Enhancing Undergraduate Materials Science Labs for Experiential Learning

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Using Bloom and DEAL to Improve the Student Learning Experience in Undergraduate Engineering Laboratories

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Abstract

Recently, there has been increased pressure from industry, the local government, and the University of Calgary to include industry-relevant learning opportunities in undergraduate curricula to improve the transition of students from the university to the workforce. In engineering education, laboratories are often viewed as a bridge between course content and industry skills by grounding theoretical knowledge in practical experiments and developing familiarity with testing techniques and analyses used in industry. Yet nearly half of undergraduate mechanical and manufacturing engineering students enrolled in a mandatory third-year materials science course at the University of Calgary report no link between their laboratories and course content or future career development. Therefore the goal of this research endeavour is to identify actions that can be taken to improve the students' learning experience in undergraduate engineering laboratories.

Critically reflective surveys were developed using Ash and Clayton's Describe, Examine, Articulate Learning (DEAL) model and the revised Bloom's taxonomy and released to current engineering students in a third-year materials science course at the University of Calgary's Mechanical and Manufacturing Engineering program. The purpose of these surveys was to evaluate where students feel their laboratories do not connect to their classes or careers, and what steps can be taken to improve learning outcomes. Following completion, these survey responses were evaluated using qualitative content analysis. Results indicate that students better perceive their laboratory learning experience when it includes a hands-on component designed using Kolb's experiential learning cycle. Students feel their time is better spent when learning outcomes are aligned with student abilities, laboratory material is clearly linked to industrial applications, and expectations and theory is clearly communicated. Group work and a design component, when relevant, can also improve this experience. The experience of the laboratory assessment can be improved by considering the purpose of the assessment when designing it. Finally, it was found

that facilitators have a strong impact on the learning experience and should receive training to ensure consistency and that learning objectives are met.

1 Introduction

In the past five years, nearly half of undergraduate mechanical and manufacturing engineering students enrolled in a mandatory third-year materials science course at the University of Calgary consistently report on their end-of-course surveys that their laboratories are not linked to their in-class learning or to their careers following graduation. There have also been calls from the local engineering industry, the local government [1], and University of Calgary administration [2] for more industry-relevant learning to be included in post-secondary curricula. Previous work by the ASEE has established that the intention of engineering learning laboratories is to relate theory and practice, motivate students, and provide a practical experience in a largely theoretical education [3]. The end-of-course surveys indicate that laboratories in the course under question fail to provide this connection to the theory covered in lecture and indicate a general lack of student motivation regarding the laboratories, while the calls from industry, the local government, and University of Calgary administration for more industry-relevant experiential learning in undergraduate education indicates that the practical experience provided by the laboratories is insufficient in meeting students' educational needs in a professional program. Therefore, a need exists to incorporate experiential, industry-relevant learning into undergraduate engineering laboratories, or for these laboratories to be perceived as such.

Note that developing a more practical and hands-on laboratory experience is an ongoing endeavour by the research team; this work will focus on the efforts undertaken thus far in understanding student motivation and perceptions of the laboratory and using this knowledge to develop recommendations to improve student perception of the learning experience, both through stronger connections to industry and theory and through analysis of how specific actions taken by course coordinators and laboratory facilitators affect the student learning experience.

The research question is thus, what actions can be taken to improve the student learning experience in undergraduate engineering laboratories? The revised Bloom's taxonomy [4] and Ash and Clayton's DEAL cycle [5] are used to develop qualitative surveys released to students in the previously-referenced materials science course.

The results are investigated using qualitative content analysis, concluding in a series of recommended course actions for improving the student learning experience that draw from experiential learning theory and its applications in the educational, engineering, and education laboratory spaces.

1.1 Theoretical Background

The revised Bloom's taxonomy [6] was used to develop surveys for the previously-mentioned materials science laboratory. Since the intent of this work is to improve the student learning experience, qualitative surveys were used to capture the subjective learner experience.

The DEAL cycle is a tool to make meaning of a given experience [7]. The cycle guides critical reflection by first asking participants to objectively describe their experience through factors such as who the facilitator was and where or when the experience took place; this was done by asking survey participants to describe their laboratory experience in objective terms. Participants then explain what happened; survey participants were asked to assess their level of learning in their laboratory. Finally, participants articulate their learning, which was done through an open-ended question asking if participants saw value in the connection between their laboratories and their in-class learning and future careers. Critical reflection has been found to enhance applied learning in professional programs such as nursing, increasing the quality of student reasoning and understanding [8]. The DEAL cycle was therefore used in developing the surveys as a method to deepen student analysis of their laboratory experience, allowing more meaningful observations and conclusions to be made.

Within the qualitative surveys, student participants assessed their learning in their current and past laboratories through the revised version [6] of Bloom's taxonomy [4]. This taxonomy is widely used in academic and professional training contexts [9], and a review of contemporary applications in engineering education shows extensive use of the taxonomy in undergraduate computer engineering education [10]. The taxonomy is a hierarchical classification of learning outcomes. From most simple to most complex, these classifications are: remember, or recall facts and basic concepts; understand, or explain ideas and concepts; apply, or use information in new situations; analyze, or draw connections among ideas; evaluate, or justify a stand or decision; and create, or produce new or original work [6]. The revised taxonomy provides a shared language of learning outcomes between the participants and researchers, as in many other applications [9]. This focuses student responses and allows for ease of analysis by researchers.

The perceived learning levels of students directly relate to the stated learning outcomes in their laboratories. In designing laboratory learning objectives, clarity is key. Historically, laboratories have been limited by a lack of coherent learning objectives, resulting in learning that is inefficient at best and incorrect or accidental at worst [3]. This work by Feisel and Rosa [3] states that clear learning objectives are key to effective systems of learning and assessment. Without learning objectives, it becomes difficult, if not impossible, to gauge the current success of the laboratory and develop an improved educational endeavour.

When analyzing surveys and recommending laboratory actions to improve the student learning experience, several frameworks were used to support conclusions. Self-determination theory, experiential learning theory, and the zone of proximal development are used both holistically and individually to understand how students learn in their laboratories, what motivates and what disengages their interest in this learning space, and how the learning outcomes defined by the revised Bloom's taxonomy may be appropriate or inappropriate in fully and effectively engaging students in learning.

Self-determination theory [11] is used to understand student motivation. The core element of this theory is that learners have three psychological needs that drive motivation: autonomy, or the sense that one has control over and endorses their actions; competence, or the sense that one can ably complete a given task; and relatedness, or the sense of belonging to a broader group. It has been shown that improving student motivation results in more comprehensive and longer-lasting learning [12]. Specifically, by offering more autonomy in evaluations, student motivation and their perception of the learning experience in the course is improved. As well, self-determination theory is particularly relevant in addressing the concerns of the surveyed students, many of whom will soon start internships and all of whom will be expected to complete their final year capstone design project. Engineering design requires creativity; it is therefore important that an engineering education nurture a creative mindset [13].

The concept of the “zone of proximal development” is also used [14]. This theory posits that there exists a zone of competence where a learner can independently complete tasks without supervision and a much larger zone where a learner cannot complete tasks. In between these zones is the zone of proximal development where individuals learn competencies. This concept is used to identify where learning levels, as assessed by the revised Bloom’s taxonomy, may be too high or too low for learners. Work in this area has shown educational endeavours situated below a students’ zone of proximal development results in students feeling they did not develop meaningful competencies or skills, instead simply being evaluated or being provided with a demonstration of a concept [15]. The zone of proximal development is therefore used in this work to identify where and how the laboratories meet, fall short of, or exceed students’ developing competencies.

Finally, experiential learning theory is a core element of this study [16], motivated by industrial, governmental, and administrative pressures to include experiential opportunities in post-secondary programming. This theory states that experience is the core of learning, and proposes that learning is a cyclical process between four modes: concrete experience, reflective observation, abstract conceptualization, and active experimentation. This theory is used as a framework for suggested changes to laboratory activities. Experiential learning has seen wide applications in engineering education. Utilizing forms of experiential learning, such as in a service learning project that paired upper-year engineering students with lower-year art students to mentor children on the autism spectrum at a local not-for-profit resulted in significantly increased levels of interest from students and faculty [17]. Applying the experiential learning cycle to a real-world community service project was found to transform and internalize the experience for students, promoting deep learning [18]. Experiential learning is a valuable tool in developing recommendations from this study, supporting calls for its use from industry, university administration, and the local government.

2 Study Approach and Design

Qualitative surveys were used to evaluate student perceptions of laboratories and released to students enrolled in a third-year materials science course with an enrolment of approximately 150 students, which is a typical cohort size for a mandatory third-year mechanical engineering course at the University of Calgary. The DEAL cycle was used in designing the surveys as a tool to make meaning of a given experience [7]. The cycle guides critical reflection by first asking participants to objectively describe their experience through factors such as who the facilitator was and where or when the experience took place; this was done by asking survey participants to describe their laboratory experience in objective terms. Participants then explain what happened; survey participants were asked to assess their level of learning in their laboratory. Finally, participants articulate their learning, which was done through an open-ended question asking if participants saw value in the connection between their laboratories and their in-class learning and future careers. Critical reflection has been found to enhance applied learning in professional programs such as nursing, increasing the quality of student reasoning and understanding [8].

Informed consent was obtained with the approval of the Conjoint Faculties Research Ethics Board of the University of Calgary. These surveys guided students through a critical reflection of their laboratory experience using Ash and Clayton's DEAL model [5]. The revised Bloom's taxonomy [6] was used as a tool to assess the level of learning required in the laboratory. The student survey questions are provided in Appendix A. Students were asked to objectively describe their laboratory. Students then fulfilled the "Examine" and "Articulate Learning" portions of the DEAL model by analyzing their learning experience and level of learning according to the revised Bloom's taxonomy and identifying actions that enhanced or detracted from the experience. Students also reported what value to their careers they saw in their laboratories, before being asked if there was anything else relevant to the laboratories they would like to say.

Most respondents completed the survey following their second laboratory, which dealt with cold rolling, sectioning, and heat treatment. The objective of this laboratory was to learn and gain experience in metal processing methods for improving the mechanical performance of metals. Students were provided with a 70/30 brass plate and recorded its dimensions before and after they passed it through a rolling mill. Students then sectioned the rolled plate into four parts. The facilitator took three of these samples and placed them in a 500° C oven. Samples were held in the oven for 1, 5, and 10 minutes before being quenched in water. Students then took their samples to a mechanical testing laboratory to conduct hardness and tensile tests on the samples. The instructor assessed student performance at the end of their laboratory with 3 short answer questions, which are provided in Appendix B.

One respondent filled in the survey following their fourth and final laboratory, which examined hardness and tensile tests. Students were provided with 5 samples of 70/30 brass, prepared during previous laboratories: one as control, one cold worked, and three cold worked after heat treatment. Samples were subjected to a Rockwell B hardness test, a Vickers hardness test, and a tensile test. The instructor also assessed this laboratory using short-form questions, provided in Appendix B.

Survey responses were analyzed for themes associated with both positive and negative laboratory learning experiences using qualitative content analysis [19]. This method is used to analyze written or other works that are subjective in nature, such as surveys or interview transcripts. The coding process was conducted solely by the primary author, Mackinley Love.

The work under question was broken down into units of analysis, which must be large enough to contain complete meanings, but small enough that analysis is still meaningful. For this work, each individual survey response to each question was treated as a unit of analysis. A smaller unit, such as a sentence, would lose the context of the broader response. The next larger unit of analysis is the collection of responses from each participant; the use of this unit was not possible, as the selected survey software does not track responses across questions.

The researcher then immersed themselves in the data, reading and re-reading to gain complete familiarity with it. While reading, the researcher added notes and headings to aid in classifying the data. These were generated inductively to allow themes to arise from responses and to apply the literature to understand specific phenomena in student responses. A deductive approach, which draws themes solely from the literature, was not used.

The notes and headings were then grouped together into a coding matrix. Similar codes were collapsed together and grouped under broader headings. Codes from the finalized matrix were then assigned to each unit of analysis. The frequency of each code indicated the dominant themes in responses. These frequencies are collated in the following section.

In analyzing the survey responses, response themes that only occur in a single response were considered to be negligible and are not considered when developing the learning laboratory revisions. As well, some response themes are presented both in the positive, as an action to enhance learning outcomes, and in the negative, as an action whose lack is detrimental to learning outcomes. Response themes presented in both manners are considered to be more strongly representative of respondent sentiment than themes which are presented solely as negative or positive.

Response themes fell into three categories: actions that either enhance or detract from the learning experience, the perceived level of learning in the current or past laboratories according to the revised Bloom's taxonomy, and the value students feel the laboratory has to their future careers.

3 Results

Of the approximately 150 students enrolled in this iteration of the surveyed course, a total of 21 responded to the surveys. As the surveys were optional, not every participant answered every question. Not including the identification question at the start of the survey, this resulted in a total of 87 responses across the 6 survey questions. Responses were coded according to themes from the aggregated survey data and literature. Similar themes were grouped together and categories of themes were identified. Each theme's frequency is the number of responses the theme occurred in reported as a percentage of the 87 total responses subjected to analysis. Note that this frequency is across all six survey questions, as most themes occurred in responses to multiple different questions.

Four categories of actions were identified as being associated with the student's perception of a positive or negative laboratory experience. "Pedagogy" themes are actions regarding how the laboratory is set up and relates to the course material and learning objectives. "The laboratory experience" themes are actions regarding how the laboratory was performed and student involvement in experiments. "Assessment" themes are actions regarding how the laboratory is assessed. Finally, "facilitator" themes are actions regarding the interaction of the lab facilitator with the students.

Figure 1 presents pedagogical response themes. The most-cited actions are to link the laboratory to industrial applications and to the lecture material, corresponding to the calls from industry, the provincial government, and the university administration that partially motivated this study. This finding also supports student end-of-course surveys that criticized laboratories for lacking these connections.

Figure 2 presents response themes referring to actions within the laboratory itself. The dominant themes are to include a hands-on experience, to use time more efficiently, and to utilize small group sizes. There are also several themes associated with efficient use of time: reducing time pressure, reducing repetition and tedium, assigning tasks of appropriate complexity, and reducing

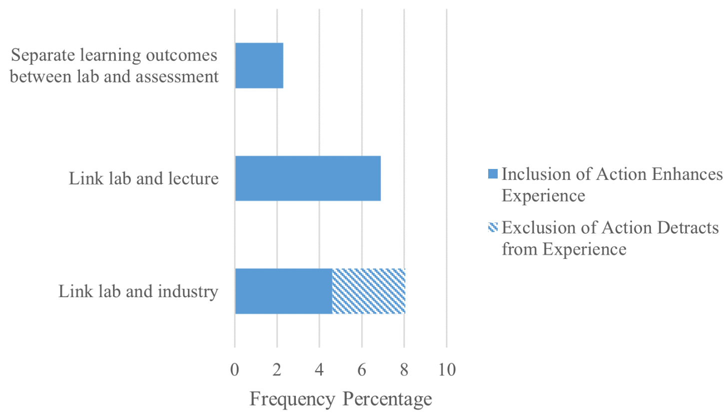

Figure 1: Survey Response Frequency of “Pedagogy” Themes

facilitator setup errors.

Figure 3 presents academic assessment response themes as they relate to the laboratory. Students primarily requested to reduce or remove the assessment, and to mark more leniently. While this finding appears self-evident, there are connections to self-determination theory that can be utilized to improve the learning experience.

Finally, Figure 4 presents laboratory facilitator response themes, showing students ask for professional and engaging facilitators. This offers insights as to facilitator training and preparation and how they relate to student engagement. Select responses, presented in the Analysis, show the strong impact facilitators have on the laboratory experience.

Respondents were asked to assign learning outcomes to laboratory experiences according to the revised Bloom’s taxonomy as well as assess whether these outcomes were appropriate for that specific laboratory. The data on learning outcomes was divided into three categories: current laboratory experiences (Figure 5), past positive laboratory experiences (Figure 6), and past negative laboratory experiences (Figure 7). The data shows students desire a high level of learning, and that students are disengaged when this level is too low. However, if this level exceeds their capabilities, students will feel incompetent and will disengage. The analysis will utilize self-determination theory and the zone of proximal development in recommending actions to ensure appropriate levels of learning.

Respondents also detailed how the laboratory under question can add value to their careers; this data is shown in Figure 8. Similar to Figure 1, students are shown to value hard skills and industrial applications in their laboratory curricula, further supporting calls to link post-secondary curricula to industrial skills and knowledge.

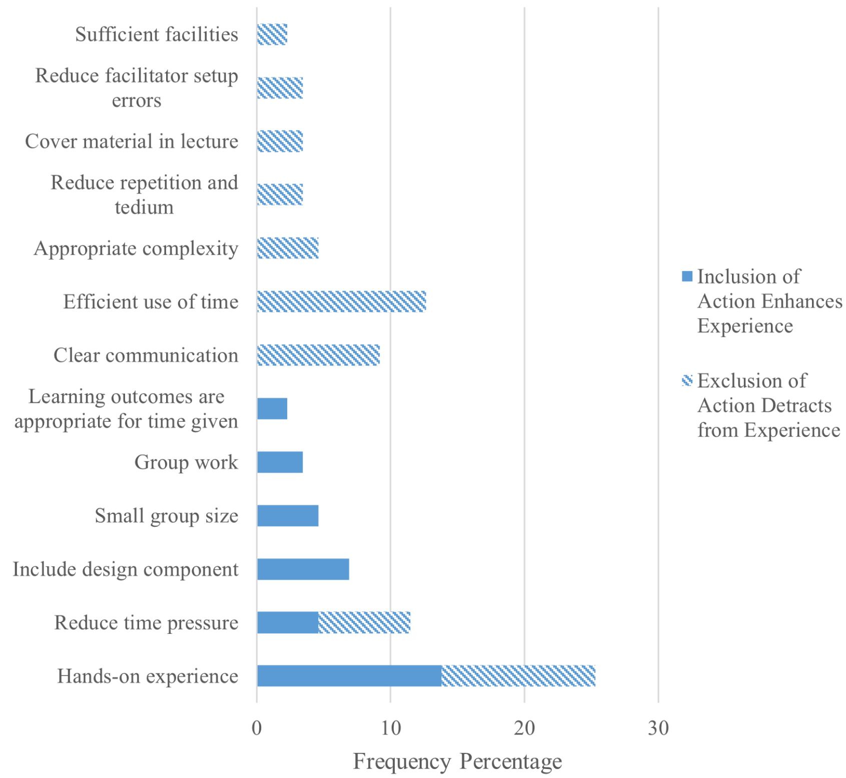

Figure 2: Survey Response Frequency of "Laboratory Experience" Themes

4 Analysis

4.1 Hands-On Experiences

Figures 1 to 4 show that, similarly to other studies in this area [20], the most-requested action from students is to include a hands-on experience in laboratories. 12 students stated this inclusion would or has improved their learning experience, while 10 stated that a lack of hands-on experiences was detrimental to their learning experience. Within the laboratory being surveyed, the hands-on experience with the cold rolling process was found to be beneficial: "It... helped aid the understanding of the concepts we were learning by giving proof through an example." The surveyed students sought out and enjoyed opportunities to directly participate in their laboratories: "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"; "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." Students had negative connotations regarding laboratories with no hands-on experience: "All students sit and record data as the TA performs the experiment... I find I do not actually learn anything from those labs"; "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."

Hands-on experiences have been found to deepen learning [21] and improve student performance [22], supporting the positive associations made by students in the selected quotes above. It is

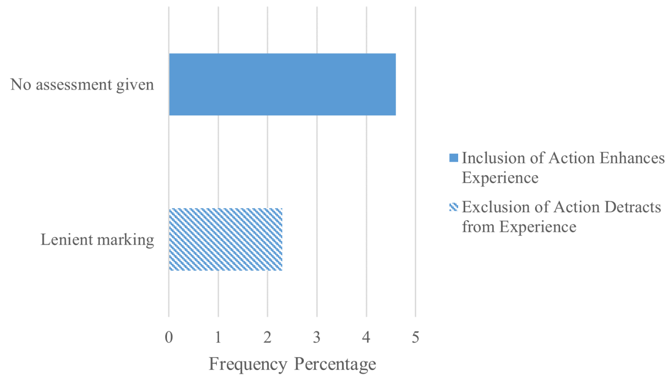

Figure 3: Survey Response Frequency of “Assessment” Themes

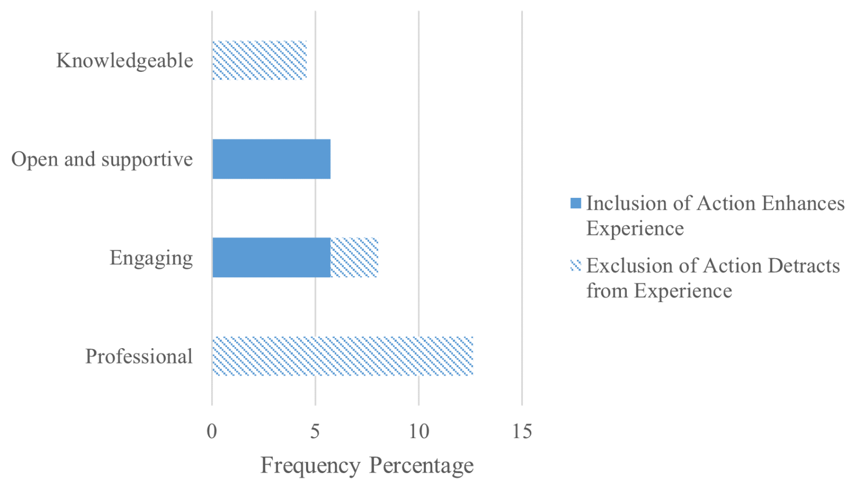

Figure 4: Survey Response Frequency of “Facilitator” Themes

therefore recommended that laboratories include a hands-on component. In developing a hands-on laboratory experience, it is recommended to implement Kolb’s experiential learning cycle [16]. Specifically, students should experience all four learning modes by the end of the activity: undertaking a concrete experience, reflectively observing the experience, undertaking abstract conceptualization to integrate their learning into their existing body of knowledge, and active experimentation to test the validity of their new learning. Implementation of all four modes into a hands-on experience has been found to deepen learning [18].

The use of Kolb’s cycle is particularly applicable in an engineering context. Every professional engineer in Canada is required to follow the Engineers Canada code of ethics, one tenet of which is professional engineers will “keep themselves informed in order to maintain their competence” ([23], pp. 3). Engineering disciplines constantly change as new technologies and scientific knowledge become available and by necessity, engineers must engage in learning throughout their career.

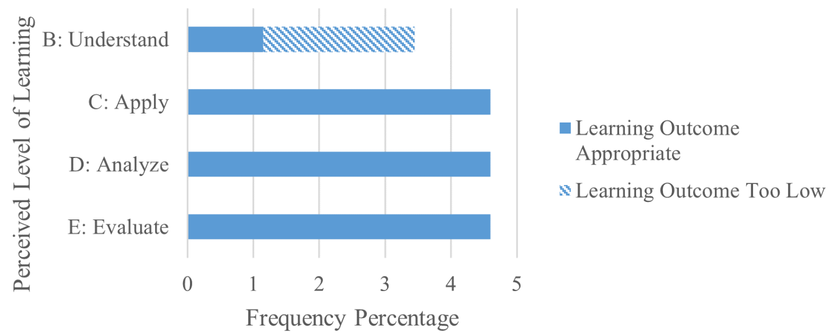

Figure 5: Survey Response Frequency on Current Laboratory Learning Outcomes

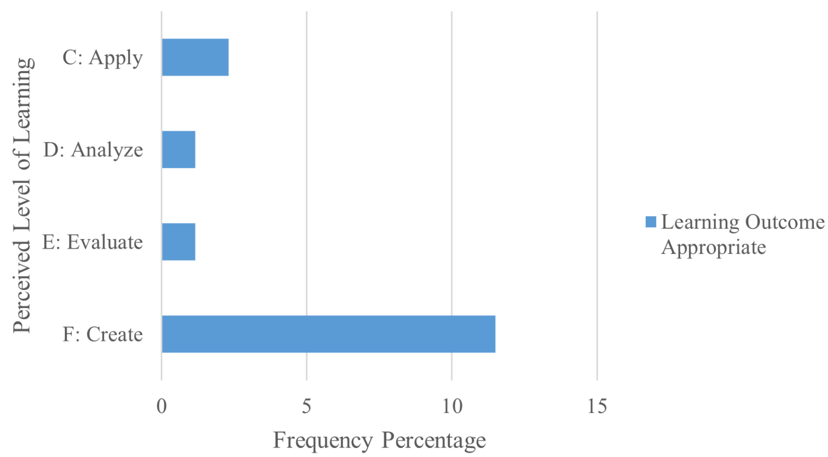

Figure 6: Survey Response Frequency on Past Positive Laboratory Learning Outcomes

The use of Kolb's cycle in undergraduate engineering has been found to accomplish this mission [20]. Students in a mechanics course undertook a laboratory intended to teach how to derive a material's yield strength. The students were given a combined torsion and bending apparatus and asked to derive equations for torque and moment. After graphing how these variables changed with the deflection of the experimental apparatus, students measured the deflection of a sample under varying loading conditions. They then were asked if any other methods could be used to determine the yield strength of a material sample. The experimental data was compared to theoretical references, and students gave their conclusions. This example utilizes concrete experience and active experimentation in students' use of the experimental apparatus, and abstract conceptualization and reflective observation in deriving models for material behaviour.

This example highlights several useful points for developing a hands-on experience using Kolb's cycle. First, the cycle does not have to start with a concrete experience. Learning activities can start with any of the four modes. Second, multiple modes of the cycle can concurrently occur. Students are capable of actively experimenting while also engaging in a concrete experience.

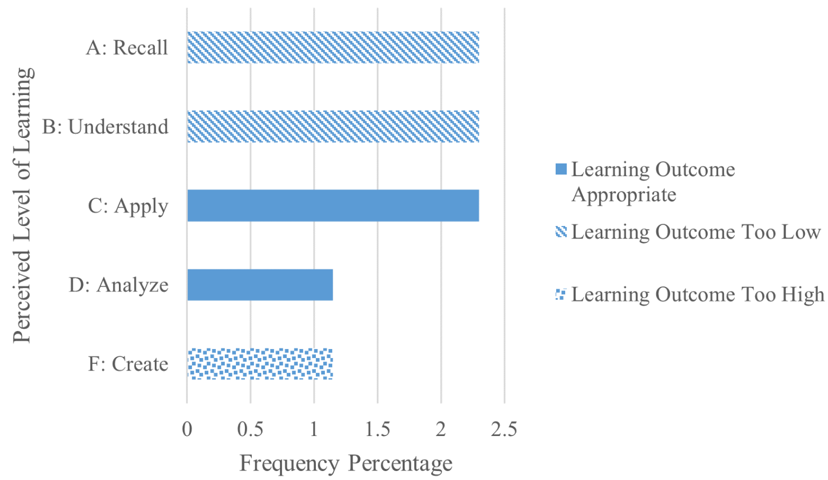

Figure 7: Survey Response Frequency on Past Negative Laboratory Learning Outcomes

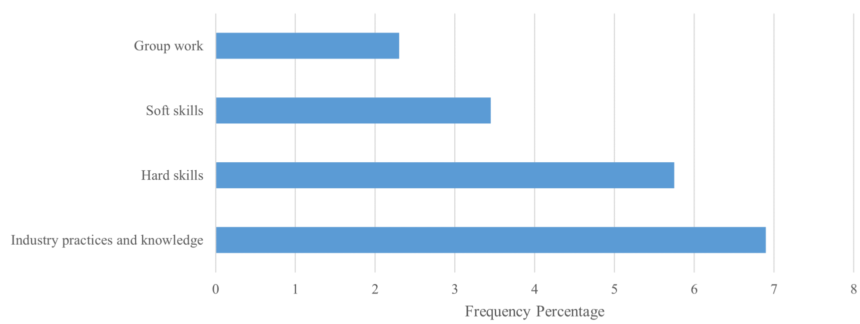

Figure 8: Survey Response Frequency on Laboratory Value to Career

Implementing hands-on laboratories that utilize Kolb's cycle may be difficult due to available resources. First, new curricula take time to develop, which may be limited due to a professor's other obligations. Students may require additional skills or training before participating, such as safety training before using a metal lathe in a manufacturing processes laboratory. Laboratory equipment may be expensive to replace and maintain, meaning that student errors can cost thousands of dollars.

There is no educational approach that is one-size-fits-all, and each course and institution will have unique concerns in implementing hands-on laboratories. It is important to note that Kolb's cycle is flexible, as shown by the previous example, and that a hands-on experience does not need to exactly mimic real-world experience; simply include a participatory experience to support learning. A common hands-on activity in chemistry courses is the use of toothpicks and marshmallows to demonstrate inter-atomic bonding. This model is immensely simplified but still aids in illustrating concepts and allows for student participation and experimentation.

4.2 Use of Laboratory Time

From Figure 2, the next most-requested action from students is efficient use of time. This theme was solely presented in the negative; this indicates that, when time is used efficiently, it does not factor into a student's perception of their learning experience. There were also several related themes that appeared in responses: repetition and tedium, delays due to experimental setup errors, and time pressure were found to detract from the learning experience.

The idea that students do not want their time wasted is self-evident. However, student responses present an intriguing insight regarding how to make laboratory time perceived as valuable. When analyzing past negative laboratory experiences, students felt time was wasted when the level of learning was too far from their current skill level: "If the lab experiment is too far from our current knowledge I feel discouraged and lost through the activities"; "Online school... didn't cover any of Bloom's taxonomy. I just forgot everything as soon as I submitted it"; "When all the students sit and record data as the TA performs the lab... I find I do not actually learn anything." This mismatch between what students are asked to do and what skills students actually have is described by Vygotsky's zone of proximal development [14]. This theory defines a zone of activities which the learner can complete unaided and a zone of activities which the learner cannot do. The zone of proximal development lies between these zones and is where learning takes place. The conclusion is that students will feel their time is better spent when the desired level of learning in the laboratory aligns with the students' zone of proximal development. In developing laboratory activities, it should be ensured the level of learning is not so high that students do not have the requisite skills to complete the activity, but not so low that the student does not develop new skills.

The idea that students will feel their time is better spent when the learning activity aligns with their zone of proximal development is also supported by Ryan and Deci's self-determination theory [11]. This theory identifies three psychological needs: autonomy, competence, and relatedness. Fulfilling these needs improves motivation. If an activity's level of learning exceeds the student's zone of proximal development, then they will feel less competent in the activity and subsequently less motivated. This aligns with another student response theme, that the laboratory experience was harmed when the material was not previously covered in lecture. If students are being introduced to a concept for the first time, they will naturally be less competent in applying it to a laboratory and therefore less motivated. The inverse is when laboratory activities are already within a student's zone of competence, such as the student who found a laboratory tedious when they simply copied down values. It can be seen through applications of self-determination theory and the zone of proximal development that aligning laboratory activities with the areas in which students are familiar, but not yet completely competent may reduce the time students consider wasted in a laboratory and therefore improve student perception of the laboratory experience.

Three tools are helpful in developing clear learning objectives. First is the revised Bloom's taxonomy, which has already been detailed. Using verbs like "the student will apply the lecture concepts" or "the student will create a project using the lecture concepts" clearly communicates the intended activity the student is expected to complete. Second, in a colloquy preceding the work of Feisel and Rosa, thirteen fundamental laboratory objectives were developed [24]. Some of these objectives align with what the surveyed students desired in their laboratories: creativity, communication, teamwork, and design. Several objectives align with the student desire for hands-on experiences and connections to lectures and industry: instrumentation, models, experiment, and data analysis. It is therefore recommended that, when constructing laboratory learning objectives, one consults this full list [24] as a starting point to identify the broad categories of learning that are expected or intended to occur. Finally, it is recommended to use the verb-context-content or VCC model of learning outcomes [25]. Outcomes begin with a specific verb, followed by the specific activity students will complete and in what context.

Another struggle in course design is the large size of class cohorts, which can number several hundred students. Due to the limited time and facilities available in a single academic semester, it may not be possible to schedule all laboratory sessions after the relevant theory has been covered in lectures. In this case, it is recommended to include an introductory presentation or other resources in the laboratories to teach the material to students, increasing their competency and sense of motivation for the laboratory activities. Surveyed students found that, when facilitators took extra time at the beginning and end of the laboratory to answer questions and explain concepts, the learning experience was improved: “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.”

From Figure 8 and select responses, it can be seen that students value the industry knowledge and skills imparted by laboratories as well as soft skills: “The last lab that was done for the course was counting grains. This was a very important concept throughout the entire course”; “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”; “I think all labs in university create better soft skills in group work”; “I believe working in group projects is a very important skill to know.” Besides confirming one of the initial motivations for this study, that laboratories should include more industry-relevant learning, this also indicates that time spent in laboratories can be perceived as more valuable if the laboratories are better linked to future careers in industry. This is shown in the second selected response, where the student understands that the tests they have conducted are applicable in their future career, but shows uncertainty as to specific applications in research and industry. This conclusion is also supported by Figure 1, which shows that students want more links to industry in their laboratories.

However, it should be noted that these students have not undertaken the internship experience that typically occurs in the surveyed program between their third and fourth years of study, or the final year capstone project that has numerous opportunities for students to partner with industry and is explicitly intended to impart understanding of the real-world design process. Therefore, student understanding of how laboratory teaching supports their future careers in terms of skills imparted is limited. However, there is still value in understanding how students perceive the connection between their laboratories and careers. If this perception is poor or inaccurate, then students are less likely to report relevant laboratory skills on resumes and in interviews, harming both their employability and the success of the engineering program in producing ready-to-hire graduates.

An addendum regarding student motivation is that another response theme was that a lack of clear communication was harmful to the laboratory experience: “I believe that bogging down these sorts of activities in... poorly defined requirements can significantly decrease the level and quality of learning“; “...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“; “...concepts were very unclear and the TA’s when reached to by email were not much help.“ Competence in a laboratory environment entails meeting the expectations of the facilitator, and clear communication, therefore, improves this competence and motivation.

This communication can also be extended to elements of laboratories that students find tedious or repetitive. While students find activities of this nature disengaging, it is a fact that industrial or research work will, on occasion, be tedious or repetitive. In this case, it is recommended to explain to students the value of repetition in industry or research. For example, in the second laboratory undertaken by surveyed students, various cold-rolling and annealing processes were repeated on four brass samples. In this case, the facilitator can explain to students that the multiple samples are used to show how different manufacturing processes result in different material properties. By linking the laboratory task to industrial applications, students may feel the task improves relevant competencies and subsequently feel more motivated for the task.

4.3 Group Size

Laboratories may be completed by students individually or in groups of varying size. From Figure 2, students saw group work as a valuable component of their laboratory experience, with Figure 8 showing that skills involved in group work are valued by students for their career. Most students preferred small group sizes: in a negative laboratory experience, “The groups were too large to work together”, and in the current laboratory, “Smaller groups would have been nice as it would have been easier to work as a group and be more involved.”

The use of group work is also supported in applications of self-determination theory: surveyed university students found relatedness to be the most important psychological need in their schoolwork [12]. In self-determination theory, relatedness is the sense of belonging to a larger group. Therefore, group work can also be used as a tool to meet this psychological need and improve motivation.

It is important to note that group work is highly dependent on personal factors and preference for group work is variable. Indeed there was variability within this study itself: one response stated individual work was more beneficial to the learning experience, while another expressed a desire for large group sizes. Group size should therefore be selected based on the factors unique to a particular laboratory experience. For example, if one is designing a hands-on experience, then group sizes should be such that everyone can participate. If a laboratory primarily involves recording data, then an ideal group size would be 2 individuals, one for conducting the experiment and one for recording the data.

4.4 Inclusion of a Design Component

From Figure 2, some students requested that laboratories include a design component, which can be equated to a “create” level of learning according to the revised Bloom’s taxonomy [4]:“...it would be nice if the lab encouraged connection of ideas to solve a new problem”; “...the primary goal of engineering laboratories should be to gain a hands on and intuitive sense of the phenomena being explored in the laboratory"; "The labs I remember best are ones where a certain concept or theory was applied to something that we had to create ourselves." Both students and instructors in undergraduate engineering have been found to value creativity [13]; a design component will therefore benefit the student experience in laboratories, particularly for the surveyed students who will soon enter internship experiences and their final year capstone design project.

Learner creativity is also found to be dependent on the learning environment rather than an inherent trait [13], meaning that instructors can take actions to improve student creativity. One way to encourage creativity in students is to accept risky behaviour [13], which encourages students to seek high achievement rather than avoiding low grades. This reduction of risk can be done both within the laboratory itself and in the laboratory assessment. This aligns with several response themes from the student surveys: the laboratory experience is enhanced when time pressure is reduced and the perceived harshness or intensity of assessments is also reduced. It has also been found that enhancing creativity, critical thinking, and problem solving skills requires engaging students in more challenging cognitive activities that apply higher levels of the revised Bloom's taxonomy [26].

Recall the definition of create from the revised Bloom's taxonomy: "produce new or original work". Including a design component does not need to be a complex process. A previous example showed how Kolb's experiential learning cycle was applied to a mechanics laboratory [20]. In this example, students were asked to think of other methods that could be used to determine the yield stress of a material. Asking open-ended questions like this that challenge students to create new connections among existing knowledge or extend their knowledge beyond the course material can be used as an opportunity for students to begin developing design or research skills.

4.5 Assessment

From Figure 3, two themes were present in relation to assessment of laboratories. Students found their learning experience to be enhanced when assessments were minimal, and harsh marking detracted from their learning experience. These results seem obvious - most students would be quite happy if their labs were marked easily or not at all! Note that student responses show more complexity than one would initially expect: "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"; "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." Rather than seeking to completely avoid assessment, students are attempting to concentrate on the laboratory experience and not split their attention with the assessment of the laboratory. As well, there is a valuable insight relating to self-determination theory [11]. Again, a key psychological need relating to motivation is competence. Assessments directly evaluate this competence. Therefore, it is important that assessments not be perceived as overly harsh and not a fair evaluation of competence, or overly simplistic and not requiring competence on the part of the student.

Another key factor in assessing laboratories is the concept of formative versus summative assessments. Formative assessments are intended to aid in learning and are generally lower-risk, while summative assessments evaluate that learning and are generally higher-risk [27]. The first step in developing laboratory assessments should be to analyze the stated learning objectives for the laboratory and decide how they can be assessed. It can then be decided whether the assessment is intended to aid or evaluate student learning. The former lends itself to lower-risk assessments which naturally exert less pressure on students, and the latter lends itself to higher-risk assessments for which higher pressure on students is expected.

Applications of self-determination theory support this assertion. In a study applying the theory in a redesign of a computer engineering course, researchers found that student motivation and their perception of the course was improved when autonomy was offered in evaluations [12]. By giving students choice in how they were assessed, students' self-perception of their competency was improved. Overall, course coordinators can promote student motivation by reducing unnecessary stress from assessments.

As seen in Figure 2, students also desire clear communication in their laboratories. Figure 5 shows that students identified a wide array of learning outcomes for their laboratories. Taken together, these results indicate that the intended learning objectives of engineering laboratories are not being clearly communicated to students, as students would otherwise identify the same learning outcome for the the current laboratory they were being surveyed on. Clear learning objectives are key to effective learning and assessment systems, and engineering laboratories have historically been limited by a lack of coherent objectives [3]; it is therefore recommended to develop clear laboratory learning.

4.6 Facilitator

Figure 4 shows that facilitators are highly impactful on the student learning experience. Positive laboratory experiences had facilitators who were open and supportive and asked engaging questions, while negative laboratories had facilitators who were unprofessional, unknowledgeable, and unengaging. Student responses show the negative impact that poor facilitators can have: "The TAs 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 TAs that infuriated everyone." It is worth noting that it is only with regards to facilitators that participants used strongly emotional words like "miserable" and "infuriated".

Facilitators for many undergraduate engineering laboratories, including the surveyed materials science course, are often teaching assistants studying at the graduate level who have little to no experience facilitating laboratories. It can therefore be concluded that facilitators should receive training before conducting laboratories, and that this training should emphasize professionalism, the technical knowledge required to lead the laboratory, and teaching skills that foster engagement in students.

Regarding the inclusion of a design component, creativity is also found to improve when facilitators lead by example [13]. Educators can share examples of creativity in engineering practice [13].

5 Conclusion

Laboratories are an important component of contemporary engineering education and must be constantly updated to reflect the current state of engineering and the society it serves. Laboratories should engage students and be perceived positively by them, as students are the primary stakeholder in the educational process. In reading the following recommendations, it is important to note that these were developed from subjective and qualitative surveys administered to 21 students in a single course; further work is needed to verify the validity of these results across multiple and varying student cohorts and courses.

In improving student perception of laboratories, it is recommended that a hands-on experience that uses all four modes of Kolb's experiential learning cycle be included. These experiences deepen learning and are valued by students, and teach future engineers the valuable skill of how to learn, which is necessary for deepening competency.

Students value their time and feel that it is wasted when laboratory activities are repetitive or are perceived as being too advanced. Aligning learning outcomes and laboratory activities with student abilities, linking the laboratory to relevant industrial skills and knowledge, and clearly communicating expectations make students more likely to value the time spent in laboratories.

Developing clear learning objectives is key to improving communication, developing an effective laboratory experience, and improving the student perception of time spent in the laboratory. The list of fundamental learning objectives described by Feisel and Peterson is an excellent starting point for understanding the general purpose of the laboratory being designed. It is recommended that the verb-content-context model be used in developing laboratory learning objectives, with specific action verbs chosen from the revised Bloom's taxonomy.

Group work is a valuable skill that imparts teamwork and communication skills and supports a need for relatedness that is important to post-secondary students. Therefore, group work can be factored into laboratories as a tool to impart valuable skills. Note that large group sizes are found prohibitive by students as they can decrease participation; tailor group sizes based on the available facilities and resources.

When appropriate, consider including a design component in laboratories. Students find design experience to be valuable, and inclusion of this component can drive creativity and engagement. It is important to note that this does not need to be overly complex, such as a term project; simply providing a space for experimentation where students can make new connections among existing ideas is highly valuable.

Assessments are an important part of any academic experience, ensuring that the desired learning outcomes were met and supporting learning. Assessments can be valuable whether they are highly intensive or very low risk. When developing a laboratory assessment, consider what the purpose of the assessment is as related to the desired learning outcomes. Difficult assessments have value, but should be justified by their relation to the learning outcomes.

Facilitators are highly impactful on students' perception of their learning experience, and so it is recommended to train facilitators. Many laboratory facilitators are graduate students who have little to no formal training in facilitating a laboratory. Training ensures consistency across facilitators and helps meet student needs.

A final note is that no educational approach is one-size-fits-all. Education is highly contextual, and how it is carried out changes between institutions, courses, professors and students. However, by keeping these factors in mind, the above recommendations can be tailored to fit the needs of specific courses and institutions.

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Appendix A: Student Survey Questions

- Please objectively describe your experience in your recent Laboratory 2 in [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 the laboratory assessed?
- 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?
- 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?
- 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?
- Did this most recent [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.
- Please consider the survey you have just completed. If you have any observations or comments on the [course] laboratories or engineering laboratories in general that was not covered in these questions, please provide them here.

Appendix B: Materials Laboratory Assessment Questions

The assessment questions for the second laboratory are as follows:

1. Give a short "scientific" summary of the lab, and what you learned today.
2. From the literature, what is the yield strength of 70/30 brass?
3. From Figs. 4a and b... estimate the yield strength, tensile strength, and ductility of 50% CW *(cold-worked)* 70/30 brass. The presented figures show the effect of cold work on yield and tensile strength for selected materials.

The assessment questions for the fourth laboratory are as follows:

1. Discuss the importance of hardness tests in engineering practice. Why is it carried out?
2. Compare your experimental values with those predicted in the Process lab *(Lab 2, described above)*. 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.