6. “Civil/Structural engineering firm.”
7. “Energy company - exploration and production focus.”
8. “Materials.”
9. “Oil & Gas Exploration and Production.”

Question 3 was, “What experience do you have in directly supervising recent graduates of the University of Calgary’s engineering program?” The responses are as follows:

1. “None - I did supervise a current student in a past co-op positions.”
2. “Supervisor/Mentor of graduated EIT’s in 1 year term rotation program.”
3. “Indirectly.”
4. “I have lead and mentored several recent graduates over the last 10 years.”
5. “Supervised 2 interns from 2013 to 2015.”
6. “Extensive. We have hired several U of C graduates over the years.”
7. “Some of them report to me.”
8. “I have supervised engineering students who work in our [work group].”
9. “Coordinator of [company’s] EIT/internship programs (1 - 2 new grads per year).”

Question 4 was, “How well do you feel that recent graduates are prepared for a career in materials science?” Respondents were asked to rate their perception of graduates as “Greatly prepared”, “Somewhat prepared”, “Neither prepared nor unprepared”, “Somewhat unprepared”, and “Greatly unprepared”. Seven respondents chose “Somewhat prepared”, and one chose “Neither prepared nor unprepared”.

Question 5 was, “In your opinion, what does the University of Calgary do well in terms of preparing engineering students for a career in materials science? What knowledge and skills does the program impart that are useful for this career?” The responses are as follows:

1. “I don’t have the experience to comment.”
2. “Problem solving skills with energy to learn.”
3. “While I don’t have much materials science background, more generally U of C does a great job of teaching engineering students the theory of their discipline.”
4. “N/A.”
5. “It does a reasonable job. The technical knowledge is imparted well.”
6. “Some theory, critical thinking, curiosity.”
7. “They have a bit of concrete knowledge but limited.”
8. “Unsure.”

Question 6 was, “In your opinion, what could the University of Calgary do better in terms of preparing engineering students for a career in materials science? Are there specific skills or knowledge that you expect graduates to have, but don’t?” The responses were as follows:

1. “I don’t have the experience to comment.”
2. “All junior engineers develop confidence over time. Presentation and communication skills are part of that.”
3. “The U of C provides engineering students with very little practical knowledge. That includes awareness of applicable codes and standards and current engineering design skills and practices. The programs teach students too much theoretical knowledge that would be beneficial only in research or academia. Students are not at all prepared for entering industry.”
4. “N/A.”
5. “It has been my experience that the U of C has been removing some of the options for specializing in area, for instance getting a minor in structural engineering. I think that maintaining the ability for 4 year students to take higher level course in specific fields is important and I don’t believe it as easily achieved as when I attended the university.”
6. “Depends on the role - difficult to generalize. Some exposure to Value of Information would be of benefit.”
7. “More exposure to concrete and how material used to make concrete affect the final product.”
8. “Unsure of current curriculum or requirements.”

Question 7 was, “In your opinion, what techniques, skills and knowledge should be taught in undergraduate materials science laboratories to properly prepare students for employment in the materials science industry?” The responses are as follows:

1. “I don’t have the experience to comment.”
2. “Communication skills: summarizing, confidence in speaking knowing risk of being inaccurate.”
3. “N/A.”
4. “N/A.”
5. “Refer to question above. Otherwise, it does a good job.”

6. “Critical thinking, reviewing cost of testing an idea vs. value from answer, applying theory in an efficient way.”
7. “They should learn that what they learn at school is the basics and that they should continue to search out knowledge beyond what they are told by others. They should get a variety of opinions from knowledgeable people and be open minded.”
8. “Ensure that the“basic” are well understood. No need to overcomplicate.”

Question 8 was, “What does experiential learning mean in your workplace or to yourself?” The responses are as follows:

1. “Innovation and trying new solutions, learning through pilot projects.”
2. “Learning soft skills. How to interact with different personality types and levels of expertise. Collaboration. Communication written and oral.”
3. “In our workplace experiential learning is the hands-on practical experience workers get in how we do things in our industry and company. It shows them how to complete their day-to-day work independent of the technical skills or background they enter our company with. Some will be company specific and some will be industry best practices that they could learn elsewhere.”
4. “N/A.”
5. “It means understanding through example and investigation.”
6. “Learning by experience?”
7. “It’s how we learn what our products can do and how we learn what new materials and ideas can benefit or change our products.”
8. “Ensuring that hands-on experience is gained through direct involvement in day-to-day work activities and/or larger project-type work.”

Question 9 was, “Are you aware that it is part of the University of Calgary’s Eyes High strategy to have at least one experiential education experience during a student’s undergraduate degree?” All nine responses were “No”.

Question 10 was, “Do you think laboratories count as an experiential learning experience?” Seven participants responded “Yes”, and two responded “No”.

Following up this question, Question 11 was, “If not, why? Please explain.” The responses were as follows:

1. “In my experience, undergraduate labs are not teaching how work is actually completed in industry. The high level lessons are relevant but it is no replacement for actual real world learning.”
2. “I don’t know what your definition of experiential learning is.”

Question 12 was, “Are you aware that the Government of Alberta will be assessing the performance of the University of Calgary partially on the number and quality of experiential learning opportunities made available to students?” All nine responses were “No”.

Question 13 was, “Do you believe that experiential learning opportunities are an important component for the training of new recruits into your firm?”

1. “Yes.”
2. “Firmly believe!”
3. “Yes.”
4. “Yes, absolutely.”
5. “N/A.”
6. “Yes.”
7. “Yes.”
8. “Yes, books are a starting point, but reality rarely follows the books.”
9. “Yes and no... Much of the value of University learning is to ensure that graduates have a firm understanding of the theory and problem-solving methods that can be applied in real-world applications. Too much emphasis on experiential learning may take away from ensuring firm understanding of first principles.”

Question 14 was, “In your opinion, should universities emphasize theory and knowledge when educating new engineers, or focus on more practical applications that are common in industry?” The responses were as follows:

1. “Both.”
2. “Balance, but needs improvement on practical application.”
3. “Yes.”

4. “There needs to be a balance between the two but there needs to be a much higher percentage of time spent on practical applications than there is now.”
5. “N/A.”
6. “Both. You will not have a good engineer if they lack in either. No short cuts.”
7. “Both. Theory in practice makes good engineers.”
8. “The theory and knowledge is the foundation, but reality and the“practical” doesn’t always follow the theory neatly.”
9. “Theory and knowledge are where universities should focus. As long as entry level jobs remain, new engineers are able to gain more practical experience after graduation.”

Question 15 was, “Since every company or industry has varying requirements and skillsets for potential recruits, do you have any opinions or ideas on balancing widely valued skills with more company- or industry-specific job skills?” The responses were as follows:

1. “Communication, innovation/entrepreneurship, business basics/finance.”
2. “Enthusiasm and energy are strong stand outs. Critical thinking. Not afraid to ask questions or admit not knowing (humility).”
3. “Managing change in contracts.”
4. “Company specific skills should not be a concern. Engaging industry to suggest general discipline specific job skills would be the ideal path forward. Or, at a minimum, training and awareness of codes, standards, and best practices of the last decade.”
5. “N/A.”
6. “See my comments on regarding being able to specialize. You need to be well rounded, however, if you intend to go into a very specialized career opportunity to learn more about that side of things should be made available.”
7. “Industry is about optimization - making things a little better every time. This is done through testing, trialing and reviewing the outcome so efficient experiments, justifying them so they are approved and understanding value are key across many industries.”
8. “No.”

9. “Not particularly. Individuals should take it upon themselves to recognize specific gaps in their skill profile and work to fill them. Focusing too narrowly on specific company- or industry-specific skills would be detrimental unless there is a very specific outcome that the student is looking for.”

Question 16 was, “Do you have any other comments or concerns regarding undergraduate engineering education in materials science that were not addressed in this survey? If so, please record them here.” No participant had further comments.

Appendix C - ENME421 Laboratory Manual

The following is the laboratory manual for the series of laboratories in ENME421 in the Fall 2023 academic semester. ENME421 is a materials science course at the University of Calgary and is mandatory for students enrolled in the Department of Mechanical and Manufacturing Engineering's undergraduate program.

This laboratory manual has been reproduced with the permission of the course coordinator.

I grant Mackinley Love permission to reproduce the document titled, “Fall 2022 ENME421 Laboratory Manual” in his graduate thesis, titled, “Enhancing Undergraduate Labs for Experiential Engineering: Can we design labs to better teach employable skills in core mechanical engineering courses?”

Name: [redacted]

Date: 2023-06-15

Signature: [redacted]

University of Calgary

Schulich School of Engineering

Department of Mechanical and Manufacturing Engineering

ENME 421: Materials I
(Fall 2022)

Laboratory Manual

Student's Name:

Student's UCID:

Lab Section:

Group #:

List other group member names & UCIDs:

Important Lab Safety Notes: **Students are required to be on closed-toed shoes and long pants for all lab sessions. Students who do not comply with this rule will not be allowed into the lab.**

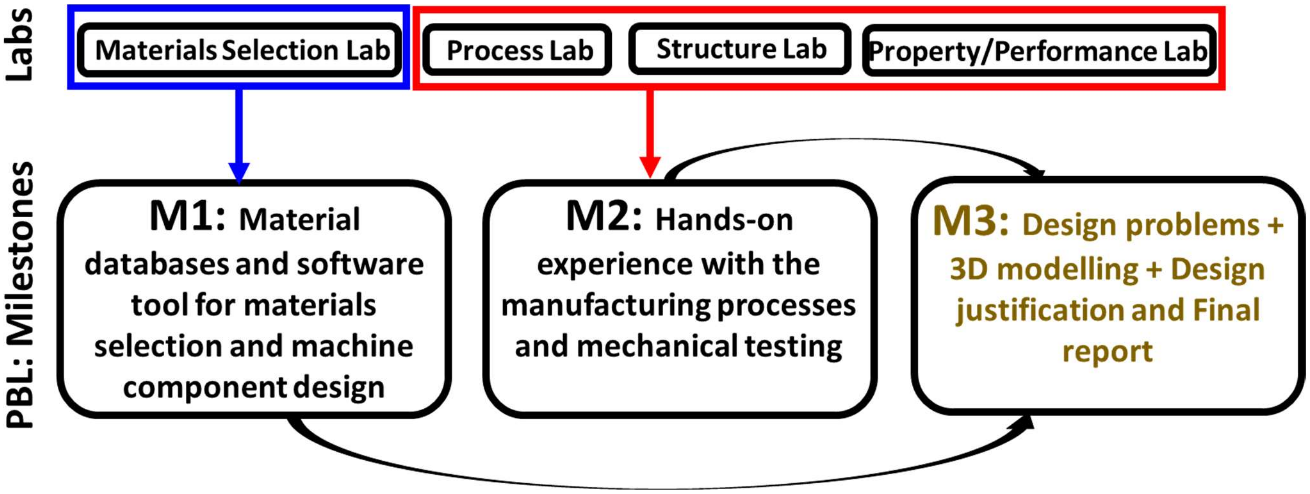
Table of Contents 2

Brief Introduction

Materials drive advancements in our society. To meet the current technology demands or search for high-performance components for various applications, existing materials are either fine-tuned or new ones are developed entirely. This lab will introduce students to the central paradigm of materials science and engineering—*processing-structure-properties-performance* relationships. Good knowledge of materials and the understanding of the aforementioned relationships are essential engineering skills for the appropriate selection of materials and processing techniques for specific applications. As such, in the first part of the lab, students will be introduced to the foremost materials selection software tool that includes a database of materials and process information, and a range of supporting resources (Ansys Granta EduPack). This will be followed by hands-on experience on standard steps for probing the influence of *processing* on the *structure* of materials and in turn, its *properties* and *performance*.

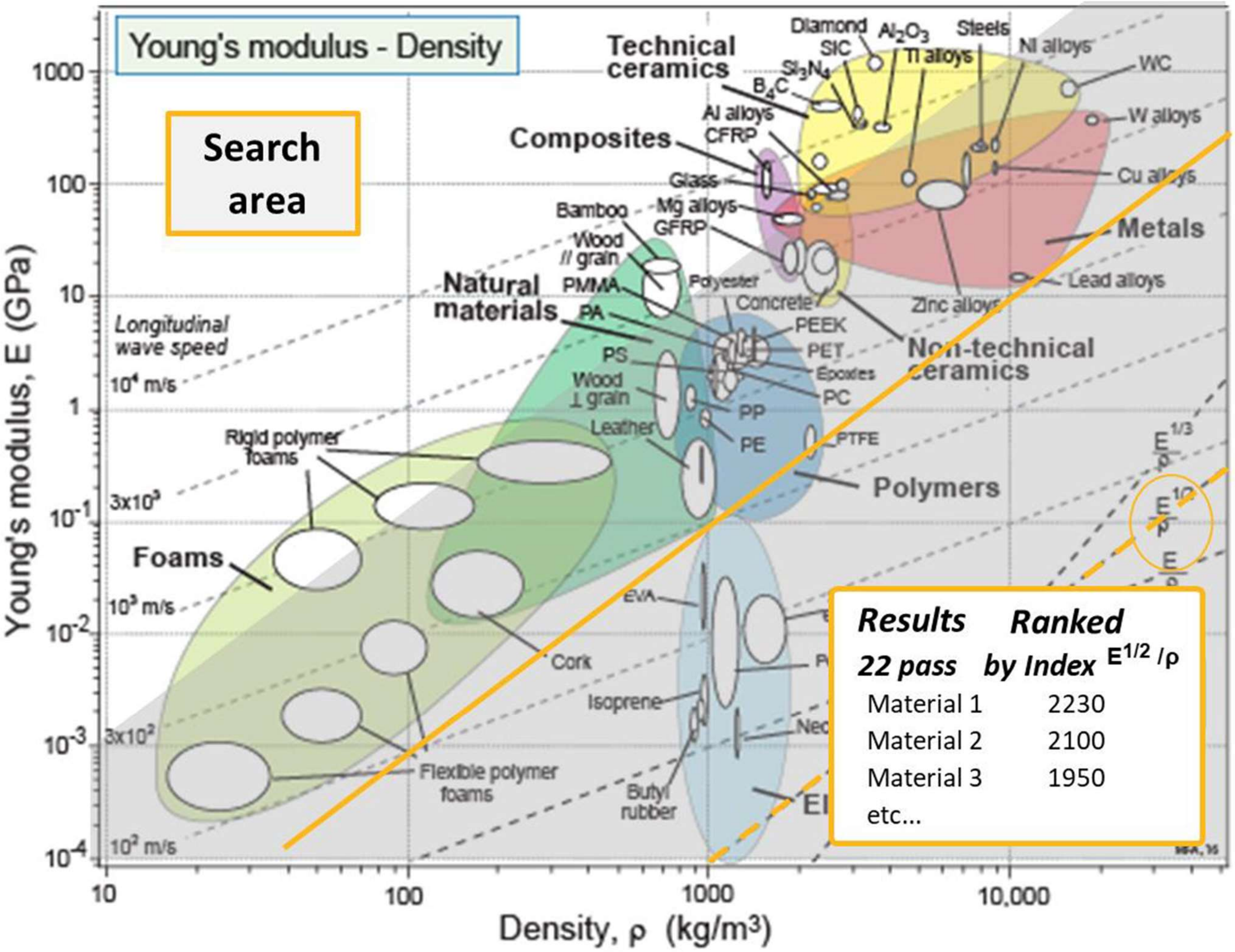
Lab connection to the project:

To enhance students' learning experiences, the Department of Mechanical and Manufacturing Engineering (MME) has developed a project-based learning (PBL) curriculum. The goal of the PBL is to help students gain ownership of their learning and "learn through the project" to solve real-world problems and systems. The uniqueness of the proposed PBL is in the cultivation of a range of skills, stimulation of innovative activities, and forging of meaningful collaborations and connections across content areas that span three MME courses; **ENME 421-Materials I, ENMF 417: Manufacturing & Production Processes, and ENME 493: Machine Component Design**. More details about the PBL will be communicated separately, but the summarized milestones, M1, M2, and M3, and their connection to this lab are shown in the figure below. While the labs and PBL have their separate grades, the experience gathered during/at the end of the lab sessions will be required to tackle the design problems assigned to your team in M3.



Acknowledgement: *The 2HI LAB ROLLING MILL (IRM MODEL #3350) used in this lab was funded by UCEE.*

A. Materials Selection Lab (Ansys Granta EduPack software)



Before attending this lab, students are required to watch ~1 hour-long easy-to-follow instructional videos here. It is highly recommended that students watch the videos while they have access to the Ansys Granta EduPack software so that step-by-step instructions can be followed. This task is **extremely** mandatory before attending the lab. The videos will give students a clearer understanding of how to use Granta Edupack, and as such, practical case studies are mainly covered in the lab session.

B. Process Lab: Cold rolling, Sectioning, and Heat treatment

Objective:

- To learn and gain experience in metal processing methods (thermomechanical processing) for improving the mechanical performance of metals.

1. Cold rolling (Estimated time: 45 mins)

Introduction: Cold working or cold rolling process (**Fig. B.1**) is a metal strengthening process through plastic deformation. It involves the passage of metal through cylindrical dies (rollers) *at temperatures below its recrystallization temperatures*. This process compresses and extends the material along the normal and rolling directions, respectively, typically to improve the yield strength and hardness.

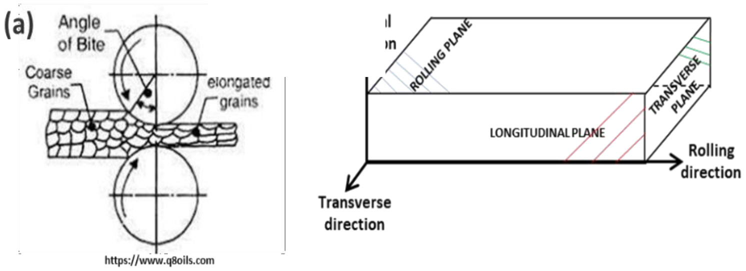


Fig. B.1: Schematic of (a) cold rolling process, and (b) plate anisotropy directions.

Strongly recommended materials/video(s)

Metal Rolling Lab
Cold Work and Hardness of Brass Specimen

Apparatus

- Rolling mill
- Vernier caliper

Personal Protective Equipment

- Safety glasses
- Disposable Gloves
- Closed toed shoes
- Long pants

Lab Details

You are provided with a 70/30 brass plate that will be strain hardened or cold worked. Cold rolling will be conducted using a **2HI LAB ROLLING MILL** (IRM MODEL #3350). The roll diameter, width, and hardness are 3.3", 5.0", and ~60-62 Rockwell C, respectively. **This equipment is proudly funded by the UCEE.** Follow the procedure highlighted below to achieve the expected outcome of the lab.

Experimental Procedure

Step 1. Measure the starting size (length, breadth, and thickness) of the 70/30 brass plate provided, and fill **Table B.1**.

Table B.1: Sample dimension

Initial length, L_o (mm)	Initial Width, W_o (mm)	Initial thickness, T_o (mm)	Initial area, A_o ($W_o \times T_o$), mm^2	Final length, L_f (mm)	Final Width, W_f (mm)	Final thickness, T_f (mm)	Final area, A_f ($W_f \times T_f$), mm^2	Total number of passes

Step 2. Mark the rolling direction on the sample with a permanent marker.

Step 3. Set the roller opening till your sample plate is firmly gripped.

Step 4. Turn on the rolling mill to have your first rolling pass.

Step 5. Keep the rolling direction, reduce the toll gap, and continue the process with multiple passes until your percentage cold work is 50%; $\%CW = (\frac{A_o - A_d}{A_o})x100$: A_o and A_d are the cross-section area perpendicular to the rolling direction of the plate before and after rolling.

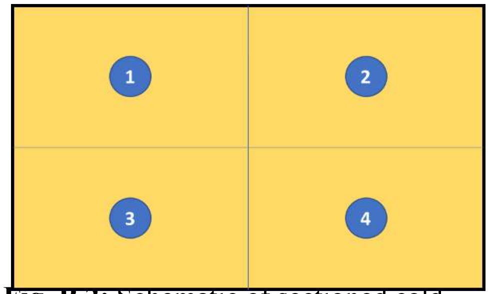


Fig. B.2: Schematic of sectioned cold-rolled plate

Step 6. Record the final dimension of the sample in **Table B.1**.
N.B.-The L_f and W_f should not be less than ~420 mm and ~60 mm, respectively.

Step 7. Safely turn off the rolling mill.

Step 8. Following the procedures in **Section 2**, cut the final coldworked plate into four pieces (1 non-heat-treated sample and 3 heat-treated samples) as schematized in **Fig. B.2**.

2. Sectioning (Estimated Time: 10 mins)

Introduction: Before heat treating the cold rolled samples, they must be sectioned into 4 parts (refer to **Fig. 2**). It is mandatory to watch the associated short training video prior to attending the lab and before carrying out the test.

Mandatory Video

Typical Band Saw Safety Training

Apparatus

- Band Saw

Personal Protective Equipment

- Safety glasses
- Close toed shoes
- Face shield
- Ear plugs/muffs
- Disposable Gloves

Lab Details

From the **Rolling** lab, you will have one cold rolled plate. Follow the procedure listed below to section the cold-worked samples into **four** parts.

Experimental Procedure

Step 1. Following the safety procedure highlighted in the video, section the cold rolled plate into four equal parts as schematized in **Fig. B.2**.

3. Heat treatment (Estimated time: 45 mins)

Introduction: Heat treatment is a combination of timed heating and cooling operations applied to a metal or alloy to produce certain microstructures and desired properties. It is usually carried out on brass specimens to reverse the effects of work hardening and improve its ductility.

Associated ASTM Standard(s)

The following report has been generated following the ASTM International hyperlinked below.
[Standard Definitions of Terms Relating to Heat Treatment of Metals (ASTM E44-84e1)]

Fig. B.3: Heat treatment furnace

Relevant terminologies (Source: ASTM standards)

Annealing: heating to and holding at a suitable temperature and then cooling at a suitable rate, for such purposes as producing a desired microstructure, or obtaining desired mechanical, physical, or other properties.
Recrystallization: the formation of a new grain structure through nucleation and growth commonly produced by subjecting a metal, which may be strained, to suitable conditions of time and temperature.
Recrystallization annealing: annealing cold-worked metal to produce new grain structure without phase change.
Recrystallization temperature: the approximate minimum temperature at which recrystallization of a cold worked metal occurs within a specified time.
Quenching: rapid cooling.
Soaking: prolonged holding at a selected temperature.
***Grain** growth:* an increase in the grain size of a metal, usually as a result of heating at an elevated temperature.
Grain size: the dimensions of the grains or crystals in a polycrystalline metal exclusive of twinned regions and subgrains when present.

Apparatus

- Furnace
- Water buckets for quenching
- Industrial tongs
- Industrial oven mitts

Personal Protective Equipment

- Face shield
- Safety glasses
- Heat-resistant gloves
- Closed-toed shoes
- Long pants
- Heat-Resistant Apron

Lab Details

From the **Rolling** lab, you have four cold-worked samples. **Three of these samples** will be subjected to isothermal annealing following the steps highlighted below.

Experimental Procedure

Step 1. The approximate recrystallization temperature for Brass is 450 ºC, but this varies with several factors, including the degree of cold work. For this lab, heat the oven to 500 ºC;

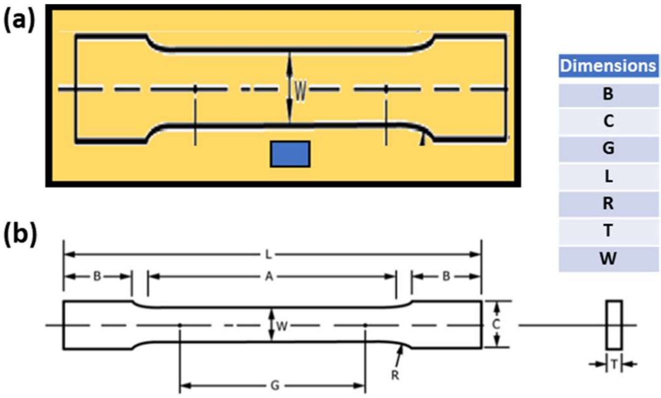
Step 2. Quickly place three cold-worked specimens inside the furnace.

Step 3. Remove and quench each sample in water at room temperature after 1 min, 5 mins, and 10 mins of *holding* at 500ºC.

Step 4. Safely turn off the furnace.

Step 5 (to be completed outside the lab). Take these plates to the *Engineering machine shop* to machine the tensile and hardness test specimens following **Fig. B.4**. ***Note:*** **Students are required to cut out tensile test samples at**

the machine shop and bring them to their next lab; please book a session at: https://schulich.libcal.com/appointments/enme-421, and also sign up for the M^2Z (makers space) here: https://schulich.libguides.com/m2z, for machine shop access. If you have any concern(s) about this process, please reach out to Jason Steinburg at jason.steinburg@ucalgary.ca (if you book a morning session) or Kevin Le at kevin.le1@ucalgary.ca (if you book an afternoon session).



Dimensions	mm
B	50
C	20
G	50±0.1
L	200
R	12.5
T	5
W	12.5 ±0.2

Fig. B.4: (a) Schematic drawing showing the tensile and hardness test samples; the tensile samples should be machined according to the dimensions provided in the table, while the hardness test samples should be 7mm (width) x 7mm (length) x 5mm (height).

Short Questions (Estimated time: 30 mins):

1. Give a short "scientific" summary of the lab, and what you learnt today.
2. From the literature, what is the yield strength of 70/30 brass?
3. From Figs. 4a and b, Callister & Rethwisch 10e, estimate the yield strength, tensile strength, and ductility of 50% CW 70/30 brass.

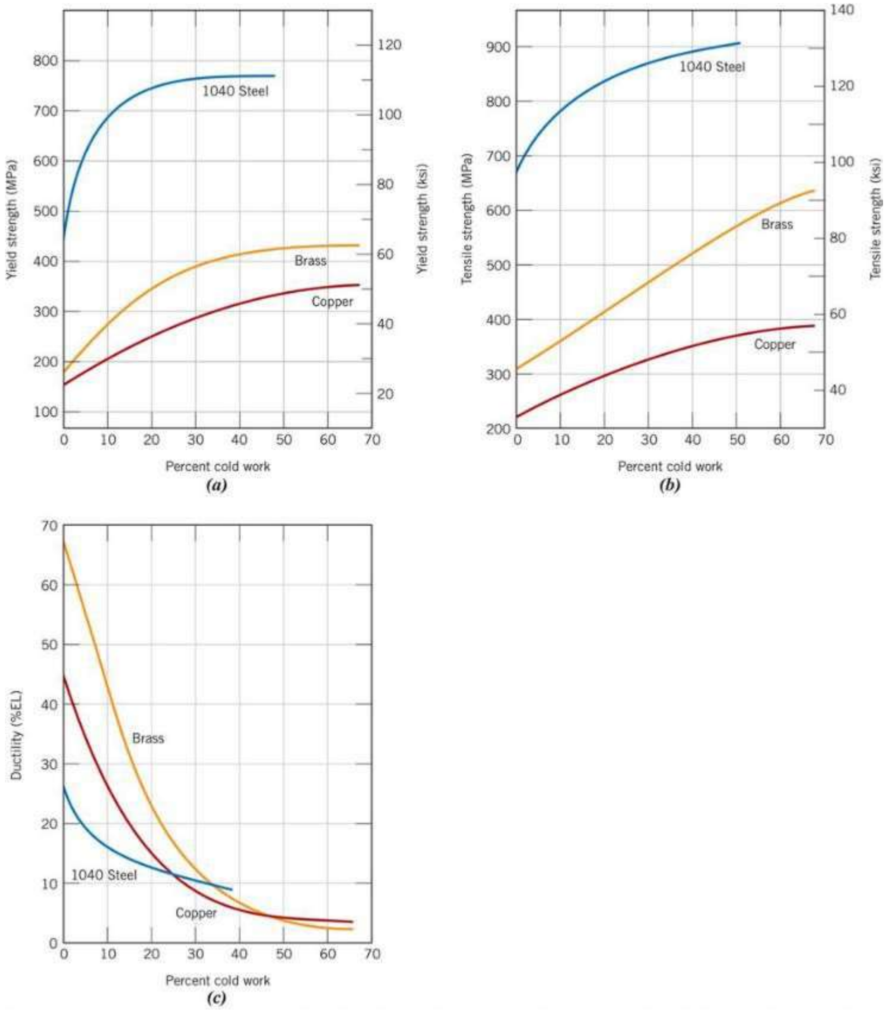


Fig. B.4: Effect of percentage cold work on (a) yield strength, (b) tensile strength, and (c) ductility of selected metals

C. Structure Lab: Metallographic sample preparation and examination

Objectives:

- To learn how to prepare metallographic samples for microstructural analyses.
- To examine and determine the effects of cold working and heat treatment on the microstructural evolutions in 70/30 Brass, within the resolution limit of an optical microscope.

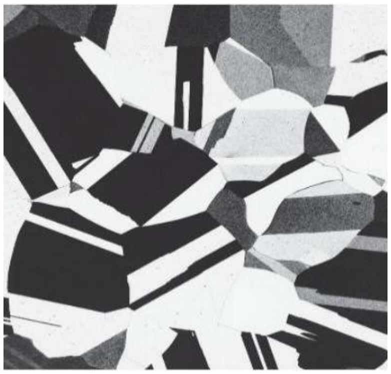


Fig. C.1: Micrography of polycrystalline brass at 60X (Callister

0Introduction: Metallography is both a science and art! It involves the study of microscopic structure of metals using different characterization techniques, depending on the scale of interest. Also, depending on the history of the metal and the features of interest, microstructural analysis can focus on assessing grain morphology, including morphology, porosity/voids, etc., all of which directly affect the mechanical performance of the metal. Metallography can be loosely divided into (i) metallographic sample preparation steps – **grinding, polishing,** and **etching**, and (ii) **microstructural examination.** In this lab, the latter will focus on the evaluation of grain morphology – size and shape. Students will learn the standard procedure for polishing a metal sample to reveal its constituent microstructure.

Associated ASTM Standard(s)

The following report has been generated following the ASTM International hyperlinked below.

Standard Guide for Preparation of Metallographic Specimens (ASTM E3-11)

Standard Test Methods for Determining Average Grain Size (ASTM E112-13)

Strongly recommended materials/video(s)

Metallography Part II – Microscopic Techniques

Apparatus

- Phenolic molding compound (cure time: 4-6 mins)
- Silicon Carbide pads (320, 600, and 1200 Grit) for grinding
- Polishing Cloth for polishing
- Diamond Suspension (6, 3 and 1 micron) for polishing
- Etchant (50 ml distilled Water and 50 ml nitric acid)
- Stainless Steel Tongs + plastic cup (for etching)
- Fume hood (for etching)
- Optical microscope
- Ruler

Personal Protective Equipment

- Safety glasses
- Disposable Gloves
- Closed toes shoes
- Long Pants

Lab Details

From the Process Lab (**Rolling** and **Heat Treatment**), you will have **four** 7mm (width) x 7mm (length) x 5mm (thickness) samples—1 non-heat treated cold worked sample and 3 heat treated cold worked samples. An additional as-received sample will be provided by the TA for comparison; this makes it a total of 5 samples.

Experimental Procedure

I. Metallographic sample preparation steps (90 minutes)

The first step of metallographic sample preparation is sample **mounting**, especially for smaller samples. The primary reason for mounting the specimens is to firmly hold them during grinding and polishing operations. This process can be done either by hot or cold mounting.

Hot Mounting:

Refer to this link when dealing with common errors in this mounting procedure.

1. Turn the machine on and bring the *movable lower arm plate* into view by using the directional keys.
2. Place specimens onto the plate and lower the plate to about 20 mm using the directional keys and ruler. You may apply a thin layer of stick glue to prevent samples from moving around.
3. Pour the *Phenolic Powder* into the rim. Lower the plate fully and position the upper arm inside the cylinder. Turn the handle to lock it in place.
4. Set mounting parameters using the adjustment button: For 20 mm mold set *Heat time to 1 min*; *Cool time to 5 min*; *Pressure to 290 bar*; *Mold size 30 mm*; *Temperature 150 ℃*.
5. Press the cycle start button and wait for the beep sound before turning the handle 45° counterclockwise. Raise the rim carefully. Also, be careful as the puck will be hot to touch. CLEAN work surface, lower the rim and close the machine.

OR *Cold Mounting:*

Refer to this link when dealing with common errors in this mounting procedure.

1. Apply soap to the walls and base of the mold; this is to ensure that cured resin is released easily from the mold.
2. Place specimen on the plastic mold with the intended plane of examination facing down.
3. Fill the sample-containing mold with resin and allow it to cure between 8-15 minutes.

Coarse Grinding: The purpose of this stage is to remove any possible damage to the specimen's surface and subsurface after cutting/sectioning. This restores the veracity of the microstructure for accurate analysis. For this lab, 320, 600, and 1200 Grit SiC papers and water as lubricant will be used.

1. Place coarser SiC paper, i.e., 320 Grit paper, on the grinding machine platen.
2. Turn on the grinding machine and water supply to wet the surface of the SiC paper.
3. Set the force, grinder speed and time to 5 lb max., 250 rpm, and 2 minutes, respectively.
4. Begin grinding.
5. Once completed, rinse your sample thoroughly under running water to prevent contamination from a coarser stage. This should be done between each paper change.
6. Turn off the grinding machine, change the SiC paper to a finer Grit, i.e., 600 and 1200 Grit papers, and repeat steps 2-5.

Polishing: This stage removes remnant surface and subsurface damage. Once completed, the true microstructure of the metal should have been restored. *N.B.: Polishing is subdivided into rough and fine (final) stages. Because rough* *polishing is most of the time sufficient for routine evaluations like microindentation hardness and grain size measurements, we will tone down this classification in this lab.*

1. Place coarser polishing cloth, i.e., 6 micron diamond, on the polishing machine platen.
2. Turn on the polishing machine and set the force, grinder speed and time to 2 lb max., 150 rpm, and 2-3 minute, respectively.
3. Shake and apply 6 sprays of compatible diamond suspension to wet the surface of the polishing cloth.
4. Begin polishing.
5. Once completed, carefully rinse your sample thoroughly under running water. This should be done between each polishing cloth change.
6. Turn off the polishing machine, change the polishing cloth to a finer one, i.e., 3- and 1-micron diamond in that order, and repeat steps 2-5.

Etching: This process selectively alters the microstructural features of a polished specimen based on composition, stress, or crystal structure. At the end of the etching process, microstructural features such as grain size/grain boundaries, and other microstructural features are optically enhanced. Etching should be conducted in a fume hood with supervision by the TA. Materials will be provided for etching

II. Microstructural examination (30 mins)

Upon etching, the grain/twin boundaries become well defined for Brass, which can be viewed under a light microscope. The goal here is to determine grain size using the Linear Grain Size Determination method highlighted in class (see *Useful Equations* below as a guide).

Short Questions (Estimated Time: 30 mins):

1. Give a short “scientific” summary of the lab, and what you learnt today.
2. Determine the ASTM grain size number and the average grain size for the brass specimen.
3. Based on the observed microstructures, which of the brass specimens [As-received (AR), cold worked (50CW), CW+heat treated for 1min (50CW1), 50CW10, and 50CW10] would you expect to be:
   - **(a)** Strongest/Hardest? Why?
   - **(b)** More ductile? Why?
4. Why must samples be washed and dried before each stage in grinding and polishing?
5. What is the purpose of etching?
6. If the ASTM grain size number of a single phase alloy is given as 5, approximate the average grain size for this alloy. (M= 100X).
7. Briefly explain the effect of grain size on the strength of a metal.

Useful Equations

The mean intercept length is given by,

$$\bar{\ell} = \frac{L_T}{PM}$$

The grain size number, n, can be determined by,

$$N = \frac{2^{(n-1)}}{\left(\frac{M}{100}\right)^2}$$

Where,

$\bar{\ell}$ = Mean intercept length

L_T = Total length of all lines

P = Total number of intersections

M = Magnification

n = ASTM grain size number

N = Number of grains/inch^2 at 100X

M = Magnification

D. Property Performance Lab: Hardness and Tensile Tests

Objective:

- To determine the effects of cold working and heat treatment on the mechanical properties of 70/30 Brass.

1 Hardness Test (Estimated Time: 45 mins)

Introduction: The hardness of a metal is its ability to resist surface plastic deformation. A variety of hardness test scales were created to assist engineers in selecting the appropriate metals and hardness for their specific application.

Associated ASTM Standards

The following report has been generated following the ASTM International Standard hyperlinked below.

Standard Test Methods for Rockwell Hardness of Metallic Materials	(ASTM E18-22)
Standard Test Methods for Vickers Hardness of Metallic Materials	(ASTM E92-17)
Standard Test Methods for Tension Testing of Metallic Materials	(ASTM E8/E8M-221)

Strongly Recommended Video(s)

Rockwell Hardness Test Demonstration
Vickers Hardness Test
Tensile Test

Lab Details

From the previous **Structure Lab,** you will have metallographically prepared five samples—1 as-received sample, 1 non-heat treated cold worked sample, and 3 heat treated cold worked samples. These samples will now be subjected to hardness tests in this lab section, using either the Rockwell or Vickers hardness testers. Refer to the procedures below and perform at least 3 micro indentation hardness tests on each of the samples to achieve the expected outcome of the lab.

Apparatus

- Rockwell hardness testing machine.
- Vickers hardness testing machine
- Indenters:
    - Tungsten Carbide Balls (Rockwell). Diameter $\frac{1}{16}$″.
    - Diamond Cone (Vickers). Square-based pyramidal diamond with face angle 136°0’.
- Samples
- Vernier Calipers

Personal Protective Equipment

- Safety glasses
- Closed toed shoes
- Long pants
- Disposable Gloves

1.1 Rockwell Hardness Test

Relevant Terminologies relating to a testing cycle shown in Fig. D.1 (Source: ASTM Standards)

Scale: a specific combination of indenter and forces used. The hardness number is followed by the symbol HR and the scale designation.

E.g.- 72 HRBW is defined as Rockwell hardness number of 72 on the Rockwell B scale using a tungsten carbide ball indenter.

Contact Velocity, v_A : velocity of indenter at the point of contact with test material.

Preliminary Force Dwell Time, t_{PF} : time beginning from applied preliminary test force and ending when the first baseline depth of indentation is measured.

Additional Force Application Time, t_{TA} : time for applying the additional force to obtain the full total force.

Total Force Dwell Time, t_{TF} : dwell time while the test force is fully applied.

Dwell Time for Elastic Recovery, t_R : dwell time beginning when the additional test force is fully removed and ending the second and final depth of indentation is measured.

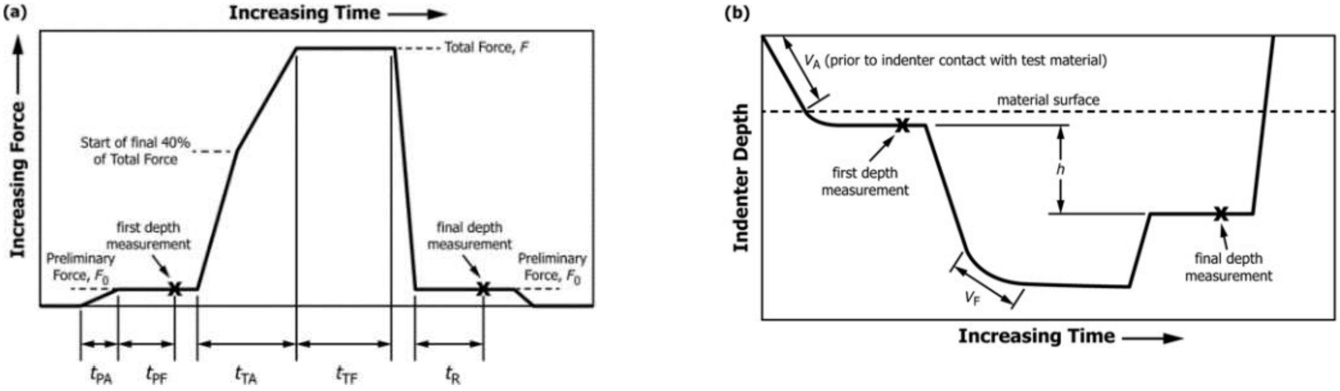


Fig. D.1: Schematic of (a) force-time plot and (b) indenter depth-time plot of an HRC test illustrating the test cycle parts.

Experimental Procedure for Hardness Rockwell B (HRB)

Refer to **Figs. D.1-D.4** when carrying out Rockwell hardness test.

Step 1.Set the major load to 980N as shown in (**Fig. D.2**).
Step 2.Refer to **Fig. D.3** to turn the handle all the way back to *unloading*.
Step 3. Place your sample onto the anvil and raise the plate until a slight contact has been made with the Tungsten Carbide indenter.
Step 4. Begin raising the plate until the small needle points from the **Black Dot** to the **Red Dot**, indicating a preliminary force of 98N has been applied. Then rotate the dial such that the large needle is parallel to **B** and **C** as shown in **Fig. D.4**. Wait for 5 seconds before proceeding to the next step.
Step 5. Turn the handle (**Fig. D.3**) to *loading*. Wait 10 seconds **after** the needle comes to rest before pulling the handle back to the *unloading* position.
Step 6.Take your reading on the scale and fill **Table D.1**.

Step 7.Create two more indentations and refer to **Fig. D.5** for indent spacing.

Fig. D.2 Major load being applied in Newtons

Fig. D.3 Unloading and Loading position

Fig. D.4 Position of large and small needle

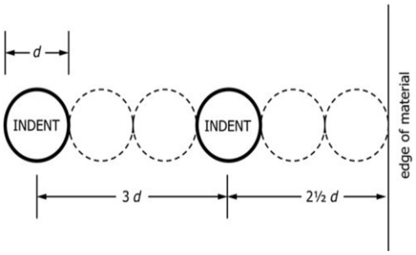


Fig. D.5 Distance between indenters

1.2 Vickers Hardness Test

Relevant Terminologies (Source: ASTM Standards)

***Microindentation hardness test**:* a hardness test, normally in the Vickers or Knoop scales, using test forces in the range of 9.807 × 10^{-3} to 9.807 N (1 to 1000 gf).
***Macroindention hardness test**:* a hardness test, including Vickers, Rockwell and Brinell, using test forces normally higher than 9.807 N (1 kgf).

Scale: a specific combination of the indenter and the test force (kgf).
E.g.- HV 10 is a scale defined as using a *Vickers indenter* and a *10 kgf test force*.

***Note**:* Use of the term "microhardness" should be avoided because it implies that the hardness*, rather than the force* or *the indentation size*, is very low.

Experimental Procedure

Step 1. Bring the indenter into contact with the test sample, select and apply test force *F*, normal to the surface. Hold for 10s and then remove.

Step 2. Measure the length of the two diagonals and record the Vickers hardness value.

Step 3. Take your readings on the scale and fill **Table D.1**.

Step 4. Repeat for two more indentations, refer to **Fig. D.6** for spacing guidelines.

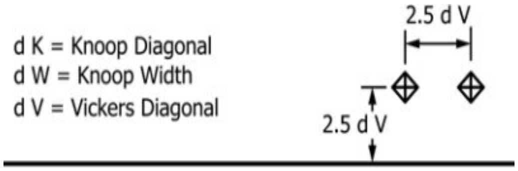


Fig. 6 Spacing between indents.

Table D.1: Hardness test results.

Test		AR	50CW	50CW1	50CW5	50CW10
Hardness	1					
	2					
	3					

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2 Tensile Test (Estimated Time: 60 mins)

Introduction: Tensile test is carried out by applying a tensile force to a test specimen until it is pulled to failure. During the tensile load application, the computer will monitor properties and generate a stress/strain curve.

Associated ASTM Standards

The following report has been generated following the ASTM International hyperlinked below.

Standard Test Methods for Tension Testing of Metallic Materials (ASTM E8/E8M-22)

Relevant terminologies (Source: ASTM standards)

Discontinuous yielding: in a uniaxial test, a hesitation or fluctuation of force observed at the onset of plastic deformation, due to localized yielding.

Elongation after fracture: the elongation measured by fitting the two halves of the broken specimen together.

Elongation at fracture: the elongation measured just prior to the sudden decrease in force associated with fracture.

Lower yield strength, LYS: *in a uniaxial test*, the minimum stress recorded during discontinuous yielding, ignoring transient effects.

Upper yield strength, UYS: *in a uniaxial test*, the first stress maximum (stress at first zero slope) associated with discontinuous yielding at or near the onset of plastic deformation.

Yield strength, YS* or *Sy: the engineering stress at which, by convention, it is considered that plastic elongation of the material has commenced.

Tensile strength, Su: the maximum tensile stress that a material is capable of sustaining. It is calculated from the maximum force during a tension test carried to rupture and the original cross-sectional area of the specimen.

Reduction of area*:* the difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross section. Usually expressed as a percentage of the original cross-sectional area of the specimen. The smallest cross section may be measured at or after fracture as specified for the material under test.

Uniform elongation, Elu, [%]: the elongation determined at the maximum force sustained by the test specimen just prior to necking or fracture, or both.

Yield point elongation, YPE: in a uniaxial test, the strain (expressed in percent) separating the stress-strain curve's first point of zero slope from the point of transition from discontinuous yielding to uniform strain hardening.

Lab Details

After the Process Lab (**Rolling** and **Heat Treatment**), you should have **four** tensile samples—1 non-heat treated cold worked sample and 3 heat treated cold worked samples. An additional as-received tensile sample will be provided by the TA for comparison; this makes it a total of 5 samples. Follow the lab procedure below to achieve the expected outcome of the lab.

Apparatus

- Test specimens
- Tensile testing machine
- Vernier Caliper
- Extensometer

Definitions arising from Fig. D.7.

Reduced Parallel Section: the central portion of the specimen that has a nominally uniform cross section, with an optional small taper toward the center, that is smaller than that of the ends that are gripped, not including the fillets.

G = Gauge Length
W = Width
T = Thickness
R = Radius of fillet, min
L = Overall length, min
A = Length of reduced parallel section, min
B = Length of grip section, min
C = Width of grip section, approximate
D = Diameter

Table D.2: Specimen dimensions

	mm
G	50.0 ± 0.1
W	12.0 ± 0.2
T	3
R	12.5
L	200
B	50
C	20

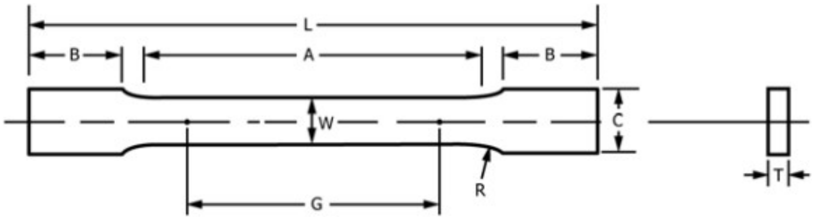

Fig. D.7 Schematic for Rectangular Dog Bone

Experimental Procedure

Step 1. **Table D.2** shows the ideal dimension of the tensile specimen used for this lab. Using a caliper, measure and record the sample dimension in **Table D.3**.

Step 2. Place the dog bone sample onto the wedge grips in the machine.

Step 3. Set all necessary parameters and begin the test until the sample fractures.

Step 4. Take your readings and fill **Table D.3**.

Step 5. Repeat test for the remaining samples

Table D.3: Tensile test results

Test		AR	50CW	50CW1	50CW5	50CW10
Sample dimension (mm)	*R*	12.5	12.5	12.5	12.5	12.5
	G					
	W					
	T					
Tensile	YS (MPa)					
	Yield strain (%)					
	Su (MPa)					
	Toughness (MJ/m^3)					
	Fracture strain (%)					

Short Questions (Estimated Time: 40 mins)

1. Discuss the importance of hardness tests in engineering practices. Why is it carried out?
2. Compare your experimental values with those predicted in the Process lab. Any similarities or differences? Why the departure, if any?
3. Write a short summary that connects the Process, Structure, Property/Performance labs, i.e., discuss how the performance of the 70/30 Brass plate is influenced by the process it has undergone.

Useful Equations

Rockwell hardness number is given by,

$$HR\ (Ball\ Indenter) = 130 - \frac{h}{0.002}$$

Vickers hardness number is given by,

$$HV = \frac{F}{A_s}$$

The *average* $\bar{H}$ of a set of *n* hardness measurements $H_1, H_2, \ldots, H_n$ is given by,

$$\bar{H} = \frac{H_1 + H_2 + \ldots + H_n}{n}$$

The *average* $\bar{d}$ of a set of *n* diagonal length measurements $d_1,\ d_2, \ldots, d_n$ is given by,

$$\bar{d} = \frac{d_1 + d_2 + \cdots + d_n}{n}$$

Stress is measured in *N/m²* and is calculated by the following equation

$$\sigma = \frac{F}{A}$$

Similarly, *Strain* has no units and is calculated by

$$\varepsilon = \frac{L - L_0}{L_0}$$

True Stress (σ_T)

$$\sigma_T = \sigma \frac{L}{L_0}$$

True Strain (ε_T)

$$\varepsilon_T = ln\,(\frac{L}{L_0})$$

Elastic/Young's Modulus and is described by the following equation

$$E = \frac{\sigma}{\varepsilon}$$