Comparison of Student Learning in Traditional Physics Labs and Labatorials

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Abstract

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Traditional, cookbook physics labs are often associated with student dissatisfaction and superficial applications, and are known to leave students with fragmented knowledge. As an alternative, we examine labatorials, a conceptually driven approach to labs. In particular, we develop labatorials to compare with traditional labs in terms of students' learning experience and the quality of their conceptual learning. In the context of Concordia University's introductory experimental mechanics course, we collect data spanning semi-structured student and TA interviews, class observations, TA surveys, post-test and final exam scores and responses, and student writing products. Upon analysis and triangulation, we find that due to the scaffolding present in labatorials, students typically exhibit a high degree of collaboration and engagement with the material in a low-pressure environment, which allows students to focus on the learning. Students in traditional labs have a tendency to rely on step-by-step instructions and focus on avoiding errors, which may inhibit their conceptual learning. Although the average final exam scores of the labatorial and traditional groups exhibit no significant difference ($p = 0.196$), differences do exist for certain question types; namely, traditional lab students tend to perform better on questions involving standardized processes or simple, memorization-based calculations, while labatorial students tend to perform better on conceptual questions.

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Introduction

All science students participate in laboratory (lab) activities at some point in their academic career. Students taking physics courses are no exception; from one's first university physics course until the end of a Bachelor's degree, labs are an essential component of a physics education, and rightly so. Experimentation is a vital component of the process of discovery that makes the sciences what they are, and so any solid science education should necessitate exposure to such scientific thinking and practices.

In spite of this, students often do not perceive the purpose of physics labs, especially at the introductory level. They believe labs to be boring and tedious exercises that do nothing but culminate in a cumbersome report (Deacon & Hajek, 2011; Tlowana, 2017; Sokoloff, Laws, & Thornton, 2007). Having myself gone through several different physics lab courses from the high school to the undergraduate levels, I can wholeheartedly confirm that I also felt this way about my labs. I was passionate about physics, and I was always a student who wanted to understand what he was learning, whether in the classroom or in the lab. And yet most labs were not providing me with that intellectual satisfaction. I would just focus on following the recipe-like instructions that I was given, collect the necessary data, and attempt to piece together my understanding of the experiment once I began writing the lab report at home.

Labatorials are an alternative approach to physics labs that aims to alleviate these common concerns about traditional labs. Being a conceptually driven approach to labs, labatorials are designed to help students develop a conceptual understanding of physics concepts through a scaffolded approach to learning and experimentation. Students work collaboratively in teams using a worksheet that gradually builds up their understanding of the material while making use of peer instruction and instructor guidance at key locations across the worksheet. In addition to being able to learn in a supportive environment, the worksheet also actively aims to connect the material to students' lives, instilling a sense of purpose and motivation for the concepts studied.

The development of labatorials was inspired by the tutorial system 'Tutorials in Introductory Physics' developed by the Physics Education Group at the University of Washington (McDermott & Schaffer, 2002) in order to assist students in understanding challenging concepts. Such an approach naturally adapts to a lab environment for several reasons: (1) a labatorial can be inserted into any lab time slot, whether the lab is integrated into a theory course or not; (2) the duration and number of labatorials are flexible; and (3) instructors can use existing equipment and experiments. Therefore, while adapting a traditional lab course to a labatorial format is relatively straightforward, the benefit it has for students is significant, helping improve their overall lab experience and allowing them to understand physics at a deeper level.

These advantages (as well as the disadvantages of labatorials) have begun to be explored more deeply in recent years at the university and high school levels. Their effect on student learning in conjunction with other interventions such as Reflective Writing has also been examined, and so the initial promise shown by the labatorial approach is continually being validated. While it is certainly not the be-all and end-all of physics labs, labatorials serve as a simple yet highly positive step forward from the status quo of traditional labs.

However, previous studies have only considered labatorials in and of themselves. Despite having been created as an alternative to traditional labs, labatorials and traditional labs have never been explicitly compared in a controlled experimental design. As such, the study presented in this thesis was designed to compare and contrast the learning that occurs in each type of lab, in particular with regard to students' affective learning experience and the development of their conceptual understanding.

We begin in Chapter 1 by surveying the literature pertinent to our investigation of labatorials and traditional labs, further motivating the alternative approach. We then briefly present in Chapter 2 the theoretical framework through which we will be interpreting our results and basing our methodology, which we present in detail in Chapter 3. The remainder of the body of the thesis then delves into the results of the study; Chapter 4 focuses on the results of the student interviews conducted, Chapter 5 focuses on the statistical and qualitative analyses of students' examinations, and Chapter 6 synthesizes the various analyses to formulate general conclusions regarding students' learning experience and their conceptual learning. We conclude by briefly summarizing the work, providing recommendations based on the research, and discussing our outlook for the future of labatorials.

Chapter 1

Background

1.1 Traditional Labs

Physics labs have long been a quintessential part of physics education. Traditionally, physics labs require that students, over the course of two to three hours, follow a set of instructions, collect data, and analyze the data appropriately to verify a relationship, which may be followed up by a formal report. Via this process, labs are in principle meant to enrich the theory learned in lectures as well as allow students to develop disciplinary experimental skills.

However, the pedagogical value of verification experiments has long been discredited. Beginning with the ideas of philosopher of science Whewell (1840), the hypothetico-deductive method of scientific inquiry—which holds the corroboration or falsification of hypotheses by experimentally testing their predictions as a primary criterion for their explanatory power—began to take prominence. This core idea of falsifiability was later furthered by the work of Popper (2005) and Lakatos, Worrall, and Currie (1979), which largely discredited the verifiability tenet of positivism that states that a statement is meaningful only if it is empirically verifiable. As such, focusing on verification in a lab might give students the incorrect impression that verifying pre-established results or absolute truths is important in experimental science.

Furthermore, there are long-standing criticisms of this traditional, cookbook lab style that often arise among educators and learners of physics. Because physics labs—which typically tackle superficial applications of concepts—often occur at isolated parts of a physics course (and sometimes as entirely separate courses), students are left with fragmented knowledge, leaving the course none the wiser about the relevant concepts (Karelina & Etkina, 2007; Lochhead & Collura, 1981; Roth, 1994; Thornton & Sokoloff, 1998; Wieman & Holmes, 2015). Traditional labs also typically do not foster creativity in methodology or experimental design, which limits the growth of students' experimental skills (Sharma, Mendez, Sefton, & Khachan, 2014). Furthermore, students are typically dissatisfied with the traditional physics lab experience, often expressing that it is boring or irrelevant to real life (Deacon & Hajek, 2011; Tlowana, 2017; Sokoloff et al., 2007).

To begin addressing these concerns, numerous alternate approaches have been developed. In terms of their learning objectives, these are typically categorizable into one of two types: approaches that focus on reinforcing students' understanding of concepts from the lecture (e.g. Wilson, 1994; Van Domelen & Van Heuvelen, 2002; Sokoloff et al., 2007; Bajpai, 2013), and those that focus on developing their experimental skills, scientific thinking ability, and/or scientific epistemology (e.g. Etkina & Van Heuvelen, 2007; Funkhouser, Martinez, Henderson, & Caballero, 2019; Zwickl, Finkelstein, & Lewandowski, 2013; Malik & Setiawan, 2015). However, instructors may wish to include both types of learning objectives in their curriculum.

1.2 Tutorials in Introductory Physics

Falling into the conceptually focused lab category, labatorials (combination of "lab" and "tutorial") were developed at the University of Calgary (Ahrensmeier et al., 2009) and directly inspired by the physics tutorial system 'Tutorials in Introductory Physics' at the University of Washington (McDermott & Schaffer, 2002). Tutorials are an inquiry-based, collaborative approach designed to help students with understanding particularly difficult concepts as identified by research. They were designed as lightweight, easy-to-implement interventions modelled off of the University of Washington's Physics by Inquiry curriculum, a fully inquiry-based course (McDermott et al., 1995).

In Tutorials, students progress through a worksheet in groups of three or four, answering a series of conceptual questions crafted to scaffold students to an understanding of a concept. These questions are sometimes answered in conjunction with simple experiments and prediction activities. At key locations in the worksheet, students are asked to examine their understanding with the instructor. If there is a misunderstanding in their question responses, the instructor guides their thinking and encourages them to explore and discuss alternative ideas. After checking again with the instructor and confirming that they understood the concept, they move on until the next "checkpoint," of which tutorials typically contain three to six. This encourages an ongoing interaction between the students and the lab instructor, allowing students to regularly receive immediate feedback.

This approach of invoking students' understanding and then examining their expectations leads to discussion between group members through which conceptual difficulties are normally resolved. However, there is still a traditional lab system at the University of Washington, with the experiments that sometimes accompany tutorials serving effectively only as demonstrations.

1.3 Labatorials

Labatorials, then, are an approach that combines the conceptual learning benefits and pedagogical approach of Tutorials with essential elements of a physics lab course. Similarly to Tutorials, students in labatorials progress through a worksheet, which now may also include calculation problems and computer simulation questions. Furthermore, the worksheets are fundamentally driven by a core experiment (or set of experiments), and so students are asked to make predictions about the outcome, perform the experiment, collect data, and interpret the results. Students may be given direct instructions for some experimental parts of the lab, while for other parts students may be asked to design their own simple protocol for investigating the concept at hand. Once completing the worksheet, students do not need to write a lab report.

Labatorials are designed in this manner in order to encourage students to thoroughly think about each step of the process, helping them understand the experiments and concepts in tandem. While the particular style with which the labatorials are implemented may vary slightly, the primary goals of using labatorials are to improve the overall student learning experience in the lab and to help students: (1) gain a better understanding of physics concepts; (2) investigate applications of physics principles in real life; (3) evaluate their preconceptions and compare them with their observations; and (4) interact with their peers and the lab instructor in a collaborative learning environment. However, it must be noted that because of the strong emphasis placed on conceptual understanding and problem solving in labatorials, there is less focus on specific experimental techniques.

1.4 Prior Work on Labatorials

The results of the approach were first described in detail by Ahrensmeier, Thompson, Wilson, and Potter (2012) and Ahrensmeier (2013), who suggested improvements in introductory-level university students' attitudes toward physics as well as their conceptual understanding and problem solving skills. The impact of labatorials in conjunction with reflective writing (Kalman, 2011), an activity that allows students to metacognitively examine textual material, on students' epistemological beliefs was also explored by Kalman, Sobhanzadeh, Thompson, Ibrahim, and Wang (2015), and it was found that with such a combination of interventions, students' epistemological beliefs could become more expert-like. The scaffolding mechanisms of labatorials and their impact on students' affective lab experience and conceptual learning were further characterized by Sobhanzadeh, Kalman, and Thompson (2017), who found that labatorials lower student anxiety and promote deeper engagement in the lab. Similar results were also found by El-Helou and Kalman (2018) when labatorials, which were originally designed for introductory university physics courses, were implemented at the high school level, particularly emphasizing the relative ease-of-implementation of the approach.

However, there has not yet been any research that has directly compared and contrasted the learning that takes place in both labatorials and traditional labs. Therefore, we build on the existing literature by exploring and comparing the advantages and disadvantages of labatorials and traditional labs in terms of the student experience and conceptual change.

Chapter 2

Theoretical Framework

The underlying theoretical framework of labatorials, and thus the lens through which we will examine the results of our study, is that of guided inquiry. Guided inquiry is a pedagogical approach based on the core ideas of social constructivism and inquiry-based learning, making it a somewhat higher-level framework. As such, after briefly explaining our epistemological stance with regards to the research, we will introduce these two key learning theories and then synthesize them into the overall theoretical framework guiding this work.

2.1 Interpretivist Epistemology

With any work directly involving human beings, subjectivities become an unavoidable part of the research. However, these subjectivities are not seen as flaws or biases on the part of the researcher, but rather are inherent to the interpretivist approach (Bhattacharya, 2017). According to this view, reality is not absolute and unchanging, but rather related to and perceived based on one's experiences and subjectivities. Based on such a relativist ontology, there is no objective reality. However, an interpretivist epistemology is also subjective in that because knowledge is constructed by people, people cannot be separated from their knowledge, and so the researcher and their research subjects are intrinsically linked.

A researcher's set of subjectivities combined with their experiences and social reality comprises their positionality, which will influence all aspects of their research (Creswell & Poth, 2018). As such, the role of a qualitative researcher is not to eliminate all subjectivities from their work, but rather to be vigilant so as to acknowledge the role that their positionality plays in interpreting their data, which will impact the rigour and trustworthiness of their work. This role that subjectivities and experiences play in one's perception of reality thus extends to the way that one constructs knowledge.

2.2 Social Constructivism

Social constructivism addresses the "guided" element of the guided inquiry framework. In particular, social constructivist (or sociocultural) theories of learning were proposed by Bruner (see Bruner, 1960; Bruner et al., 1966; Bruner, 1996) and are based on the work of Vygotsky (1980).

The pivotal idea of all forms of constructivism as a cognitive theory is that learners actively construct new knowledge from experiences. Practically speaking, this implies that learning does not take place as a result of changing behaviours in response to instruction (i.e. the viewpoint of behaviourism of J. E. Mazur (2015)); rather, students come to understand a new idea through their own thinking. Constructivist models of learning are then further distinguished by the degree to which the learner engages in this process of knowledge construction independently as opposed to receives expert knowledge in order to facilitate the process. In the former case, which is referred to as psychological constructivism, emphasis is placed on the learner's internal reorganization of new information or experiences, i.e. the independent integration of new ideas into one's own knowledge structures (Dewey, 1997; Piaget, 2005). In the latter, which is referred to as social constructivism, emphasis is explicitly placed on the role that the relationships and interactions between the learner and more expert-like individuals play in the learner's knowledge construction process, in particular on the more knowledgeable individual's role in scaffolding the learning experience.

The term instructional scaffolding, based on the ideas of Vygotsky and coined by Bruner, is the way that complex knowledge structures are constructed with the support of appropriate guidance and resources put in place by those with more expert-like knowledge. By installing appropriate temporary structural supports, more permanent, stronger structures can be built up into the eventual final product, by which point the scaffolding is no longer required.

Vygotsky's framing of this idea stems from thinking about the way children learn. When a child, i.e. a novice, is attempting to learn a new skill or solve a newly-encountered problem, they can likely perform the task much more effectively when guided by an expert. Kalman (2017, p. 19-20) notes:

> Vygotsky critiques the assumption that a student's developmental level is entirely given by a battery of tests of varying difficulties. Judging how well they solve them and at what level of difficulty is in Vygotsky's opinion only one measure of the student's developmental level. In his opinion, what the student can do "with the assistance of others might be in some sense even more indicative of their mental development than what they can do alone." The difference is called "the zone of proximal development. It is the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under ... guidance or in collaboration with more capable peers."

When students are in this cognitive zone (Vygotsky's "zone of proximal development"), they begin to construct their own knowledge. Such scaffolding is to be distinguished from simple telling or instructing, where the expert simply tries to transmit their knowledge to the student; the student performs the mental task independently, but with appropriate guidance as provided by the expert. In labatorials, this idea of scaffolding is what allows students to overcome the cognitive dissonance (Festinger, 1962) that they may experience when they realize that their own understanding of a concept differs from the accepted correct understanding, and so it plays a vital role for students' conceptual learning.

Scaffolding is manifested in three distinct ways as purposeful aspects of labatorials' design. At the forefront is the collaborative learning aspect of labatorials, wherein students actively engage in peer-instruction (E. Mazur & Hilborn, 1997; Crouch & Mazur, 2001). This form of interaction is one of the main means by which students are intended to learn in labatorials, as this is where much of students' independent thinking takes place. Because students often come from different backgrounds and each possess their own strengths and weaknesses, peer-instruction is a natural process in such an instructional setting, with teammates helping each other learn and proceed through the worksheet. In this case, the students are provided scaffolding by their potentially more knowledgeable peers.

However, this does not imply that the instructor no longer plays a role. Rather, they serve as the next level of scaffolding for students. Although students will discuss ideas with each other, there will be moments when the group needs to examine their understanding, either due to encountering some difficulty or arriving at a checkpoint. This role is critical as the instructor is typically an expert in the subject matter of the course. Additionally, as an educator, they are in the best position to guide students' thinking in the right direction and to help arrange their learning experience so as to optimize their learning.

One final way in which the idea of scaffolding manifests, albeit indirectly, is through the very structure of labatorials themselves. As with Tutorials, labatorials are designed in such a way that students can bring their current understanding of a concept to the forefront (via the prediction questions) and acknowledge any possible inconsistencies. From there, the questions are designed so as to gradually build up their understanding of the concept, progressively complexifying until they have constructed a full understanding. While such a progression is an idealization, labatorials are designed with this intent in mind, with the worksheet structure itself serving as a scaffold for the students toward this complete state of understanding.

2.3 Inquiry-Based Learning

The idea of inquiry in learning is intrinsically linked to the core ideas of constructivism. Namely, it is posited that if students are to construct their own knowledge, then they should be experientially learning; it is by actively participating in personal or authentic experiences that students will be able to derive the most meaning from their learning (Dewey, 1986; Roth & Jornet, 2014). This meaning-making process thus elicits the engagement of students with the course material through investigation and collaboration.

No matter the form of inquiry-based learning, there are certain learning processes that are characteristic of the general approach (Bell, Urhahne, Schanze, & Ploetzner, 2010; Pedaste et al., 2015). Namely, students should:

1. Formulate their own questions.
2. Collect data as evidence to answer the questions.
3. Explain the evidence collected.
4. Make connections between the knowledge obtained while investigating and the proposed explanation.
5. Justify and make an argument for the explanation.

In contrast to verification labs, a truly inquiry-based lab would help students partake in an authentic process of scientific investigation through the above steps, which would help them attain a deeper understanding of the course content.

How the inquiry-learning environment is setup depends on the course context, in particular on the instructor's goals and their class's level. However, Banchi and Bell (2008) define four possible levels of inquiry:

1. Confirmation inquiry, where students are given a research question whose answer is already known and an experimental procedure with the goal of confirming the results. (This is equivalent to a verification lab.)

2. Structured inquiry, where students are given a research question and a procedure to carry out but must form a conclusion and justify their results using the collected data.

3. Guided inquiry, where students are given only a research question but must develop and carry out their own procedure with the aim of answering the question.

4. Open or true inquiry, where students must develop their own research question as well as develop and carry out an appropriate procedure for answering that question.

While each of these approaches incorporate the fundamental elements of inquiry-based learning, the amount of independence afforded to the students increases with each successive level. As such, if instructors begin at the lower levels and work their way up, then students can gradually develop their inquiry skills as well as scientific thinking ability.

2.4 Guided Inquiry

For our work, which considers labatorials, guided inquiry is the most appropriate level of inquiry to serve as a theoretical framework (Kuhlthau, Maniotes, & Caspari, 2015). At a fundamental level, guided inquiry involves the instructor only providing the research question for the students. From this point, students are expected to design an appropriate protocol for investigating the question, collecting data, and presenting their findings.

In the case of labatorials, the "guided" element is further enhanced by virtue of labatorials being designed around the constructivist principle of scaffolding. While students are asked to investigate independently, they are scaffolded by their interactions with their peers, the course instructor, and the worksheet structure so as to explore their ideas in a safe environment. They may also be given an outline or elements of the procedure for more complex experiment at times, although doing this consistently would make the approach one of structured inquiry rather than guided inquiry. While the specific implementation details may change according to the course context, this scaffolded process of inquiry ultimately guides students toward an understanding of the relevant concepts as they discover them for themselves in the lab.

This need for students to discover concepts, devise procedures mostly independently, and receive appropriate scaffolding are focal points of any lab approach based on guided inquiry (Allen, Barker, & Ramsden, 1986). These points are in stark contrast to traditional labs, which involve concept verification, detailed step-by-step procedures, and a largely supervisory instructor role. Investigating these differences and their consequences on students' learning is thus the primary goal of this work.

Chapter 3

Methodology

We are interested in comparing labatorials and traditional labs with regards to the student learning experience and conceptual change. As such, we aim to answer the following two primary research questions and their component sub-questions:

1. How can the learning experience differ between labatorials and traditional labs?
    (a) How do social interactions in the lab impact the learning experience?
    (b) What elements of labs play a role in providing a satisfying learning experience?
    (c) In what ways do physics labs affect student perspectives on physics?
    (d) In what ways does students' self-efficacy evolve through physics labs?
2. In what ways do labatorials and traditional labs promote the development of conceptual understanding?
    (a) What elements of physics labs help students achieve conceptual change?
    (b) How do students get cognitively engaged with material in physics labs?
    (c) How do students' learning outcomes compare between the two lab approaches?
    (d) What is the difference in students' thought processes when answering questions in each type of lab?

While many of these questions are largely qualitative in nature, others are more suited to quantitative analysis. Still others could benefit from being addressed both from qualitative and quantitative angles. As such, we choose to work with a methodology that reflects this type of diversity and allows us to attain greater depth of analysis: a mixed methods approach with qualitative priority. In particular, our mixed methods design involves concurrent qualitative and quantitative data collection, which will be integrated at the data interpretation phase of the research using a concurrent triangulation strategy. Differently stated, we will first complete all types of data collection (whether qualitative or quantitative), then analyze each type of data separately, and finally corroborate the qualitative and quantitative data sources (if appropriate) in order to derive a meaningful interpretation of the results.

3.1 Course Context

The study takes place in the context of the course entitled 'PHYS 224 – Introduction to Experimental Mechanics' at Concordia University (Montreal, Canada). This is a one-credit, freshmen level lab course (the first in a sequence of introductory labs) that must be taken either prior to or concurrently with the introductory mechanics lecture course 'PHYS 204 – Mechanics'. As with most universities offering such courses, both PHYS 204 and 224 are services courses, i.e. they are required of all students wishing to pursue a science major. Furthermore, non-science students also often take this course either to acquire an extra credit for their degree requirements or to learn something new outside their field. As such, the student population of PHYS 224 is typically very heterogeneous in terms of gender, background, and goals.

The course utilizes a traditional lab approach and involves six two- to three-hour, bi-weekly experiments when taken during a normal semester. (As an intensive summer course, the experiments occur weekly.) Students work in self-assembled teams of two to four for Labs 1 and 6, but work individually for the other labs. Because the number of experimental setups is insufficient on individual lab days, students sign up for one of three groups that rotate through the associated experiments, meaning that there is no absolute order in which students are required to perform the experiments of the course. Furthermore, there are no pre- or post-lab activities, and students are given instructions to follow for each experiment as well as key points to address in their reports. For writing lab reports, students are given a template filled with an example to follow at the beginning of their lab manual. Reports are short (one to two pages) and written at the end of class, typically handed in directly to the teaching assistant (TA) overseeing the lab section and then returned to the students the following class.

A major pedagogical challenge associated with this lab course is that many students do not take the associated lecture course concurrently. Indeed, many students take the course much later. Therefore, while there may exist some overlap between the labs and the lectures (even if only in terms of the topics involved and not the order in which the experiments are conducted), students may have trouble making connections between the experiments and the material learned in the lectures. In many cases, students in non-physics majors take the course at the very end of the degree in order to satisfy their degree requirements, by which point they may not have done any physics since their freshman year and thus not remember much of the material. Because of this possible asynchronicity and the aforementioned diversity of students, very few assumptions can be made about the physics background of the students in PHYS 224, which makes it difficult for a given curriculum to be suited to the levels of all the students.

3.2 Design of the Labatorial Course

3.2.1 Course Structure

Considering these challenges, we created a labatorial-based curriculum for comparison with the traditional one. To that end, we designed six labatorials analogous to the existing labs in terms of the core concepts and the experiments performed. One notable difference in implementation is that we fixed the order of the labs in order to maximize their concurrency with the lecture course topics, which posed no problem since labatorials are always performed in groups. Furthermore, it was necessary to modify some of the core lab content because some traditional labs involved several concepts or experiments, thereby making it difficult to adapt to a labatorial format. In many cases, this was because incorporating conceptual and other types of questions would make the labatorial too long (despite in-class lab reports no longer being required), and so we eliminated one of the experiments or concepts addressed. For example, while the traditional lab students focus on determining the spring constant by two different methods in Lab 3, labatorial students focus on applications of Hooke's law and the effect of the non-zero mass of a spring on its period. In another case, there appeared to be no meaningful way to adapt the experiment for labatorials, and so we introduced a new experiment that could more naturally elucidate the core concept. For example, while the same concepts (the acceleration due to gravity and the coefficient of restitution) are addressed for each group in Lab 5, labatorial students perform a single redesigned experiment instead of two for greater cohesion between the concepts. The main experiments and concepts for each lab for both traditional labs and labatorials, presented in the order of the labatorial course, are summarized in Table 3.1, and a sample labatorial worksheet is shown in Appendix A.

Another important consideration in the design of the labatorials for the course was that labatorials are meant to be performed in conjunction with a corresponding lecture course. Namely, students are meant to be exposed to the ideas in the lecture, from which point they refine the most challenging concept(s) in the labatorial. Were students to not have any

	Lab Number		
Version	Lab 1	Lab 2	Lab 3
Trad. Concept	Density	Force addition	Spring constant
Trad. Exp.	Pycnometer	Force table	Measuring F_s, T
Laba. Concept	Density	Force addition	Spring constant
Laba. Exp.	Pycnometer	Force table	Measuring T
Version	Lab 4	Lab 5	Lab 6
Trad. Concept	Centripetal force	Collisions and g	Pendulum period, energy
Trad. Exp.	Horizontal tension	Measuring coefficient of restitution, g	Verifying T, $KE+PE=C$
Laba. Concept	Centripetal force	Collisions and g	Pendulum period
Laba. Exp.	Pendulum tension	Measuring coefficient of restitution	Deriving T

Table 3.1: Core concept(s) and experiments(s) addressed in each lab

preparation before a labatorial, they would likely not be able to participate in discussions with their teammates and thus not be able to get the most out of the labatorial. Since there was a high chance of students not taking PHYS 224 at the same time as the corresponding lecture course, as explained in Section 3.1, we introduced mandatory pre-readings for the labatorial version of PHYS 224, which were selected webpages and/or selected sections from the textbook used for the lecture course. In turn, we introduced mandatory summary writing, which was to be shown to the TA at the beginning of each lab. We chose summary writing rather than a more effective technique like Reflective Writing (see Kalman et al., 2015) since we wanted to be able to compare the two lab approaches only for what they are fundamentally, not including the influence of other techniques.

3.2.2 Team Formation

Because PHYS 224 students only all meet in the lab, we believed it important to also explicitly consider the formation of the student teams, particularly since the peer-instruction interactions in the lab are critical to students' learning in labatorials. However, note that the issue of formation of groups can be approached differently depending on one's own course context, and there are surely strengths and weaknesses to any approach. In this case, we decided to use heterogeneity as the fundamental heuristic in forming the groups. Namely, having access to the class lists before the start of the course—which contain information regarding students' gender, current major, and year in the major—we aimed to construct groups of three or four students that were as balanced as possible in all those regards. The intent of this approach was to capitalize on the inherent diversity of the students who enroll in PHYS 224 and allow their different strengths and weaknesses to compliment each other, thereby improving group effectiveness. This is a perspective supported by the literature (e.g. Felder & Brent, 1994; Lee & Farh, 2004; Cheng, Lam, & Chan, 2008). However, there are also arguments for having more homogeneous groups (e.g. Miller & Otto, 1930; McGaughy, 1930; Blumenfeld, Marx, Soloway, & Krajcik, 1996). For a critical analysis of the approaches as well as of their arguments and implications, see the work Esposito (1973). Regardless of the approach, forming teams in advance was valuable for our particular course context since students begin working immediately after an introductory speech at the first class session.

However, one major challenge that we encountered with this approach was that students still had the possibility of dropping the course before the first class. As such, we sometimes needed to partially reorganize the teams at the start of the first class. Furthermore, even if we were able to form complete, ideal teams at the beginning, students had the possibility of dropping the course later on as well, and some team size reduction and/or reshuffling of students was also necessary on occasion, reducing the ideality of the teams. Another challenge was that there were many students who had not yet declared their major, or were in an exploratory or general science program. In this case, deducing their specific strengths or interests, and thus placing them with potentially ideal teammates, was not possible. However, such a team formation strategy is merely a heuristic measure that can be used as a plausibly preferable alternative to pure randomization or self-assembly.

3.2.3 Lab Evaluations

To further try and optimize the collaborative learning taking place in the lab, we also implemented a modified form of the peer-evaluation scheme of Kalman (2017), shown in Appendix B. Besides effective collaboration being important for their success and learning in the lab, students were also partially graded on their teamwork. As an aside, it should be noted that because Tutorials are not originally graded, labatorials need not be graded either in general. However, because PHYS 224 is a standalone lab course, the labs themselves constitute a significant portion of the course grade. Since we did not include lab reports in the labatorial version of the course, grading needed to be associated with the completion of the labatorial itself. The grading scheme for each labatorial session (also shown in Appendix B) was largely participation based, containing both an individual and group component and a worksheet completion component. Therefore, the peer evaluations also served as an extrinsic motivator for participating in the activities since there was a grade attached. However, after observing the students during the pilot phase of this experiment (which will be described in the next section), we saw that participation was generally a non-issue, and so the peer evaluation and grading scheme served largely as formalities.

3.3 Design of Study

3.3.1 The Pilot Study

After designing drafts of all six labatorial worksheets, each of three graduate students tested two of them, going through them independently (with me there to provide clarifications if necessary) and then providing feedback. We then made modifications based on this feedback. This initial design phase took place over the course of the Fall 2018 semester. In the Winter 2019 semester, the labatorials were implemented for the first time at Concordia as a pilot with the aim of further refining the worksheets as well as the interviews and targeted conceptual questions designed for the final exam, all of which will be discussed in Section 3.4. Of the 16 course sections for PHYS 224 that semester, only one, which contained 12 students, was run as a labatorial course. While interview data was collected during this phase, these results will not be considered in the formal analysis process, which will be detailed in Section 4.1. Furthermore, no quantitative analysis was performed at this stage.

In the subsequent semester (Summer 2019), the primary study was conducted. Based on my experiences observing class sessions, the data collected during the pilot, and my discussions with colleagues, there were certain changes that I decided to make in moving from the pilot to the full-blown study. Firstly, I originally tried having students respond to a "takeaway" question at the end of each lab as in the work of Ahrensmeier et al. (2009), which asked, "What was your biggest takeaway from this lab?" However, while there were several responses expressing that they learned something, such self-proclamations of understanding do not provide much insight as to whether or not they actually understood the concept. The other types of responses were too scattered and not especially insightful. At the same time, my colleagues suggested adding post-test questions as another means of data collection, which we believed would be more fruitful. Therefore, given the above considerations and the time constraints of the lab, the takeaway question was removed from the analysis. My colleagues also suggested designing weekly post-lab surveys for the TAs to complete as a means of triangulation, and so this was also added in for the full-blown study in Summer 2019.

3.3.2 Participant Recruitment

Because this was a summer course, there were only 54 students enrolled in total. The experimental group, i.e. the labatorial lab students, consisted of 30 students across three course sections (sections 40, 42, and 44 containing 11, 9, and 10 students, respectively) and the control group, i.e. the traditional lab students, consisted of 24 students across two course sections (sections 41 and 43 each containing 12 students). This count of students includes only the students who remained in the course from beginning to end, which are the students for whom we have complete quantitative data. A subset of the students in the

	Interviewee Characteristic		
Pseudonym	Section	Major	Prior Physics Experience
Catherine	40	Biology	10 years ago in HS
Quincy	40	Environmental Science	Recently in college
Emma	42	Exercise Science	No physics in HS
Derek	44	Behavioural Neuroscience	Recently in college
Jessica	44	Exercise Science	10 years ago in HS
Stacy	44	Biochemistry	10 years ago in university
Adrian	41	Exercise Science	10 years ago in HS
Oscar	41	Biology	Recently in HS
Amir	43	Chemistry	No physics in HS
Evelyn	43	Behavioural Neuroscience	Recently in HS
Lauren	43	Behavioural Neuroscience	Recently in HS
Zion	43	Aerospace Engineering	Recently in university

Table 3.2: Labatorial and traditional lab interviewee metadata

course participated in interviews, and so of those students, only those who participated in both interviews (to be described in detail in Section 3.4.1) were included in the study sample.

Students were placed by the registrar's office into one of the five course sections upon registering for the course. Although the students were not given the choice before the course began, all students were made aware of the details of the study and were asked to give consent to participate through a consent form, and arrangements could have been made on a case-by-case basis had anyone opposed. (Only those who consented were included in the study sample.) Students could then volunteer to participate in the interviews. Although interviewees were solicited during the course introduction speech, participation in the interviews was voluntary. Ultimately, there were six students from each group (i.e. experimental and control) who volunteered. As these students form the core of the qualitative data analysis, a summary of their pseudonyms and characteristics of interest is shown in Table 3.2.

3.4 Methods of Data Collection

3.4.1 Interviews

Given that this is a mixed methods study, various forms of data were collected, the bulk of which being qualitative. One of the main sources of data was the student interviews, which were conducted in a semi-structured fashion. This means that while we did have questions prepared in advance with the intent to ask them in a certain order, the interview was not limited to a rigid question-and-answer format, but instead could ebb and flow with the ideas elicited from the participant. In such an interview, if the participant begins to move toward a different (albeit related) topic of conversation, then I as the interviewer should allow them to go there and explore their thoughts. This often brings about unexpected insights, and the casual atmosphere of a semi-structured interview helps students feel more comfortable sharing their thoughts. This is furthered by being friendly and transparent with the participants throughout the research process, which helps build a rapport of trust and thus increases the likelihood that they honestly respond to the questions.

Student interviews were conducted at the beginning of the course (the pre-interview) and at the end of the course (the post-interview). More precisely, the pre-interviews were conducted between the first and second labs since we could not meet the students until the first lab session, and the post-interviews were conducted after the sixth lab but before the final exam. This latter point does not cause any issues for our analysis since the interview questions were focused on the research questions targeting general features of the labs, not those that are content-based. An important point regarding the design of the interview questions was that they could not always be the same for the labatorial students and the traditional students. However, because this is a comparative study, all incompatible labatorial student interview questions have a corresponding traditional student interview question that essentially targets the same point of interest. An example of this design choice can be seen in the question regarding the way students work in teams:

Labatorial: Could you tell me what it felt like doing a lab like this [without a protocol] for the first time?

Traditional lab: What do you think about the protocol format of labs?

However, some questions could be asked in the same way for both groups, such as this question asking about their interactions in the lab:

Both: Can you describe how you felt about your interactions with your partners and the TA throughout the session?

The full labatorial and traditional lab student interview guides are shown in Appendices C and D, respectively.

The course TAs were also interviewed in a semi-structured fashion. However, the main differences are that the TAs were only interviewed at the end of the course as opposed to pre- and post-, and that their interviews are being used as data for triangulation rather than as a primary data source. It is also worth noting that while there was one TA present at each lab section, there were only three distinct TAs; two TAs (pseudonyms Isaac and Liam) each overlooked one labatorial section and one traditional lab section, and one (pseudonym Justin) was only responsible for a labatorial section. This means that Justin could not necessarily comment on experiences both from labatorials and traditional labs for PHYS 224, limiting his responses to a degree. However, by virtue of also being the TA for a different course in the introductory lab sequence during the Summer 2019 semester, he mostly makes up for the inconsistency since the introductory lab courses are traditionally all run the same way.

3.4.2 Quantitative Course Assessments

Because we are trying to compare students' conceptual learning in labatorials and traditional labs, we will also be looking at student scores. The first type of these are the conceptual post-tests containing one to two questions that were designed for each of the lab topics. A sample post-test is shown in Appendix E. While there were pre-tests for students in each group for each lab, we could not perform pre-post comparisons since the pre-tests could not be the same for both groups; this was in part due to logistical constraints and in part to the distinct natures of the preparation and lab content for each group.

However, we take a different approach that does retain some of the essence of pre-post testing. Namely, we administer a general pre-test (distinct from the weekly pre-tests) to all the students at the beginning of the course. This pre-test serves not as a base for pre-post comparison, but rather as a means of establishing equivalence of the two groups, which would still allow us to meaningfully compare scores between the groups. Because this is a mechanics lab course, we compile six questions from the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992) that span some key topics in kinematics and dynamics and possess some relation to the lab topics. This general pre-test is shown in Appendix F.

In addition to the post-tests, we will also examine the final exam for the course. In part due to logistical constraints, we did not completely modify the original final exam. However, as hinted at when discussing the pilot implementation of the labatorials, there were six conceptual questions specifically targeting the core concepts of each lab that were introduced into the final exam. Furthermore, some of the original questions that were either not conceptually interesting or simply redundant with the added questions were removed. Although the final exam was slightly longer overall than previously, the students were given additional time to compensate for this.

3.4.3 Additional Qualitative Data Sources

In order to enrich the quantitative results and gain further insight into students' learning outcomes, we qualitatively examine the 12 interviewees' responses to selected post-test and final exam questions. (The selection criteria for these questions will be discussed in detail in Section 5.5.1.) These responses serve as the main source of data in addressing the research sub-questions that involve content-specific learning outcomes. We also examine the responses of six other students from each group who are selected in order to ensure that we examine the results of a diversity of students in terms of their overall final exam grade, gender, and major. This is important for increasing the reliability of the results as it helps establish whether or not our interviewees are representative of the whole class.

Some other qualitative data sources are also considered for the purposes of triangulating with both the interviews and examination responses. Firstly, I alternately attended the lab sessions of the different course sections and took observations as a passive observer, i.e. an observer who does not interact directly with the participants. I took notes according to the time at which a particular event a occurred, the description of the event, and my thoughts on the event. A sample set of observations is shown in Appendix G. In addition, the TAs were asked to fill out qualitative surveys at the end of each lab regarding students' understanding of specific concepts targeted in the lab, an example of which is shown in Appendix H. For a labatorial, they would complete the survey immediately at the end of the class, while for a traditional lab, they would do so after grading the students' lab reports. Lastly, students' writing products are also examined. For labatorials, this refers to to the labatorial worksheets, while for traditional labs, this refers to the lab reports with particular focus on the discussion and conclusion sections since this is where concepts are the most likely to be mentioned considering the report template they are instructed to follow.

There are clearly many sources of data to consider simultaneously as well as many aspects to the research questions. Therefore, for the purposes of better conceptualizing the structure of the data in relation to the research questions and sub-questions, let us note that not every data source will be equally relevant to addressing different sub-questions. Differently stated, each sub-question can only be answered by considering specific types of data. (For example, Question 1a, which considers how social interactions in the lab impact the learning experience, can only be answered via the student and TA interviews in our case due to the nature and contents of the data.) Cross-tabulating the data sources versus the research sub-questions reveals additional structure, as shown in Table 3.3. Namely, there are questions

Research Question	Sub-Question	Student Interviews	TA Interviews	Observations	TA Surveys	Worksheets/ Reports	Quantitative	Final/ Post-Tests
1	A	✓	✓					
	B	✓	✓	✓				
	C	✓	✓	✓				
	D	✓	✓	✓				
2	A	✓	✓	✓	✓			
	B	✓	✓	✓				
	C			✓	✓	✓	✓	✓
	D					✓		✓

Comparison of general features of labatorials and traditional labs

Analysis of content-based learning outcomes

Table 3.3: Structure of research questions and sub-questions for triangulation

that involve general aspects of the lab approaches, while there are others that are tied to the specific content of PHYS 224. Furthermore, only certain data sources can be used to address each of these question types. This observation will guide us during the triangulation process. In particular, the interviews will serve as a foundation for investigating the aspects that involve comparing general features of labatorials and traditional labs (the orange sections of the table), and the examination responses will serve as that of the aspects involving content-specific learning outcomes (the blue sections of the table), with all other data being used for triangulation within their respective sections of the table.

Because there are different types of data involved, an assortment of data analysis techniques will be required. In order to only introduce as much as is necessary to understand the progression of the research, the specific techniques shall be introduced prior to the analysis of the relevant data over the course of Chapters 4, 5, and 6. To better understand the progression of these various steps, a timeline of the project is shown in Figure 3.1.

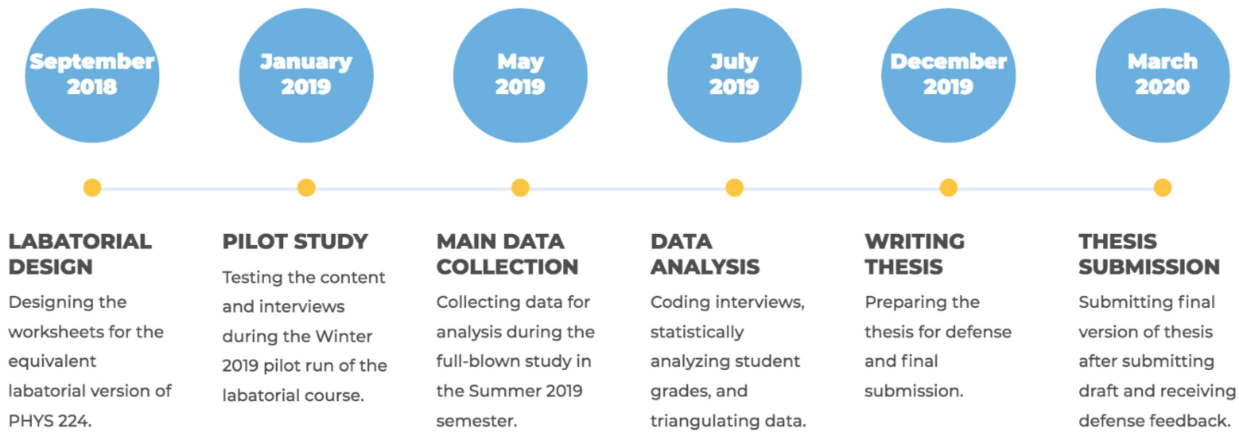

Figure 3.1: Timeline of major phases of the research project ordered by starting date

3.5 Validity

3.5.1 Researcher Roles

As the principal investigator of this study, I wanted to maintain that role as strictly as possible by minimizing my interactions with the students (except for the interviews) so as to not influence students in the lab. This was particularly important from the perspective of power and influence for all the roles that I played, as there was the possibility of a power differential between myself and the students. When introducing myself and the study at the beginning of the course, I made especially clear that while I would be present during lab sessions, I would not have any influence on their in-lab grades. I also reassured them that while I would be conducting the interviews, neither their participation in the interviews nor their particular responses would have any influence on their course grade. Furthermore, I reminded the students that the TA should be the main point of contact in class for all questions regarding the lab content in order for me to not have any impact on their learning. Although I was nevertheless asked questions at times, I always redirected them to the TA. However, I did answer (and in fact welcome) questions regarding the study or the course in general, as I wanted to be as transparent as possible regarding the study procedures and help them feel comfortable with the whole process.

To mitigate possible issues of bias in grading their post-test and final exam questions, I designed a simple grading rubric for each post-test or final exam question before grading. This allowed me to grade students' responses as objectively as possible regardless of the group they belonged to. A set of sample solutions and rubrics is shown in Appendix E.

One final role in which I needed to be cautious as to my interactions with students was as an interviewer. Because this study is explorative in nature, regardless of existing literature on labatorials and traditional labs, I needed to ask my interviewees questions in a way that would allow me to interpret the results as impartially as possible. Additionally, because the interviews were semi-structured, I needed to be aware of the way in which I responded to them in the conversation so as to not ask leading questions or influence their thinking.

3.5.2 Rigour

In conventional quantitative work in the natural sciences, generalizability and reproducibility are ubiquitously considered to be key determinants of the rigour, and thus the quality, of the work. But in qualitative (and quantitative) work in the social sciences, the objects of research are people. Because all human phenomena are inherently subjective according to an interpretivist epistemology, one cannot use the same criteria for rigour. However, while the results of qualitative work are typically not generalizable or reproducible (at least not in a way that would be conventionally deemed rigorous), the systematicity with which a qualitative researcher documents their thought processes and the depth to which they reflect upon their data before constructing an interpretation can act as suitable indicators of the rigour of their work.

To attend to the first of those criteria, I have been keeping a research journal since early on in the study. The journal serves not only to document procedures and results, but to record one's thinking and reflections on a matter as it arises. Like in any form of research, a researcher's thinking will change in many ways throughout a research project, and I was constantly making decisions that influenced my work on various levels. If one can be aware of and keep track of each of these thought processes throughout the research processes, then the research process is, in the sense of systematicity, reproducible; someone else could understand the progression of the work from beginning to end and know how every decision came about, allowing them to have confidence in the results and interpretation put forward by the researcher.

3.6 Limitations

Despite all efforts made to ensure the rigour of the research, there are certain limitations inherent in the methodology described. One major limitation is due to sample size, both in terms of the number of student interviewees and the total number of students in the course. Although the student interviews constitute the core of much of the qualitative portion of my analysis, the results derived are limited by the number of perspectives upon which they are based; differently stated, they are limited by the diversity of the interviewees. This is the main weakness of interviewing participants on a volunteer basis since one might expect certain types of students to be more willing to volunteer. Similarly, because the qualitative analysis of the post-test and final exam responses is based only on a subset of the questions—of which I only examined the responses of 24 out of 54 students—there may be interesting results that I missed in the unchecked responses that could have led me to a different conclusion. The quantitative analysis may also be limited; because the class size is small, the power of the statistical tests used is reduced.

There are several other limitations related to various aspects of the quantitative analysis, one of which is the design of the rubrics for grading the post-test and final exam questions. Because the rubrics were designed on a 5-point scale (i.e. 100%, 75%, 50%, 25%, or 0%), it is not possible to solely use the most standard statistical test to test for differences in means on those questions, i.e. Student's t-test, since the score variable is not continuous, which violates a core assumption of the t-test. There is also the possibility that the questions themselves were not sufficiently tested for validity, as only the conceptual final exam questions were tested during the pilot study. This makes it more difficult to meaningfully interpret the results and thus potentially more difficult to differentiate the performance of the control and experimental groups. Furthermore, on the level of the overall exam score, the significance of the difference of the mean scores between the two groups could perhaps have been more meaningfully interpreted for the purpose of answering our research questions had additional purposeful conceptual questions been used or had all the conceptually uninteresting questions from the original exam been removed entirely.

One other possible limitation is in the structure of the study itself, namely in terms of the formulation of the research questions and the ordering of the data collection and analysis phases. I chose to complete all data collection and then perform all the data analysis so as to ensure that I was always being guided by my research questions and to limit the scope of this project. However, this precluded the possibility of taking the research in other potentially interesting directions that came to light during the data analysis. The possible avenues of this research may additionally have been limited by my very role as the principle investigator and data collector for this project, as there exists the possibility that any unacknowledged biases in my decision-making process could have affected the data collected.

Chapter 4

Interview Analysis

Interviews are a common form of data collected in qualitative work as they allow one to gain deeper insights into the thoughts of the participants than other methods. Such an insight may lie at various levels in the interviewee's words, with certain ideas reoccurring in different forms throughout the interview. As such, interview data is highly detailed and rich with information. In order to derive meaning from (often extremely voluminous) interview data, an appropriate method of data analysis is required. There are many approaches to interview analysis, which may each be suited or not to a given research methodology. Here we aim to present the most important elements of all qualitative coding procedures, justify our choice of approach considering our methodology, and show a concrete example of the approach being applied to the interviews. We will then present an in-depth analysis of two particular students' interviews and discuss the main results derived from the interviews as a whole.

4.1 Qualitative Coding

The fundamental goal of qualitative coding is to identify the most prominent themes that permeate the data. This generally occurs through an iterative process of categorization; this involves dividing the interview transcripts into (possibly overlapping) segments, labeling segments (or words or sentences within the segments) with codes, organizing the codes into categories (when possible), and then collapsing codes and categories into high-level themes (Creswell & Poth, 2018). As one examines each successive interview, comparing each segment with their originating interview as a whole and the other interviews examined so far, one iteratively groups together redundant codes so as to ultimately derive five to seven core themes or categories. Upon coding all the interviews, the ideas that are common across all interview transcripts are then considered general by assumption (Corbin & Strauss, 2014; Packer, 2017).

4.1.1 Deductive vs. Inductive Coding

Approaches to coding can be classified into deductive and inductive approaches. With deductive approaches, one approaches the coding process with prior ideas about the data in mind. This is often done when one wishes to identify specific ideas in the interviews, which may stem from prior data analysis, the research questions, etc. As such, deductively coding an interview is akin to classifying the interviewee's words into pre-conceived categories. While this will limit the themes that can be derived from an interview, this does not pose a problem considering the purpose of the deductive approach.

Contrariwise, with inductive approaches, one approaches the process with no (or minimal) prior assumptions. This is done when one wishes to explore the data and discover new themes as they emerge, or when one wishes to derive new theory based on the data. Without pre-conceived categories, it is the researcher's task to come up with appropriate codes and categories and refine them into themes. Due to the open-ended nature of this approach, the researcher must be even more aware of their inherent biases in considering the data, particularly in a comparative study.

4.1.2 Our Approach to Coding

Because this study is explorative in nature, we begin by applying an inductive coding procedure on the student pre-interviews; this allows us to identify ideas in the transcripts of both labatorial students and traditional lab students without any preconceptions, allowing us to compare the results with the literature and present a minimally biased comparison. After examining the transcripts of all 12 interviewees, we derive a set of themes and major categories that we believe will not change greatly with the post-interviews. While new ideas could most certainly still emerge in those interviews, our code structures are created such that existing categories and themes can simply be added to or modified should a segment of the post-interviews not naturally fall into an existing bin. As such, we turn to a predominantly deductive approach for analyzing the post-interviews.

While this can be seen as undermining the purpose of an explorative study, we believe that a combination of approaches as described is appropriate when investigating a phenomenon that is already documented fairly thoroughly in the literature. The inductive aspect allows us to derive themes in a minimally biased way, and the deductive aspect allows us to further build our comparison as well as target our research questions more purposefully.

When moving on to the TA interviews, we again apply an inductive coding procedure since that data is used for triangulating with the student interviews, which form the core of the data for addressing the research sub-questions pertaining to general characteristics of labatorials and traditional labs. As such, it is necessary to minimize the biases present in the themes derived and verify if the comments of the TAs are consistent with those of the students. However, since we are prioritizing the student interviews, the remainder of the discussion on qualitative coding will be with regard to the students.

4.1.3 The Specific Coding Process

In order to derive meaningful results from the interview data, one needs to become deeply familiar with it. This involves not only reading through the transcripts several times, but constantly writing down questions, comments, and observations as they come to mind. This allows one to establish a dialogue with the data, generating new ideas that may come into play in the coding process.

In my case, I began this process of constant questioning from the beginning of the interview transcription. Since I transcribed the interviews by hand, there were often interesting questions or ideas that came up. In order to not forget these ideas before beginning to code intensively, I took notes of these thoughts in my research journal. I transcribed the six labatorial student pre-interviews followed by the traditional lab student pre-interviews and then proceeded similarly for the post-interviews.

In order to begin coding, it was critical that I properly conceptualize how I want to organize my coding structures for the purpose of comparison. Since my goal is fundamentally to compare labatorials and traditional labs across various dimensions, I believed it would be most fruitful to produce two primary sets of codes: one for the labatorial students and one for the traditional lab students. However, I did not formally distinguish between codes that originated from pre-interviews and those that originated from post-interviews. This is because I used the NVivo software to organize my codes, which made it straightforward to keep track of the various codes across various dimensions including whether they were pre- or post-, the participants from whom they were derived, their association to a particular participant, etc. Additionally, in NVivo one organizes codes according to a tree-like structure; each node corresponds to a code, which can be grouped together under other nodes to form categories or themes. Since these nodes are simple to modify and reposition, it is straightforward to reorganize one's codes. This tree-like structure, combined with NVivo's feature to keep track of the number of references to a given code as well as the number of interviewees that referenced it, allows one to tentatively evaluate the relative importance of different codes as well as track the relationship between different codes and participants.

It is also worth noting that I chose to maintain a third grouping of codes for points raised that I believed were relevant and worth considering but not did not directly pertain to the research questions or the labs specifically. These codes, which I refer to as "contextual codes," allowed me to keep in mind important elements of the context within which the course took place, which is important for accurately and meaningfully interpreting students' responses.

Once all the interview transcriptions were completed and verified for accuracy by the students, I began coding the pre-interviews in the same order that I transcribed them. In order to deeply immerse myself in each interview, I would (after again reading the completed transcript) subdivide the transcript into sections according to the interview question being asked at the given point or a big idea being discussed by the student. Then, with each section coded, I would reflectively write about my ideas and construct questions about the passage. This allowed me to begin deriving deeper meaning beyond the codes and connect the ideas across the current and other interviews, developing ideas for possible themes. I repeated this process until the entire interview was coded. Since new codes were identified with each successive interview analyzed in this way, I would take some time after coding each one to reorganize my codes and categories as guided by my reflections. I also found that some categories were simply convenient to form since they were directly pertinent to some of the research sub-questions, and so this was a heuristic at play in organizing codes.

This coding process continued until all the labatorial student pre-interviews were analyzed. Before moving on to the traditional lab student pre-interviews, I re-organized the labatorial categories, by which point some of the main themes had already begun to emerge. I then repeated this whole process for the traditional lab students, building up a new set of codes and categories, ending that portion in a fashion similar to that just described for the labatorial students. With a set of probable main themes established for both student groups, I then began coding the post-interviews similarly to the overall process just described. Because I took on a mostly deductive approach for this portion of the interview analysis, my reflections were typically shorter. However, I attempted to propagate the spirit of constantly reflecting on and comparing and contrasting new ideas with the ones previously encountered.

4.1.4 An Example of Coding Across Interviews

In order to concretize the essence of qualitative coding and the dynamic analysis process just described, I provide an example of a set of statements by labatorial students from pre- and post-interviews that exemplifies a certain code (albeit there are other statements still) and then proceed to elaborate upon on their relationship to the overall coding hierarchy:

> Catherine (post): *Working through, not feeling alone in your confusion or your knowledge, feeling like you had three minds working together toward a common understanding. And so much in life is like that anyway, that it could build those team interactions, and especially on things that you don't know about. And to feel like you're in a safe enough space that it's like, 'Hey, I actually don't know what I'm doing. Could you explain to me why you understand this?'*
>
> Quincy (pre): *In this [class], everyone is so nice to each other and very helpful.*
>
> Emma (post): *We waited for each other, and the other two were very kind in helping me understand concepts.*
>
> Derek (pre): *I'd say it's sort of helpful to throw back ideas, like how to solve a problem, and also again, for me at least, it's less stressful. You're not just there sitting by yourself and working on it. And then yeah, it's good, the group dynamic. Although, I am a bit more introverted, but it's kind of good to talk to other people about the lab and all that. So it's a good experience just in general.*
>
> Jessica (post): *Labatorials are way more... They're better for people who are not into physics or maths or things like that because it's much more engaging when you get to work with someone. It's much less intimidating because you know that you'll have someone to work with when you're like, 'Ok I read through it, I did the notes, but I still don't know what I'm doing.'*
>
> Stacy (post): *There was help, so even if you didn't get it, the team was there.*

These quotes highlight the code "support by team." In one form or another, the interviewees' interactions with their peers had a positive impact on their experience in the lab.

I chose the word "support" since these comments all reflect the affective aspect of students' learning experience. In particular, Catherine refers to "not feeling alone in your confusion" and feeling "like you're in a safe enough space" to voice your doubts; Quincy expresses how his peers were all "nice to each other and very helpful"; Emma appreciates how her teammates were "very kind in helping [her] understand concepts"; Derek expresses how the lab was "less stressful" and "a good experience in general" since it was "good to talk to other people about the lab" as opposed to "sitting by yourself and working on it"; Jessica indicates that the team aspect of the lab made it "much less intimidating" and said that "it's much more engaging when you get to work with someone"; and Stacy voiced how her "team was there" for her even if she did not understand.

Many of the quotes also explicitly or implicitly indicate the role that interactions with peers played in helping students learn, such as Catherine's reference to peer instruction or Derek's reference to group discussion. However, separate codes (including "peer-instruction" and "discussion," respectively) were used to capture these points. What these statements indicate is that for all the interviewed students, the positive relationship they had with their peers set the foundation for their learning, suggesting that students' affective experience of is an important consideration in the design of a lab course.

The specific consequences of this peer support was captured by separate set of codes, e.g. "teammates reduce stress," "environment is relaxed," and "coping with difficulty," which were grouped under the category "consequences of support." The "support by team" code, together with the "support by TA" code and its sub-codes, is a core element of the more general theme of "support." These codes and themes are all affective in nature, and so they directly address the first research question, which pertains to students' learning experience. They are important elements of yet higher-level themes; after establishing codes and themes regarding the promoters and inhibitors of conceptual understanding, the learning aspect of the peer and TA interactions, for example, can be related to the aforementioned support codes via the themes "peer scaffolding" and "TA scaffolding," which together comprise the highest-level theme of “scaffolding.”

These themes and codes have numerous other aspects that have yet to be discussed, but this overview of some of the main themes exemplifies how I approached coding in general and my way of thinking about the themes. The other important themes will be discussed in detail in Section 4.3.

4.2 Example Student Interview Analyses

Although we will discuss the general themes that emerged across all the interviews, it is worth first presenting a more fine-grained analysis of some specific students's pre- and post-interviews with regard to their learning experience and conceptual learning in the lab in order to show how a consistent interpretation of a student's perspectives can be formed, which will build upon the prior discussion of thematic structure and thus be helpful in framing the results of the interviews as a whole. In particular, we analyze in detail the pre- and post-interviews of a labatorial student followed by those of a traditional lab student.

4.2.1 An Insightful Labatorial Interview: Catherine

In the pre-interview, Catherine expressed her desire to care about physics, although she said that her difficulty with the subject and prior experiences had given her a negative perception for the subject upon entering PHYS 224. Additionally, as a biology major with minimal experience with physics, she felt that she had not been receiving the support necessary in PHYS 204 for understanding the material. Her prior lab experiences outside of physics have also reverberated this lack of support.

Having completed the first lab, Catherine stated that she did not feel isolated in tackling the physics in the lab, feeling that she and her teammates could support each other in figuring out problems. Although she considers herself introverted, she enjoyed the team aspect and views it as important, taking a perspective of camaraderie and stating that “[they're] all in it together." This shows that peer scaffolding was important for her learning as well as on an affective level. Furthermore, she stated that she felt "very supported by the TA." She felt comfortable asking him questions whenever she was unsure, and appreciated the checkpoints for how they allowed the TA to explicitly make sure she and her team understood. This shows that TA scaffolding in conjunction with scaffolding by the structure of the labatorials also played a large role in her learning experience in the lab.

Considering the first labatorial as a whole, Catherine expressed a sense of fulfillment upon completing the lab, mentioning that she enjoyed working hard in the lab and then not having to worry about lab reports until next time. She also expressed that the labatorial helped her understand how the concepts applied beyond the lecture, thereby giving her a positive outlook for the rest of the course and helping her perceive the relevance of the material:

> *It really helped me feel like, 'Ok, this is what I'm doing. This is why this is important. This is why this matters,' because otherwise it's just a bunch of numbers on a piece of paper.*

In the post-interview, Catherine's positive feelings about labatorials were confirmed and expanded upon. She said that she was pleased by how she and her team were committed to the course, always putting in full effort in the lab. Despite moments of non-understanding in the lab, Catherine expressed feeling a sense of unity as well as comfort among her teammates:

> *Working through, not feeling alone in your confusion or your knowledge, feeling like you had three minds working together toward a common understanding. And so much in life is like that anyway, that it could build those team interactions, and especially on things that you don't know about. And to feel like you're in a safe enough space that it's like, 'Hey, I actually don't know what I'm doing. Could you explain to me why you understand this?'*

To Catherine, the TA also played an important role in her experience of camaraderie in labatorials, stating that "he really elevated [the experience] and made [them] feel like [they] were supported in the class" and that it felt like a "team effort toward understanding." This helped her alleviate a form of stress by helping her not see herself as unintelligent in front of him when asking questions. This TA support combined with the low-pressure grading of labatorials also reduced her stress in the course since knowing that she would not be docked marks for minimal mistakes allowed her to focus on and enjoy the learning experience. Catherine said that the grading was fair, calling mistakes "springboards to learning." Notably, her feelings on this point during the lab reflected a core design element of labatorials:

> *Even if I don't 100% understand this right now, not only is he going to help me learn it, but the grade is going to reflect the learning I had after, not the confusion I had before.*

Catherine expressed many positive developments after taking the course. Although she expressed that physics is still a difficult subject for her, "this class helped it be a little less scary" to her, and she stated that "[she thinks] that [she feels] better about moving forward in physics in general." And despite coming from a background with minimal exposure to physics, she "ended up thinking about these things a lot more than [she] did before because now [she] has a kind of wondering," indicating a major transformation in perspective:

> *So my takeaway is that physics is doable, and it is interesting, and it is applied to daily life, and it's not just found in an amusement park or... It kind of has to do with waking up in the morning. Everything that you do follows these rules and these principles, and there is a reason why this learning is important.*

In summary, based on the pre- and post-interviews with Catherine, I concluded that her experiences of learning in labatorials were very positive. She expressed her satisfaction with the various support mechanisms in place in the course, which helped her enjoy the experience in the course and undergo positive affective transformations. Catherine's full pre- and post-interview transcripts can be found in Appendix I.

4.2.2 An Insightful Traditional Interview: Lauren

In the pre-interview, Lauren, who is now majoring in behavioural neuroscience and psychology, shares that while she was good at physics in high school and found some enjoyment in it, her recent negative experience in PHYS 204 affected her perception of physics for the worse. While she has not had a physics lab before, she draws from her experiences in her other university labs in reflecting upon PHYS 224.

Overall, Lauren's experiences in the first lab were fairly positive. She felt that she could always turn to her teammates or the TA for help whenever she needed help with something, always turning to her teammates first. However, she said that she generally likes working independently and "[being] in control of the things [they] do [and the] results [they] get." As such, while she would ask her teammates questions, it was usually in order to verify that her results were consistent or that she did not make any procedural errors. Namely, she expressed that despite being in a group, the team experience was "like checking with your partner, but still working individually." The TA interactions were similar, serving mostly to clarify the lab manual, explain how to do a certain step, or verify her numerical values. Nevertheless, she did indicate that she felt supported by the TA in this way, always being willing to help whenever she needed help.

This general mindset regarding interacting with others in the lab reflects a focus on error avoidance, i.e. obtaining the correct numerical results. This stems from a pressure to get a good grade in the lab, which necessitates obtaining an accurate enough result and low enough experimental error in order to receive full marks. This is why she "[hasn't] enjoyed very number-specific corrections that [she has] had" until now, appearing to be a source of stress in her labs. However, she stated that she enjoyed the first PHYS 224 lab because the instructions were detailed and straightforward to follow. They acted as a form of support to her in the sense that they helped her feel more confident that she was proceeding correctly. This corroborates her error-avoidance mindset, incurred by the grading structure of the lab. She also felt that having instructions helped her understand the material better:

A very recipe-like lab is very good, I think, since you won't miss something and you'll follow the steps very well, which helps you actually understand. And it helps you understand before the lab [since] you know what's happening step-by-step, rather then when it's just like a vague text where you have to pick out the steps for the procedure.

Nevertheless, when asked about her opinion on hypothetically including conceptual questions in labs, she expressed that she understands their value (despite thinking that they would be difficult for students) and thereby acknowledged a major risk of recipe-like labs:

It makes sure we understand what we're actually doing and not just blindly following the steps. It makes sure that I understand what I just did and that I can apply it somewhere where I need to think.

In the post-interview, she expands upon many of the same big ideas as well as addresses some other important aspects of traditional labs. Lauren reiterates that the TA was always willing to help and would often "[explain] things several times." Furthermore, whenever he did explain something, he did so very clearly, which helped her understand and created a friendly lab environment. Therefore, the TA did affectively have a large positive effect on her learning experience. However, his role was still mostly one of directly answering questions and clarifying the lab manual. Her peers played a similar role for her; she still generally preferred to work independently, not engaging with her peers beyond checking her results. While she did acknowledge that "working in a group can be helpful since they might know something that [she doesn't]," Lauren still did not seem to embrace a fully collaborative mindset, instead prioritizing the need to perform the experiment as correctly as possible.

She also expressed once again that the highly structured and detailed instructions of the labs were useful, further suggesting a memorization mindset:

The fact that it's really structured that way, it makes it more and more clear to see how... Not only clear to understand, but also at the same time, clear to remember *things for longer. Like now when I remember a lab, I'm going to remember the instructions.*

She added that this was further reinforced by the introductory theory explanation given by the TA at the beginning of each lab, which she said helped "[make] sure that everyone [knew] what [they were] doing." Nevertheless, these are both aspects of a verification-driven, recipe-based lab framework, and so it is not clear from her interview to what degree she engaged with the concepts during the lab. She did however express that writing the lab report discussions and doing the post-tests also played a large role in helping her absorb the key ideas, albeit these are not core elements of traditional labs themselves and take place after the lab is already over.

In addition to feeling that her overall understanding had improved after taking the course, she stated that she became more comfortable with performing the labs. Namely, once she "[realized] that there's a standard form they're going to look like," she became more comfortable, learning how to read and apply the instructions thoroughly. While her confidence in problem solving did not change as much, she stated that "[she knows] how to approach problems maybe a bit more now." These helped her feel more prepared for future lab courses. Lauren's full pre- and post-interview transcripts can be found in Appendix J.

4.3 Discussion of General Themes

In order to structure the discussion of the most poignant themes that emerged from the student interviews, we present a summary of the main themes in Table 4.1. The table is structured so as to compare and contrast the themes for labatorials and traditional labs with regard to students' learning experience and their conceptual learning, thereby allowing us to directly address the two primary research questions. Each theme will then be discussed in turn within the context of the pertinent sub-question.

Lab Type	Dimension of Research Questions Support Types	 Promoters of Learning	 Inhibitors of Learning
Labatorial	Peer scaffolding TA scaffolding Support due to low-stakes grading	Peer instruction TA scaffolding Labatorial structure Deeper engagement Real-world relevance	Peer over-dependence
Traditional	Peer support TA support Support due to explicit lab instructions	Peer interactions Intro theory explanation Real-world tangibility	Focus on error avoidance Recipe-like instructions Trying to understand after lab is already done

Table 4.1: Summary of themes from student interviews

4.3.1 The Student Learning Experience

Consider the first primary research question:

How can the learning experience differ between labatorials and traditional labs?

By "learning experience," we refer to students' collective affective experience in the lab. In particular, we are interested in investigating (1) the role of social interactions in the lab on students' experience, (2) what makes a lab course satisfying to students, (3) the effects that labs can have on students' perspectives on physics, and (4) the effects that labs can have on students' self-efficacy. After analyzing all the student interviews, we found that there is a unifying theme that can be used to mostly address these first two points. Therefore, we will begin by discussing this theme in detail for labatorials. Any other pertinent themes as well as the final two points will then be addressed before discussing the corresponding themes and addressing the research question in the context of traditional labs.

As introduced in Section 4.1.4, the idea of scaffolding is the highest-level theme that emerged from the labatorial student interviews. In particular, we discussed the affective element of scaffolding, which we referred to as "support." This theme of support also emerged from the traditional lab student interviews, and it is this theme and its sub-themes (as listed in the first column of Table 4.1) that are essential for addressing the first two aspects of our research question.

Labatorials

In labatorials, peer scaffolding or support was very important for creating a positive experience for students. As suggested in Catherine's post-interviews, many students perceived a sense of camaraderie in their teamwork. Beyond simply working together for the purpose of completing the lab, they found reassurance in knowing that they were going through similar struggles, helping them feel comfortable in sharing their doubts and relatively relaxed despite the challenges of the labatorials. When asked what was most special about the teamwork in labatorials, Derek stated that:

> *...it's the, I don't know if it's the right word, but the camaraderie of it. Because by myself in labs, if I get frustrated, I just feel so lost. You kind of feel like, 'Oh god, everyone else maybe gets it and I don't. What's wrong with me?' But when you're in a group it's more like, 'Oh, they don't understand either!' Or I know more about some things and they know more about some things. It's a lot more just relaxing, easier to just focus on the lab itself. And it's good to bounce off ideas and ask for help from your partners. So I'd say it's just a better experience, just less stressful like in terms of being by yourself.*

Jessica also strongly resonated with this idea, additionally commenting that the team's mutual dependence instills a sense of group accountability as individual accountability:

> *So when you're doing it with the misery of... Not that we were miserable, but if you're going through something that's challenging, it's much easier to do when you're with other people who are in the same boat and feeling the same stresses and things like that. And that they're rooting for you, because their success also depends on you, whereas in other labs it's like, 'Screw you, I'm just gonna do my own thing and you can go ahead and drown.'*

Interestingly, many interviewees indicated that this sense of camaraderie extended beyond their peer interactions to their interactions with the TA as well. Jessica stated that she "really liked, like not working with him, but how he came through" whenever they were struggling. Catherine additionally expressed that "the nice thing about [the lab] is that even with the TA [...] it felt like a team effort toward understanding." This suggests that the TA relationship was one of collaboration as much as one of guidance. Additionally, all students expressed that they felt that the TA was always very involved, regularly checking in on students. This helped Catherine "really feel supported by the TA."

The checkpoints in the labatorials in particular helped encourage students to share their doubts with the TA and feel supported by him, particularly due to the checkpoints being a core element of the lab itself. Namely, Emma expressed that:

> *...it's expected to ask questions, and it's expected to get the go-ahead before moving on. I like that so much more than just feeling like you're on your own if you don't understand it because you haven't prepared properly. I like having the help available, and that you're expected to use the resources and help of somebody there.*

The checkpoints additionally helped alleviate students' stress in the lab by helping them feel confident in progressing through the worksheet. As expressed in part by Stacy, this is because "if you made a mistake, the TA will tell you right away. You don't have to keep going and then figure out [later on] that you screwed up." However, being a relatively strong student in the course, Stacy also experienced a certain drawback with this form of TA scaffolding. Often reaching a checkpoint and already understanding the material quite well, she "[had] to wait for the TA to come" despite feeling ready to move on. Even so, she had no other qualms, understanding that "it's more for [her team] to make sure [they're] on the correct track and try and interact together."

Related to the TA's support was the support incurred by the grading scheme of the labatorials. Because the labatorial grading scheme shown in Appendix B is largely participation-based, students did not have to worry about making mistakes in the lab, which helped them feel more comfortable expressing their doubts. As expressed by Emma, "you're not being tested on if your assumption is right at all, but you're kind of asked to think about it beforehand and test it out. So there's no penalty in making a guess." Jessica also echoes this sentiment, indicating that not feeling any pressure due to grades also benefited her team, helping them interact more smoothly:

> *Here because we're kind of working together in a way that it's okay to ask questions, it's okay to not get the answer completely right, like as long as you understand why it's not right it's okay... Even that was more relaxed. It was easier to laugh and learn instead of feeling like crap because you're the teammate at the bottom or like, 'Okay, I have to drag these two.'*

As a result of the various forms of support present in labatorials, many students also underwent changes in their perspectives on and feelings toward physics. One common sentiment was that they felt more confident in not only problem solving, but in thinking about physics concepts in general. Derek thought that as the course progressed, his ability to answer the conceptual questions in the worksheet "improved overall, especially working with the group," adding that "then you learn yourself how to apply those concepts later in the lab." In addition, Quincy felt that he "got more confident" in precisely expressing his ideas about physics. Emma in particular, who had never taken a physics course before taking PHYS 204 and 224 that summer semester, also experienced considerable growth, stating that:

> *...near the end, since I was also keeping up with the theory portion of the other course, I got a little bit more confident and trusting of my instincts I guess, and I ended up making a few good points here and there. So as I got more comfortable with the material, I felt more comfortable participating in theoretical discussions.*

In addition to improvements in self-efficacy, Catherine, whose feelings about physics before taking PHYS 224 were bleak, underwent a major transformation in outlook, as discussed in Section 4.2.1. She now "[thinks] that [she] feels better about moving forward in physics in general," and she and Jessica both expressed that physics became less scary to them by the end of the course. Additionally, Stacy said that she came to better appreciate the importance of "not just accepting the equations as they are, but trying to figure out what each letter is doing, what each component is doing," suggesting a shift toward expert-like thinking.

In summary, students' interactions between both peers and the TA in labatorials served as a form of scaffolding that was affectively perceived as mechanisms of support. Although the constant scaffolding (in particular by the TA) could be seen as restrictive by stronger students, most students indicated that the overall lack of stress and sense of ease incurred by such support made for a more enjoyable overall learning experience, with many additionally undergoing positive shifts in their self-efficacy and their perspectives on physics. This is reinforced by several unprompted vocalizations of satisfaction by all the interviewees regarding the labatorial style. Such a positive lab experience also suggests benefits for students' conceptual learning, which will be thoroughly discussed following the discussion of the learning experience in traditional labs.

Traditional Labs

In traditional labs, the themes of peer support and TA support also reverberated across several interviews. However, the ways in which these types of support manifested in the lab and the role they played for students are different from the scaffolding of labatorials. In particular, the group aspect of the lab was not as fundamental a part of the lab experience as it was for labatorials. While there were labs where students needed to work in teams, the interviewees appeared to often not work in a very unified way. Students would at times proceed at a similar pace, but take their own approach to different steps of the experiment. While not an experience from PHYS 224, Catherine expressed that in many of her past non-physics labs that were run under a similar traditional format, although "[they had] all read the same lab [...], [they] kind of [came] at it with a different approach, or [they didn't] know who [was] going to do what." As such, the interviewees' group work experience was often more akin to working individually in their groups rather than collaboratively driven. As expressed by Lauren:

> *Since we didn't know our teammates very well, we decided to kind of go alone but share with them. So we'd do things on our own and share the process. So we'd do every step, write the results next to it, and then keep going, and then ask if everyone's ok with it.*

This is consistent with most interviewees expressing that they prefer depending only on themselves. Some students do appreciate the value of teamwork, with Amir in particular stating that "[he] would love working with a teammate and having a discussion and working together, so long as their work ethic and personality is aligned." However, Adrian said that "[he enjoys] working alone, and if [he has] questions, [he'll] go up to someone and ask them," and most of the interviewees were of this mindset. He and most of the other interviewees expressed that they would ask each other "[questions] like, 'How did you set this up?' or, 'What value did you get for this?' Just to make sure [they] were kind of on the same track in terms of what they were doing." The interviewees indicated that because interacting with peers is expected in a university setting, they were all comfortable doing so as needed, with Zion saying that "if one of [his] peers doesn't do something right, [he calls] it. If [he does] something wrong, they call it out." However, he also said regarding one of his teammates that he "[didn't] know if she was okay with [the experiment] or not since she wasn't really verbal about it or anything like that," and so other students may not have been as comfortable interacting with their peers as the interviewees. Nevertheless, through being able to verify each other's work, peers appear to serve as a source of support for many students.

The TA in the traditional labs served as another source of support for similar reasons. While students would ask their peers first if they were not sure about something, they felt comfortable asking the TA questions if they needed additional help. Evelyn said that "he seemed to be receptive to the sort of questions that [she] had," with Amir adding that "he's always willing to help [them] figure out things in a way that works for [them]." As with the questions peers would ask each other, the support provided by the TA typically involved clarifications or verifications. Furthermore, the TA would always answer students' questions very directly, "without being hesitant or questioning what's going on," as phrased by Zion.

While the students all appreciated this support by the TA, many also indicated that the TA was less directly involved throughout the lab, taking instead a more managerial approach. As described by Zion:

> *He was [...] going around, looking everywhere, seeing how students are doing and all that, but he wasn't interacting with the students. He was just looking, and if he saw something wrong, he would say, 'Well this is wrong, you should probably not do it this way, you should do it that way.' And that's it, that's all he did. He didn't really do much other than that.*

Students nevertheless appreciated this managerial TA style as it reassured them that they were proceeding correctly, with students including Lauren feeling that he was "always very involved and very helpful" in this regard. However, this type of managerial support is distinct from the TA support of labatorials, which is fundamentally tied to the way that the TA scaffolds students' learning experience.

As discussed for Lauren in Section 4.2.2, the main source of stress experienced by students in traditional labs was that incurred by grades. Because students want to score as well as possible, they want to follow the instructions as closely as possible and constantly verify that they are not making any mistakes. Adrian also added that "if your percent error is off by more than 10% [when checking in with the TA], you'd have to redo everything," expressing frustration at this possibility. As a result, the highly detailed nature of the lab instructions for the traditional lab experiments acted as a form of procedural support for the students; with instructions that are overall clear and easy to follow, there is a lower likelihood of making errors. Additionally, most of the interviewed traditional lab students were new to physics labs. As such, some expressed that having the detailed, step-by-step instructions helped explicate the basics of conduct in a physics, thereby providing a source of guidance to beginners in physics. In particular, Evelyn stated that:

> *...for the material that we're doing, it's sort of the only way that makes sense. Not that I know any other teaching methods, but it makes a lot of sense to have it that way just because for some people, maybe it is the first time they're in a scientific lab for these things. So it does make sense to sort of become acquainted with physics labs and labs in general. It does make sense to sort of spoon feed the material, or the experiment, I mean.*

However, Oscar felt that there was a lack of guidance at times with regard to both the TA and the lab manual. Namely, he expressed that:

> *There should be much much more guidance, much much more. There should be like, 'We should do that and that and that, and if you have any questions just ask more and more,' you know? More guidance in, even the manual should have much more guidance in the labs.*

Catherine's comments about her past lab experiences also complement Oscar's frustration, adding that "if you don't know to ask the questions leading up to that moment, you're docked a bunch of points, and you don't really understand what you're doing because nobody's guiding you." Ultimately, we can see that many students, including Evelyn, feel that "to get the result that you want, [...] you do need that sort of support in terms of the procedure and the instructions." Therefore, although most of the interviewees appeared to be satisfied with the support present in the labs since they could get help whenever they needed it and felt at ease doing so, the need to get a good grade in the lab may still be a large motivator and source of stress for some students. The impact that this mindset may be having on their learning will be discussed in the following subsection.

Regardless of the stress, some students did indicate positive changes with regard to self-efficacy. Although no students commented on their problem-solving ability, some students did express improvements in confidence in different ways. Adrian felt that the post-tests "helped in terms of feeling a little bit more confidence, or like relating [the experiments] back to [the concepts]"; Lauren said that seeing the theory applied in the lab helped "bring [her] back to reality and see how it is, remembering that [real-world] connection"; Oscar appears to have become more comfortable with evidence-based argumentation, saying that "you need to really really know what you're talking about" if you want to argue something; and Zion, who was a frequent source of guidance for many of his peers (in particular during the individual labs), indicated an improvement in "[his] confidence in [his] own thinking and all that [...] because [he] was on [his] own and thinking on [his] own" and "wouldn't really ask much questions to anyone except for to the TA." Adrian also indicated that his outlook on physics changed since taking the course, expressing that "physics is everywhere. Like it exists in everything that we do, [...] it exists outside of the lab as well." On the other hand, some students like Evelyn, for example, were more apathetic regarding the impact of the course, sharing that the labs were "a little bit boring" and that "as much as [she] wanted to have a takeaway from it... It was [just] the information that it was supposed to give [her]."

In summary, while the interviewees all had different takeaways from the course, many were not affective in nature, and only one student referred to their general outlook on physics. With the exception of Adrian, who expressed that the lab "wasn't as bad as [he] thought it was going to be," none of the interviewees vocalized satisfaction with the course without the prompt of a question. Nevertheless, there were certain forms of support present in traditional labs, namely the procedural support provided by the lab manual and that provided by peers and the TA in acting as a resource for students to voice their doubts and verify their work. These often helped students partially cope with the stress in the lab and thus feel more at ease, although some students felt that the lab experience was not scaffolded enough.

4.3.2 Conceptual Learning in the Lab

Second primary research question:

In what ways do labatorials and traditional labs promote the development of conceptual understanding?

In examining the student interviews, we are interested in (1) the general promoters and inhibitors of conceptual learning in each type of lab as well as (2) how students get engaged with the concepts in the lab. While the learning outcomes are also of interest, these will be examined in detail in Chapter 5. As such, we focus on conceptual learning in general for the remainder of this section, structuring the discussion according to the themes listed in Table 4.1 as with the first research question. Furthermore, most of the main themes pertaining to the second research question are directly related to the constructivist idea of scaffolding (the highest-level theme across the labatorial student interviews), and so we will discuss those themes from the lens of theoretical framework developed in Chapter 2.

Labatorials

For labatorial students, the forms of scaffolding inherent to the design of labatorials (see Section 2.2) all played a significant role in students' conceptual growth. Consistent with students' comments regarding their affective learning experience, peer instruction was an important mechanism to assist students' learning. This occurs in part because of the reciprocal nature of the process. In particular, Derek noted that he and his teammates did not simply provide each other with the solution to a problem or the answer to a question, but rather frequently engaged in discussion, saying that:

> *It wasn't just like, 'Here is the equation that you use for this. Solve for this.' [...] That's what was really helpful for the groups. It's that back and forth talking about which direction we should take it.*

As such, the students in labatorials were deeply cognitively engaged with the concepts of the lab, discussing until they all came to the same answer. This type of collaboration was also encouraged by the design of the labatorial questions themselves, which were challenging enough that students usually needed to collaborate if they wanted to proceed. Therefore, students became more engaged in the problem solving process while simultaneously developing their ability to think independently.

The highly supportive nature of the teamwork in labatorials also encouraged more meaningful discussion between peers, often strengthened by the heterogeneity of the teams. Catherine perceived both of these benefits, saying that:

> *To feel like you're in a safe enough space that it's like, 'Hey, I actually don't know what I'm doing. Could you explain to me why you understand this?' We all had moments like that, where one of us was the one who knew more, and the other was the one who knew less. We were even, but we all came out more knowledgeable.*

The proficiency differences inherent in heterogenous grouping schemes implicate both a strength and a weakness of heavily collaborative learning frameworks. As stated by Jessica, "it's good to learn [in a team] since when someone has a deeper level of knowledge, it's easier for them to teach others." Furthermore, because students need to "understand how to tackle explaining [...] at different levels," as phrased by Stacy, students at all levels also learn through act of teaching. In particular, Emma, a weaker student, expressed that "[they] started to understand a little bit better each other's learning styles, so [they] adapted to each other better," feeling that her teammates "were very very patient with [her]." However, while Emma put in a great deal of effort despite struggling in the course, there is nevertheless the risk of the weaker students in the group over-depending on the stronger students for proceeding through the lab. Aside from the case where a student is unwilling to cooperate, which can occur in any type of lab, a student may not have sufficient time to ponder on the concepts, even when they are explained by their peers. This pace-matching of students' work is inherent to the structure of the labatorials, imposed via the checkpoints, and so the associated difficulty may be mitigated by reducing the amount of content in the worksheet.

Nevertheless, the labatorial worksheet structure in conjunction with the TA's guidance served as an important form of scaffolding for helping students learn. In particular, the strategic interventions of the TA at the checkpoints helped guide students to an understanding of the concepts while ensuring that all students came to the same conclusion and did not build on misconceptions. As expressed by Catherine:

> *I'm seeing step-by-step kind of what's happening, and the fact that [the TA] would come over and check in with us each time, and kind of affirm, 'Yes, you're doing this right,' or, 'Actually, why don't we think about it this way instead?' is very helpful. It makes me feel like, 'Yeah ok, this makes a lot of sense.'*

The overall design of the worksheet, which aimed to build up students' understanding of the concepts question-by-question, also helped students understand. Jessica "felt how the manual was structured and how it progressed throughout," which helped her gradually construct her understanding. Stacy also "really liked the way that [the worksheets] followed teaching something that was very important, but without really [saying], 'That's just how it works.' It was kind of like, 'Figure it out by yourself how it works,'" which helped her fully grasp the concepts by the end of the lab.

This was also enhanced by the inclusion of explicit conceptual questions. Stacy stated that they "[made] sure you were actually thinking, critically thinking about things and not just accepting [them]" as well as "[helped] set up the brain to keep going [through the worksheet]." In addition, many students including Jessica felt that the questions "helped [them] later for the actual experiment. The conceptual problems changed how [they] were actually looking at the experiment [compared to] when [they had] just read [the instructions]." Emma indicated that such a lab format, which allows students to tackle concepts in tandem with the hands-on work rather than try and figure things out after the lab, was helpful for her conceptual development with regard to dealing with misconceptions:

> *It's because it's hands-on and it's also theory, and actual data gathering at the same time. So you have to apply what you know and what you're learning reciprocally to each other. So you have kind of two chances to correct what you wrongly thought, I guess.*

Many students also indicated that the inclusion of conceptual questions helped with problem solving and understanding the mathematical formalism associated to the concepts. Therefore, the conceptual questions played a large role in deepening students' engagement with the concepts as well as the experiments of the labs, encouraging them to not passively proceed without understanding.

The prediction questions of the labatorials were also important for developing students' conceptual understanding. According to Quincy:

> *All the predictions, they just helped you write out and then discuss with your teammates about your own ideas, about that event, about that problem. And then when you go through the lab, they start to change because not exactly everything you think is right. After you go through the lab, you go through all the experiments and all the work, and you will find the final result of that problem. And then you will understand that, 'Ok, I was thinking wrong at first, and now I need to think in that way for things to make more sense.'*

Quincy's description of this learning process in the lab, which most of the interviewees expressed in one form or another, is exactly consistent with the elicit-confront-resolve sequence for tackling misconceptions described by McDermott et al. (1995) in the context of the Physics by Inquiry curriculum on which the approach of labatorials is intrinsically based; the worksheet elicits students' pre-understanding of the concept, allows students to confront their misconception(s) through the experiment, and then resolve the conflict(s) in their understanding through discussion. It is the extensive scaffolding inherent in labatorials that allows this development of conceptual understanding to occur.

In addition to the scaffolding elements of the labatorials, many students perceived a sense of relevance in the material due to the connections made with the real world. In particular, Emma stated that in addition to "making sure you get the concepts," the experiments, which were posed as real-world problems, were "relatable to other areas that you're gonna study in the future or presently," making the experience "much more satisfying" and motivating for students. In addition, making such explicit connections had a reciprocal benefit for students' learning; not only was it "very helpful for understanding the lab cause you kind of like apply that external knowledge to the actual like, the mechanisms within the lab," as phrased by Derek, but using "those kinds of analogies to bring it back to [students'] real [lives made it] really nice for [them] to kind of figure out what's going on in a way that [made] sense to [their brains], not just [as] very far away physics concepts," as phrased by Stacy.

In summary, the integration of diverse mechanisms of scaffolding in labatorials provided numerous benefits for students' conceptual development. Although the risk of over-depending on one's peers exists due to the extensively collaborative nature of labatorials, peer-instruction was nevertheless a powerful means to assist learning. The additional affective benefits of such scaffolding (as well as those due the overall absence of pressure due to grading) also allowed students to focus more on their learning in the lab, which, in conjunction with the inherently scaffolded worksheet structure, improved their overall engagement with their peers and the concepts in the lab. Furthermore, although labatorials emphasize understanding concepts over developing experimental skills in this way by design, such an approach also proved to be beneficial to students' understanding of the experiments. These benefits were further enhanced by the explicit connections of the lab content to the real world. By virtue of these pedagogical advantages and the aforementioned forms of support inherent to the labatorial approach, all of the interviewees "think very highly of it overall" and expressed a preference for labatorials over their past traditional labs, as with Emma; Quincy stated that he "[thinks they] can learn more from it than the traditional [labs]," and Catherine said that she "would choose this over a traditional lab every time."

Traditional Labs

In traditional labs, there was also some scaffolding present due to the interactions between peers, which had a positive impact on their learning. However, such scaffolding was limited in scope. As previously mentioned, these interactions typically involved students checking each other's results. Furthermore, Adrian, among others, described a divide-and-conquer style of group work wherein students would subdivide tasks and assimilate their progress for the sake of efficiency. Namely, "[his peer] did one thing, [and he] did another thing. [They] kind of just worked together" without working together on each mental task. Therefore, the group work in traditional labs was typically not very collaborative. Nevertheless, students did also at times explain things to struggling peers. Even during the individual labs, Adrian stated that he "would just ask [his] neighbour doing the same experiment and then see if they're having the same issue, or if they could give [him] an explanation or help [him] out," and Amir said that "if there [were] enough people [with the same issue] and one person says, 'I don't have any experience with this,' then [they created] kind of like a little side gig where, 'Let me show you how,' or 'Is anyone confused with this?'"

Zion indicated that he understands the conceptual benefit of discussion in the lab. He and his teammates would "communicate to one another. [They would] say, 'Why is this happening? Why is that happening?' so [they] understand what's going on. Because sometimes, even following the procedure, it doesn't mean [they] understand the results." He also indicates that there is the potential for very fruitful collaboration in traditional labs, albeit it often does not occur unless the students take the initiative:

> *If, for instance, there's a problem going on and somebody asks this question and goes against the idea of what's going on like, 'I don't think this is okay to do, maybe we should do it another way,' like this kind of, not attack, but confrontation about the idea is beneficial for the team, beneficial for the experiment, and that would be ideal.*

However, most student responses indicate that the discussions that took place between students largely did not exceed the procedural aspects of the lab. This may be due in part to traditional lab students' focus on error avoidance, as previously introduced, which may be acting as an inhibitor to conceptual growth.

While experimental accuracy and precision are important from an experimental standpoint, it can lead students to focus solely on following the lab instructions as closely as possible and not think through the core conceptual ideas as they work through the lab. Furthermore, because there is a grade associated to these criteria, there exists a pressure due to grades that can cause students to not be focused on the learning in the lab. There are often students like Zion who typically do care about understanding what they are doing in the lab, including understanding the concepts. Oscar, for example, felt that avoiding experimental errors was also important for conceptual understanding since "if you do it in a wrong way, you'll understand a really really wrong principle." However, the recipe-like, correctness-focused lab structure was generally less conducive to conceptual learning in the lab, which is well-explicated through Zion's comment:

> *You would have to kind of do a little extra work if you really want to understand it. And if you don't, then you're going to go in, you're going to follow a bunch of steps, [...] and then that's it.*

A related inhibitor to conceptual learning is that because students may go through the motions of the experiment without thinking through the concepts deeply, they may not address any conceptual difficulties while in the lab. In most traditional lab courses, where lab reports are written at home, submitted a week later, and then returned the following week, students will often only begin trying to understand the ideas of the lab after the lab has already ended. Additionally, they only receive feedback on their understanding when their report is returned to them, which limits the possibility of difficulties being addressed while the ideas are still fresh as well as that of productive feedback being given by the TA. Although the lab reports for this traditional lab course were written at the end of class, many labatorial interviewees addressed such issues with regard to their prior traditional lab experiences. Catherine, for example, expressed that you may not thoroughly understand what is going on during the lab, and so you "just have to figure out what you did and why you did what you did since you don't know going into it why you were doing half the steps." Stacy additionally compared the value of thinking through the concepts in the lab to that of doing so at home, further illustrating why students likely will not confront their misconceptions through traditional labs:

> *I think [traditional labs are] less about thinking, and more about if you can follow steps. [...] Sometimes we just try to rush and do whatever we can to get results, and then we get home and deal with it. In class, you have the opportunity to talk with your lab mates, and the TA trying to figure out [a problem] on the spot, and sometimes that's more valuable than trying to Google it once you get home.*

Nevertheless, one element of the lab that played a role in helping students begin thinking more about the concepts was the TA's introductory theory explanation for each lab. This explanation would summarize all the essential theory for the experiment as well as the core experimental steps and apparatuses. Adrian expressed that "having the little discussion at the beginning, clarifying and kind of information" helped prime his mind before "seeing [the experiment] live and in action and actually performing it." Evelyn also added that it "[helped] to know sort of what the actual essence [was] if there's something [she] didn't understand and things like that." Therefore, the introductory theory explanation can serve as a base for students to more deeply understand the experiment and the related concepts. However, because it does not directly address common misconceptions, it will not help students overcome cognitive dissonance.

Moreover, Amir expressed that the learning experience in the lab was nevertheless not scaffolded enough overall. In particular, the recipe-like lab instructions of the labs made him unmotivated to learn:

> *I found when I started off, 'Ok just memorize everything in the lab manual. Read it, memorize it, memorize it.' And then I just stopped kind of... Like I'd read it, take a few notes, make sure I see [the basics]. But that doesn't really encourage, you know? It kind of just makes you... Makes me go complacent, apathetic.*

This sentiment extended to the lab reports for the course, saying that he “found [the format] really formulaic. And [he understood] where it was kind of like, ‘Data. Conclusion. Error. Discussion.’ But [he thinks] if there was a way where it started off and tapered,” he would be able to learn more from it. “[He’s] not saying [they] should be spoon-fed through it, but [he’s] saying there could be a lot more of, ‘Do you understand this concept?’ [Talking] about it and [asking] very specific questions.” Additionally, “[he thinks] if it were more kind of like a guided approach in conjunction with the lectures, [the lab] would be solid.” These comments exactly reflect the type of scaffolding present in labatorials in an ideal situation, alhough labatorials do not require lab reports.

Nevertheless, many students found value in performing the actual experiments. In particular, applying the concepts in a hands-on way through the experiment helped students make the connection between theory and reality. However, rather than having relevance to one’s life experiences, the connection was purely in terms of tangibility of the concepts, which is a given in any type of lab and may not help with conceptual learning if the student has misconceptions. Some students additionally expressed that this connection to the real world helped them become aware of and overcome misconceptions that they had. For example, Oscar said that “you’d think that the mass of the object makes a difference in the period [of a pendulum], but it doesn’t,” which he realized upon performing the associated experiment. In other words, the experiment “changed [his] understanding with the proof.” Some students like Evelyn attributed this benefit to the hands-on aspect, which “sort of [helped] with learning the material,” and Lauren said that being “in contact with these experiments [...] [helped her] solidify what [she] actually just learned and what [she] learned before [in the lectures],” although there may still have been misconceptions embedded within that prior understanding since the traditional experiments simply promote the verification of equations. Lauren additionally attributed this to a type of seeing-is-believing effect:

> *The fact that not only would we see the formula, but we also see it in real life. That not only proves it even more, but makes you remember things more just*

cause you saw it in an experiment, and you saw how it happens. So it makes you not only fix your knowledge from before, but also make it really stick.

Note that the hands-on aspect, which emphasizes when students actually, touch, manipulate, or play with the equipment, should be distinguished from the seeing-is-believing aspect, which emphasizes the act of students seeing a phenomenon with their own eyes to reinforce their understanding or intuition. Both of these helped students feel a sense of reality in the physics concepts by increasing their tangibility, although it is not clear to what degree these can help students overcome deep misconceptions.

In summary, while peer interactions in traditional labs played a role in students' learning in the lab, the style of cooperation was typically not collaborative enough to promote deeper learning. The labs themselves did not emphasize learning concepts, although the theory explanation at the beginning of each lab helped direct students' thinking. Furthermore, both the hands-on and visual aspects of performing experiments helped solidify concepts for many students as well as helped them see connections with the real world. Nevertheless, one student in particular felt that the overall lab experience was not scaffolded enough, with the recipe-like instructions of the lab not encouraging students to thoroughly think through the ideas of the lab. This, combined with the focus on error avoidance induced by the pressure due to grades and further encouraged by the recipe format, made the traditional labs generally less conducive to conceptual learning.

Chapter 5

Analysis of Student Assessments

In this chapter, we wish to examine the various quantitative data collected throughout the study with regards to students' conceptual understanding. Namely, in addition to examining the general features of labatorials and traditional labs, i.e. students' affective experience in each type of lab and the way each type of lab promotes the development of conceptual understanding, we will now consider the content-specific learning objectives of the course and compare the performance of each group.

To do so, we will first discuss our approach to statistically analyzing the data. Once the key statistical tests and their realms of validity are established, we will continue by confirming the initial equivalence of the labatorial and traditional lab groups, from which point their performance can be meaningfully compared along various dimensions. In order to enrich this analysis, which may at times be difficult to interpret due to the small sample size ($N_{laba} = 30, N_{trad} = 24$), we will also qualitatively examine key questions from students' examinations (the selection criteria will be discussed in Section 5.5.1) to compare students' conceptual understanding between the two groups. Note that the statistical tests utilized in this chapter are performed using the SPSS statistical software.

5.1 Statistical Tests Utilized

5.1.1 Student's t-test for Comparing Means

In general, we are most interested in comparing means between labatorials and traditional labs, i.e. the scores students obtained on individual questions or entire assessments. Due to its statistical power, the statistical test most often used for the comparison of means of a continuous variable is Student's independent samples t-test (Boneau, 1960), which tests the null hypothesis that the means of two groups are equal. We thus implement it as the starting point of our analysis at the 95% confidence (i.e. $\alpha = 0.05$) level. Because this is a parametric test, there are certain assumptions that must be met for its results to be interpreted with confidence and accuracy. In particular, the t-test imposes the following assumptions:

1. The observations of the groups being compared are independent of each other.

2. The data should be approximately normally distributed.

3. Homogeneity of variance is satisfied, i.e. the standard deviations of the samples are approximately equal.

As we will see in the following sections, the variances of the samples may not always be equal. In this case, Welch's t-test may be used instead, which has power lower than albeit comparable to that of Student's t-test and typically yields nearly equivalent p-values (Ruxton, 2006). Such a case of unequal variances, which is detected when running a t-test in SPSS, will be explicitly indicated by writing "UEV" beneath the tabulated p-value.

More notably, the data often deviates from a normal distribution, which lowers the reliability of the t-test when used on its own. This difficulty is worsened by the relatively small size of our sample since $N_{laba}, N_{trad} \leq 30$. Therefore, the appropriateness of the t-test can be verified using the Shapiro-Wilk test for normality (Razali, Wah, et al., 2011), which tests the null hypothesis that a distribution is normal. However, even if normality or some other assumption is violated to a degree, interpreting the p-value reliably is mostly problematic when it is near 0.05, the threshold for significance. The same holds true for other tests with such a threshold. As such, we will need to consider other modes of analysis as well as use our own judgement to draw meaningful conclusions for such edge cases.

5.1.2 Measuring Correlation With ANOVA

In addition to comparing various mean scores of the labatorials and traditional lab groups in and of themselves, we also need to test if there exists any underlying correlations between the scores obtained in each group and other key categorical variables such as gender (see Section 5.3). To do this, we utilize an ANOVA. In particular, we consider the η^2 statistic (Richardson, 2011). The statistic is a measure of the proportion of the variance in the data that can be attributed to one or more "effects." As such, η^2 acts as a measure of the effect size, which allows us to compare the effects of different grouping variables on the dependent variable, i.e. any given student score. While there are different conventions for classifying the effect size of a grouping variable given an η^2 value, we will adopt that of Richardson (2011): $\eta^2 > 0.0099$ is a small effect size, $\eta^2 > 0.0588$ is a medium effect size, and $\eta^2 > 0.1379$ is a large effect size. The ANOVA η^2 value can then be used as an indirect means of detecting a significant difference between the means of two groups in conjunction with the significance result of a t-test.

As with Student's t-test, certain assumptions must hold in order for an η^2 value to be meaningfully interpreted, beyond the continuous scale of the dependent variable:

1. The samples are independent.
2. The residuals of the data are normally distributed.
3. Homogeneity of variance is satisfied.

As previously discussed, not all scores (and thus not all residuals) are normally distributed, which can be problematic for parametric statistical tests. An ANOVA is no exception, and so care must be taken in interpreting the η^2 value. However, using this test in conjunction with other tests and gaining an approximate quantitative understanding of the data will be sufficient for our purposes, as we will complement the quantitative analysis with a qualitative analysis in Section 5.5.2.

While the η^2 statistic works well in conjunction with a t-test p-value, we cannot rely on an ANOVA or a t-test if the distribution of the data is excessively non-normal, which does at times occur in our data. Namely, due to the way that some questions were graded, their score distributions are highly bimodal, making these tests inappropriate. This could have been due either to a very coarse grading scheme (which would additionally violate the necessity for a continuous variable) or due to the essentially all-or-nothing nature of the question, making partial marks unlikely to be obtained. For these cases, we need to adopt a different statistical test. To address the nearly bimodal distributions described, we utilize Fisher's exact test.

5.1.3 Fisher's Exact Test for Bimodal Distributions

For analyzing situations with two possible outcomes for both the independent and dependent variables, one can use Fisher's exact test (Agresti et al., 1992). Because such a situation can be described using a 2×2 contingency table, Fisher's exact test is used in place of a χ^2 test. Moreover, it is used in cases where the sample size is small. It tests the probability of getting a table that is as diagonal as the one sampled due to random chance; if the table is heavily diagonal, then there is a strong correlation between the independent and dependent variable. In our case, this would means that there is a significant difference in outcome on a given question depending on the type of lab.

Because the majority of the score distributions under consideration are not exactly bimodal (i.e. the scores are not all 0 or 100, but rather there are some intermediate scores), the requirement of a binary dependent variable is not typically satisfied for our data. As such, we must first binarize the data. For the majority of questions, if a student did not answer a question completely correctly (i.e. did not receive a score of 1/1), then we set their score to

0. However, if a score of 0.9/1 was only assigned due to a minor error that does not imply that they did not understand the concept (e.g. a calculation error), then we set this score to 1. In both cases, students can only receive a score 1 or 0 on a question for the purpose of this analysis. By virtue of this binning procedure, Fisher's exact test can also be used as an alternative (albeit approximate) way of testing for a significant difference between two groups regardless of the distribution, although we will take this into consideration only when appropriate, i.e. for the question-by-question analysis of students' scores in Section 5.5.1.

5.1.4 Mann-Whitney U Test for Corroborating Parametric Tests

As one final quantitative means of solidifying the upcoming analyses, which we wish to base on the aforementioned parametric statistical tests whenever possible due to their relatively high power, we consider the Mann-Whitney U test or Wilcoxon rank sum test (McKnight & Najab, 2010). For an ordinal dependent variable, this tests the null hypothesis that a randomly selected value from one population will be greater than or less than one selected from a second population. This allows us to investigate whether or not the distributions of two independent samples are equal.

This test is often used as the non-parametric equivalent of the t-test since, unlike the t-test, it does not require that the data is normally distributed. However, because it only allows one to determine whether or not the samples come from the same distribution unless the distributions have the same shape (which will generally not be the case for us), it is less powerful than the t-test, which explicitly addresses whether or not the difference in their means is significant. Nevertheless, if a t-test result is to be meaningfully interpretable, then we would expect the Mann-Whitney U test result to be consistent with this result, in particular in the significant case.

5.2 Establishing Equivalence of the Groups

As the first step in our analysis, we must establish the equivalence of the labatorial group and the traditional lab group. Namely, because we are not conducting pre-post testing, instead only comparing the performance of various assessments, the two groups must be equivalent at the start of the course in order for any differences detected later on to be meaningful.

To do so, we analyze the results of the FCI-based pre-test administered at the start of the course, as described in Section 3.4.2. The pre-test was graded out of six points, with only integer scores being possible due to the multiple choice nature of the FCI questions. While this scale is evidently not continuous, we use the t-test as a starting point. The descriptive statistics for each group are shown in Table 5.1, and the score distribution of each group is shown in Figure 5.1.

	N	Mean	Standard Deviation
Labatorial	30	2.130	1.676
Traditional	24	2.290	1.459

Table 5.1: Descriptive statistics for labatorial and traditional lab pre-test scores

Applying the Shapiro-Wilk test for normality to each distribution yields $p_{laba} = 0.017$ and $p_{trad} = 0.028$. Because these are less than 0.05, we reject the null hypothesis and conclude that the pre-test score distributions are not normal. Therefore, a t-test or ANOVA is individually insufficient. A t-test yields $p = 0.717$, which means we cannot reject the null hypothesis that the means are different, and an ANOVA yields $\eta^2 = 0.003$, which indicates a small effect on the pre-test score due to the lab type. However, a Mann-Whitney U test yields $p = 0.703$, which means that we cannot reject the null hypothesis that the distributions are the same. Considering that the means of the two groups are similar and the standard deviations are large, it is reasonable to conclude from the t-test and Mann-Whitney U test that the two groups did not perform differently at a statistically significant level. Although η^2 indicates a

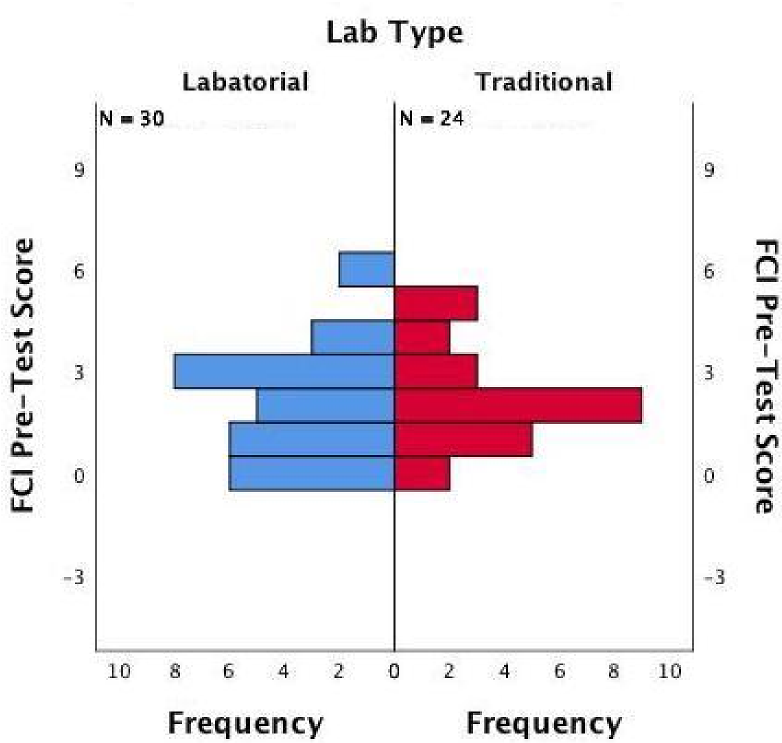

Figure 5.1: Labatorial and traditional lab pre-test score distributions

slight effect, this may simply be due to the differing maxima of each distribution. Therefore, we proceed under the premise that the two groups are equivalent.

5.3 Correlations With Gender and Major

With equivalence established, we now wish to verify whether or not there exist any correlations between relevant categorical data about the students and their final exam scores, the main measure we possess on their performance in the course. In particular, we are interested in students' gender and their major, as these are often points of interest in educational studies and are important to forming a meaningful interpretation of the overall results. For simplicity of analysis, we choose a binary gender classification, i.e. male and female. However, the notion of "major" should be elaborated upon.

When one considers the effect of major in a study, one must consider exactly what one means by "major" and why it is important for one's analysis. For example, one could simply classify major according to science and non-science, which could be meaningful since non-science majors may not always enjoy physics as much as science majors or be as proficient in it. However, we believe that this categorization alone is insufficient for two reasons. The first reason is practical. In the summer semester of PHYS 224, there were only seven non-science majors while there were 45 science majors (two students could not be classified due to being in the "independent studies" program, and so they were excluded from this correlation analysis); such an imbalance in sample sizes would render the statistics largely uninterpretable.

The second and arguably more important reason involves the relevance of one's major to one's success in physics. What many people often consider a difference between physics and other sciences is the amount of math required, which is often strongly tied to their performance in physics courses. For the purposes of this study, we deem this a more relevant categorization, and so we also check for a correlation between the final exam score and whether or not a given major is math-heavy. (We consider physics, chemistry, computer science, etc. math-heavy while we consider biology, exercise science, psychology, etc. not math-heavy.) The key descriptive statistics associated to each of the three grouping variables under consideration along with the appropriate statistical test results are summarized in Table 5.2. We consider each variable in turn.

		N	Mean	Standard Deviation	Shapiro-Wilk p-value	t-test p-value	Labatorial η^2 Value	Traditional η^2 Value
Gender	M	27	70.8	16.1	0.172	0.785	0.001	0.001
	F	27	69.6	16.3	0.192			
Major	Non-Science	7	59.8	14.1	0.778	0.076	0.039	0.114
	Science	45	71.6	16.2	0.010			
Math	Not Math-Heavy	31	64.6	16.7	0.129	0.004	0.324	0.044
	Math-Heavy	17	78.7	12.6	0.100			

Table 5.2: Descriptive statistics and test results for correlations with the final exam score

Focusing our attention to the gender row of the table, we see that neither the male nor the female distribution can be said to be non-normal, and so a t-test can be safely used here. A t-test comparing the mean male score and the mean female score yields $p = 0.785$, and so we cannot say that there is a difference in performance between males and females on the final exam. Upon examination of the grade distributions of males and females in both labatorials and traditional labs in Figure 5.2, it is clear that there is no significant difference between genders in either lab type. Performing an ANOVA for each lab type, which yields $\eta^2 = 0.001$ for both types, further supports the conclusion that there is a negligible effect of one's gender on one's performance on the final exam for both lab types. Note that a Mann-Whitney U test was not required since a t-test could be used reliably here.

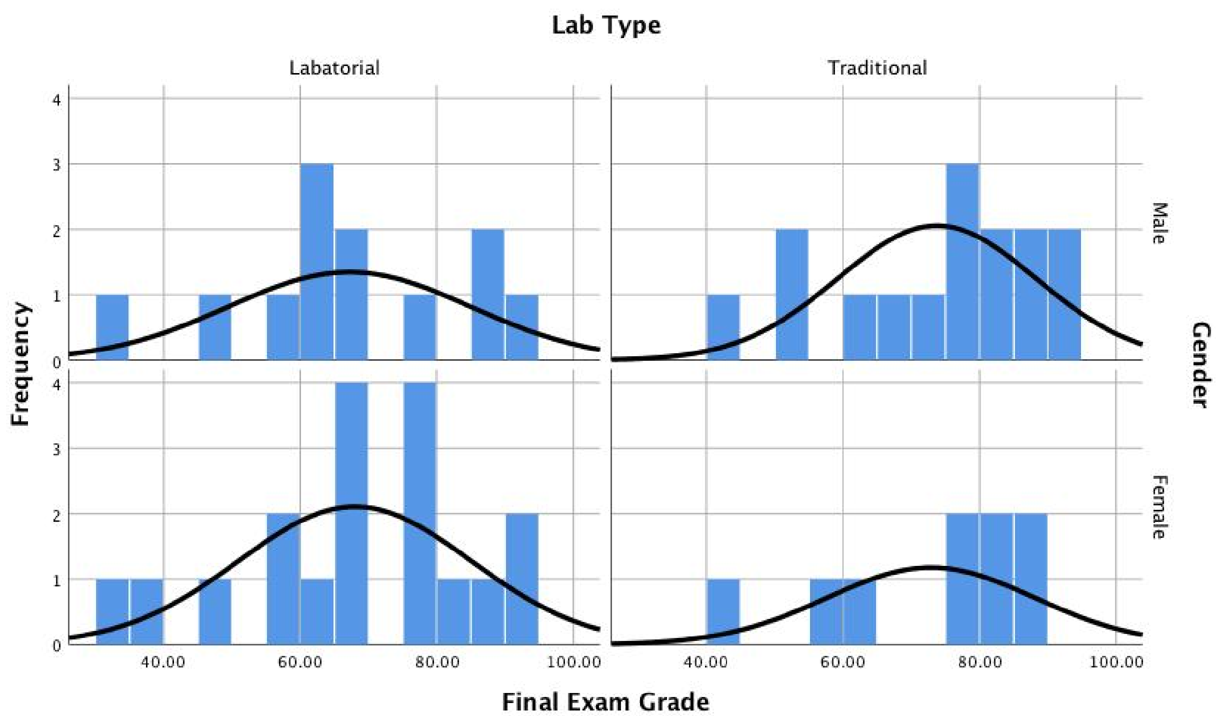

Figure 5.2: Final exam grade distribution as a function of gender for labatorials and traditional labs

As discussed, checking for a correlation between one's major and final exam grade is not meaningful here due to the imbalance in sample sizes. While $\eta^2 = 0.114$ for the traditional group would normally indicate a medium effect size due to major, this result is based on less than seven students, and so we shall not perform any further analysis of this row.

On the other hand, the final row of Table 5.2 reveals that there is a strong dependence

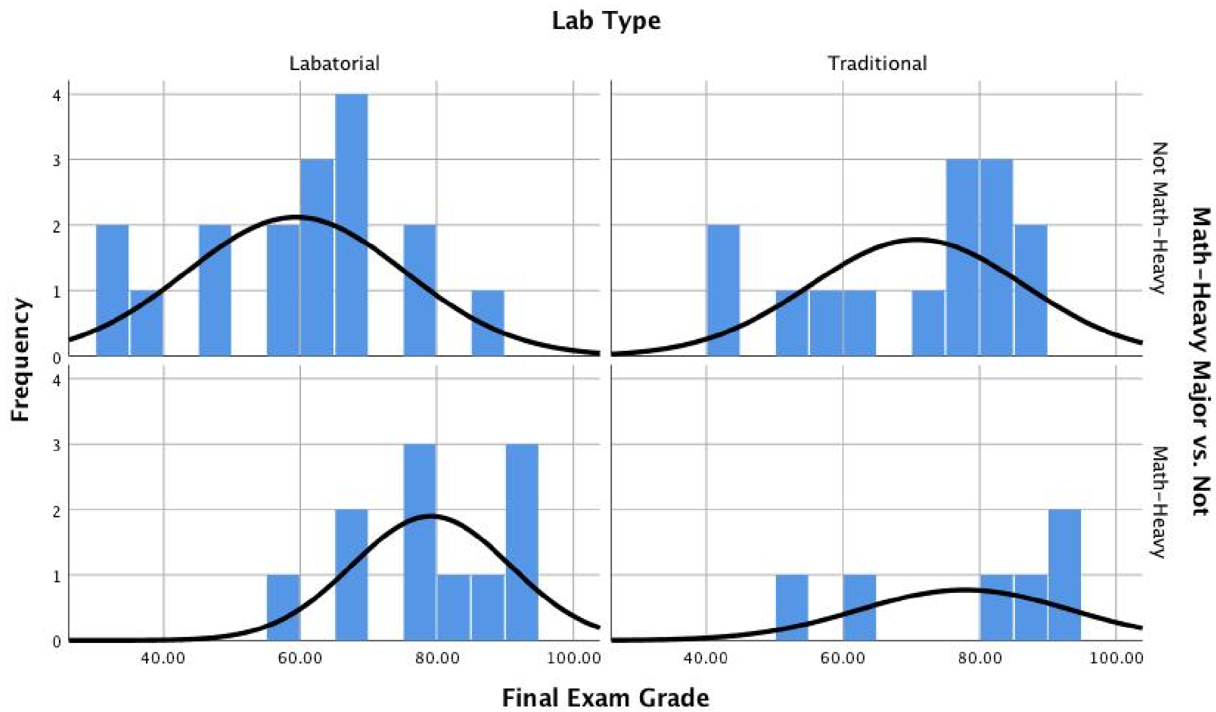

Figure 5.3: Final exam grade distribution as a function of the math-heaviness of a student's major for labatorials and traditional labs

of one's performance on the final exam on the math-heaviness of one's major. The t-test comparing the mean scores of students from math-heavy majors and those not yields $p = 0.004$, which can be used to confidently (due the non-significant Shapiro-Wilk test p-values) reject the null hypothesis that the means are equal. Note that this effect is more severe in the labatorial sections; $\eta^2 = 0.324$ for the labatorial group indicates a very large effect size, and $\eta^2 = 0.044$ for the traditional group indicates a small effect size. Examining Figure 5.3, we see that the labatorial group students from math-heavy majors performed significantly better on average than those who were not, while the difference was small for the traditional lab students (although there may not have been enough students not from math-heavy majors in the traditional group to compare meaningfully). Additionally, the labatorial students from math-heavy majors appear to have performed better than the traditional lab students in general, while those not performed worse. While a difference in performance due to a difference in math ability is not unexpected, the specific causes may require further research.

5.4 Comparing Overall Performance

We may now begin to examine how the labatorial and traditional groups compare in terms of their performance in the course. The two main types of assessments that were used in the course were the post-tests after each lab and the written final exam, the latter of which contained six targeted conceptual questions designed for the study. Similarly to the previous section, we perform a t-test complemented by an ANOVA η^2 value along with a Shapiro-Wilk test for reference in order to compare the means. We additionally perform a Mann-Wilson U test to reinforce the results. The various test results along with the relevant descriptive statistics are summarized in Table 5.3.

Test	Group	N	Mean	Standard Deviation	Shapiro-Wilk p-value	t-test p-value	η^2 Value	Mann-Whitney U p-value
Post-Tests	Labatorial	30	77.50	8.69	0.906	0.569	0.006	0.937
	Traditional	24	75.76	13.60	0.138			
Final Exam	Labatorial	30	67.69	17.04	0.216	0.196	0.032	0.233
	Traditional	24	73.42	14.50	0.026			
Concept Questions	Labatorial	30	77.50	14.91	0.129	0.422	0.013	0.372
	Traditional	24	74.13	15.54	0.047			

Table 5.3: Descriptive statistics and test results for comparing the mean post-test and final exam scores of the labatorial and traditional lab groups

Let us first examine the post-test row of the table. The scores being analyzed are the average scores of the eight post-test questions (distributed across the six post-tests) for each group. Shapiro-Wilk tests yield p-values greater than 0.05, which indicates that both the labatorial and traditional lab score distributions (shown in Figure 5.4) do not deviate significantly from a normal distribution. As such, we can confidently base our interpretation of the results on a t-test. The t-test p-value was found to be 0.569, which means that the group means are not significantly different. Although $\eta^2 = 0.006$, suggesting a small effect of the lab group on students' performance, the Mann-Whitney U test p-value of 0.937 is not significant. Therefore, we can conclude that the score distributions do not differ significantly and thus that neither group performed better than the other on average on the post-tests.

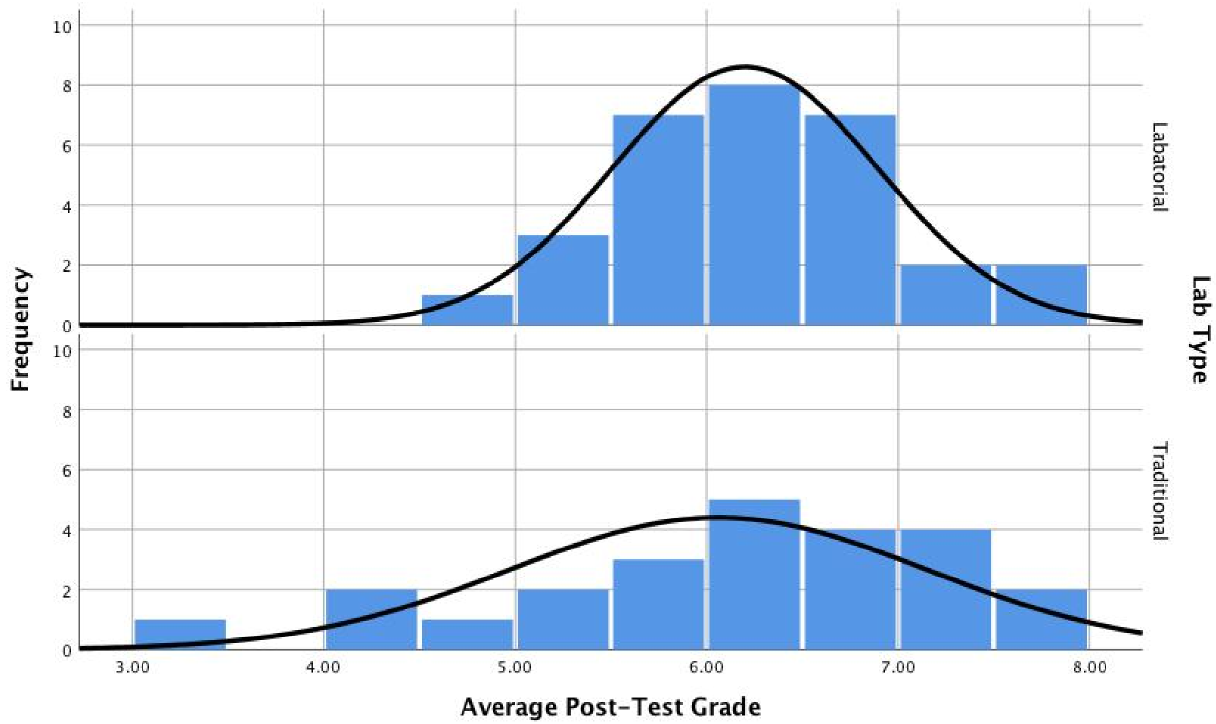

Figure 5.4: Average post-test grade distributions for the labatorial and traditional lab groups

We now focus our attention on the final exam row of Table 5.3. Upon examining the tabulated means along with the score distributions in Figure 5.5, there appears to be a non-negligible difference in the means of the two groups, although the standard deviation is still large. Moreover, while a Shapiro-Wilk test yields a p-value of 0.216 for the labatorial group, which is not significant, the p-value for the traditional group is 0.026. Therefore, while a t-test yields a p-value of 0.196, suggesting a non-significant difference in the means, this alone is insufficient to draw any conclusions. Note that an ANOVA yields $\eta^2 = 0.032$. While this is larger than for the post-test case, this is still considered a small effect size. Moreover, the Mann-Whitney U test p-value is 0.233, which is also not significant. This suggests that the two distributions cannot be considered significantly different, which is consistent with the result implied by the t-test. Therefore, we cannot conclude that either group performed better than the other on the final exam as whole.

We lastly examine the final row of the table in conjunction with Figure 5.6, which pertain to the average scores of only the conceptual questions for each group. We see that there is

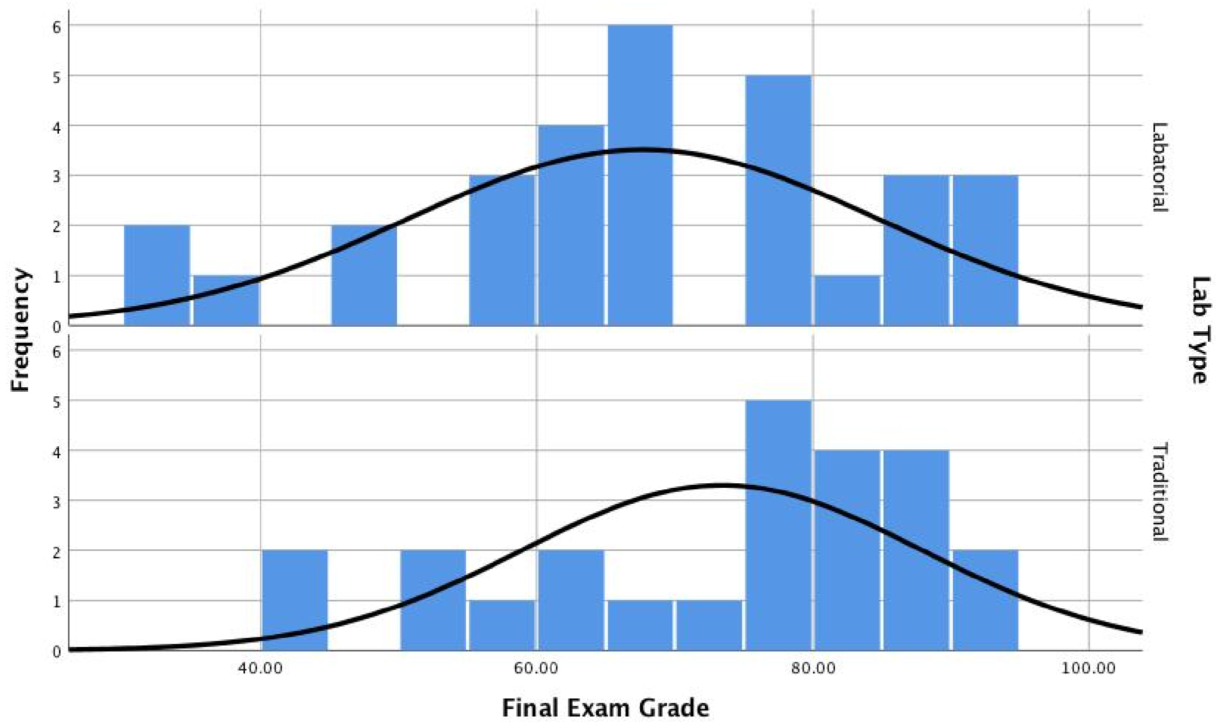

Figure 5.5: Final exam grade distributions for the labatorial and traditional lab groups

a small difference between the means of the two groups. The Shapiro-Wilk p-values for the labatorial and traditional lab groups are 0.129 and 0.047, respectively. The latter indicates that the traditional lab score distribution may not be normal. However, upon examination of the statistical test results, we see that this possible deviation is unimportant; the t-test and Mann-Whitney U p-values are 0.422 and 0.372, which are much larger than 0.05, and $\eta^2 = 0.013$, which corresponds to a small effect size due to the lab type. Therefore, as was the case for the average of the post-tests and the final exam score, we cannot conclude that there was a significant difference in the mean conceptual question scores of the two groups when considering the questions on average.

In interpreting the data in this fashion, we must tread with caution. The standard deviations of the mean scores are very large, and so it can be difficult to discern differences. For the final exam score in particular, the traditional lab distribution is notably not normal and so the t-test could not be applied ideally, albeit the Mann-Whitney U test results corroborate the conclusion that the means are not statistically different. Furthermore, while the η^2 value

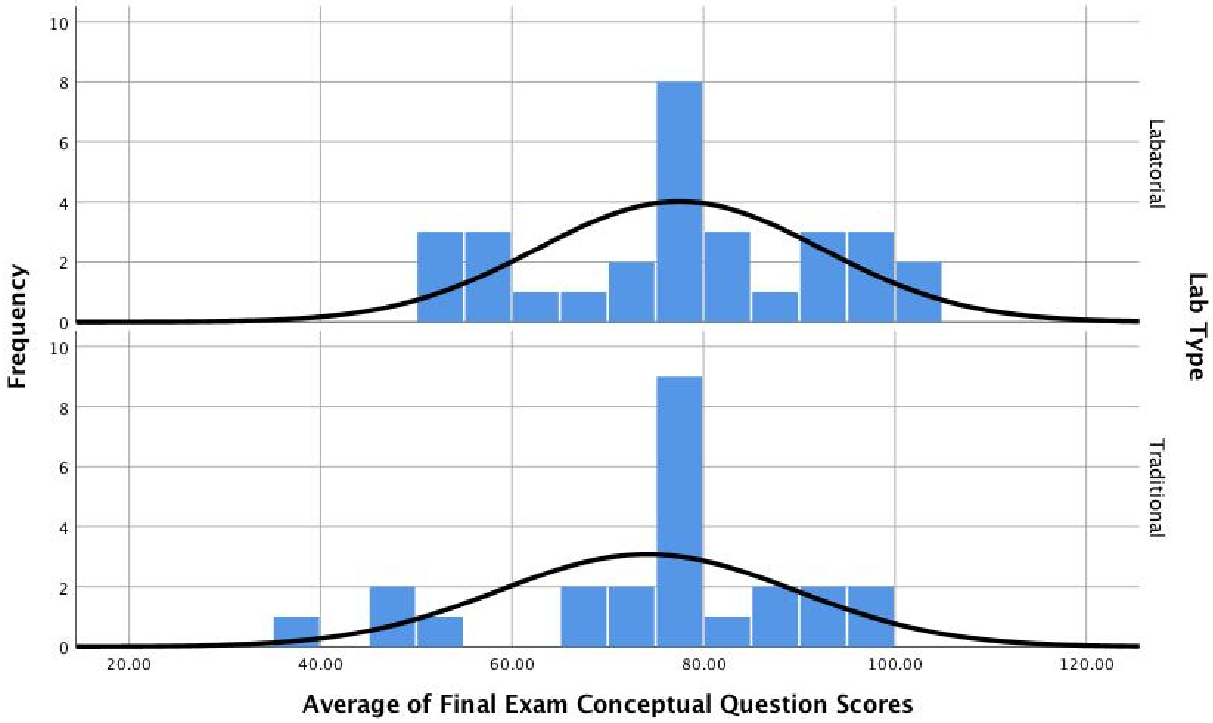

Figure 5.6: Final exam conceptual question average grade distributions for the labatorial and traditional lab groups

is small, it is non-negligible, and so there may yet be undetected differences between the two groups that are obscured by the averaging process. The possible importance of a lack of difference for a given learning outcome is also not clear from this analysis alone. As such, we proceed with a finer analysis of students' performance on the final exam and post-tests.

5.5 Comparing Performance by Question

While examining the overall scores of the labatorial and traditional students is useful as a first step in comparing the two groups, it does not reveal more nuanced differences in conceptual understanding. To gain more insight into students' understanding of the various topics of the course, we will statistically analyze each question on the post-tests and final exam and then analyze specific questions qualitatively.

5.5.1 Quantitative Analysis

The purpose of quantitatively comparing the performance of students in each group is two-fold: (1) to determine which questions are most worth qualitatively investigating, and (2) to determine which types of questions students perform better on in each group. Regarding the former point, aside from the fact that there are too many questions to analyze fully within the scope of this project, likely not all questions will exhibit an interesting difference between the two groups, and so we would like to focus on questions that can provide us with the most insight regarding the differences in students' conceptual understanding. While the lack of a difference may also be insightful, we choose to not address such questions at this point so as to limit the scope of the analysis.

Because the question scores often exhibit different distributions, we adopt a heuristic scheme to analyze and select those most notable. Due to their increased statistical power by virtue of being parametric tests, we run a t-test, an ANOVA, and a Fisher Exact test (via the binarization scheme described in Section 5.1.3) for each post-test and final exam question. Then considering how many of these tests return significant results for each question, we can heuristically determine which questions exhibit statistically significant differences in score. We do so under the premise that even though each test may not individually be ideally suited to the data, a conclusion may be drawn about the question more confidently if several different tests suggest similar results. (If a test is completely inappropriate, however, we may then simply disregard the test's result.) We then verify this one step further by running the Mann-Whitney U test (which is non-parametric and thus weaker) in order to verify if its results are consistent with those of the parametric tests. Note that this procedure is designed not to rigorously statistically analyze each question, but rather promote further thought about them.

For ease of understanding, we present the test results only for the questions for which at least one of the tests yielded a significant result. Furthermore, in order to more easily visualize the possible importance of these questions, we highlight in orange entries that we consider significant (i.e. a p-value less than 0.05 or at least a medium effect size for η^2) and highlight in yellow results that are close to significant (i.e. a p-value greater than but close to 0.05 or a small effect size for η^2). It is important to also consider such potentially important cases since the small sample size reduces the reliability of the statistical results. We then approximately sort the questions in decreasing order of importance based on this scheme, also labeling them by their question type. The statistical test results and their interpretations are summarized in Table 5.4.

	Final Q9	Final Q15	Final Q10	Final Q17	Final Q5	Final Q14	Post 1 Q2	Final Q8
t-test	0.006 (UEV)	0.003	0.008	0.050 (UEV)	0.068	0.049 (UEV)	0.034 (UEV)	0.019 (UEV)
η^2	0.138	0.206	0.075	0.072	0.096	0.056	0.033	0.006
Fisher	0.011	0.001	0.055	0.044	0.036	0.133	0.273	0.577
Mann-Whitney U	0.009	0.010	0.010	0.075	0.057	0.054	0.052	0.096
Stronger Group	Traditional	Traditional	Labatorial	Traditional	Traditional	Labatorial	Labatorial	?
Question Type	Short calculation	Short calculation	Concept	Short calculation	Short calculation	Concept	Concept	Long calculation

Table 5.4: Summary of t-test, ANOVA, Fisher's exact test, and Mann-Whitney U test results for selected final exam and post-test questions

We see that for some questions (typically the conceptual questions), labatorial students appear to perform better, while for others (typically the numerical questions), traditional lab students appear to perform better. These questions are shown in Appendix K.

In order to illustrate our approach to validating the results of this heuristic, let us discuss the distributions more thoroughly for three particular questions. The distributions currently of interest are shown in Figure 5.7, though those for all eight selected questions are shown in Appendix L. The distribution for Question 15 of the final exam, for example, evidently possesses a bimodal nature. Therefore, it is not the t-test, but rather the Fisher exact test, that is most indicative of the difference in the means between the two groups. On the other hand, the distributions for Question 9 of the final exam, which do not resemble any standard distributions in particular, could be informed by Fisher's exact test (by virtue of

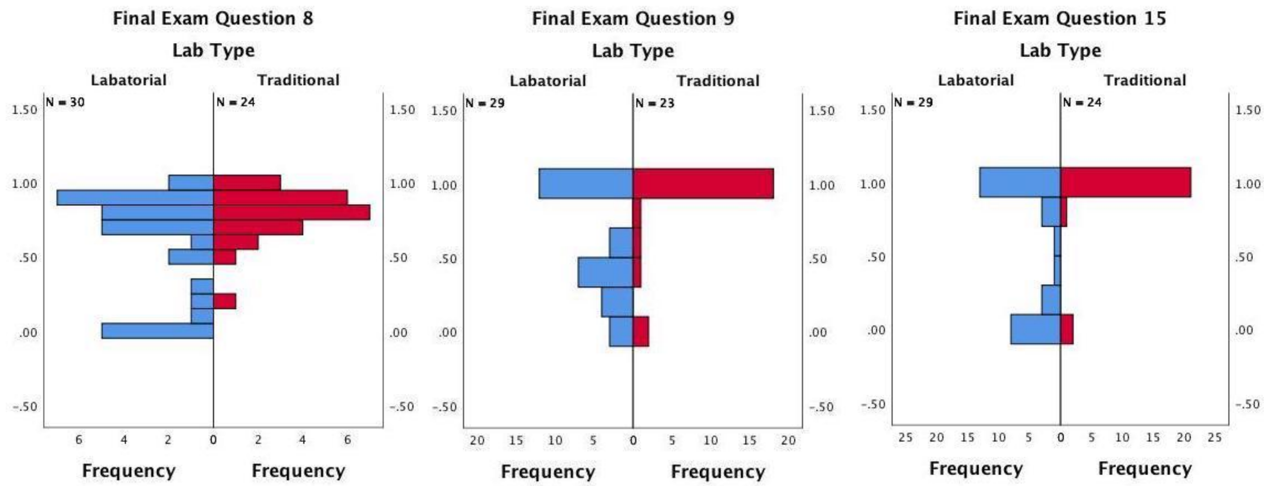

Figure 5.7: Score distributions for three select final exam questions for the labatorial and traditional lab groups

the binarization) as well as perhaps by the other tests. Because the figure clearly indicates that the traditional lab students performed better on this question, we can be reasonably confident in inferring such a conclusion by considering the tests together.

Question 8 of the final exam also requires some attention. At first glance, the two groups' distributions look very similar and nearly normal (albeit skewed), and so we would not expect there to be a significant difference between the mean scores. However, the t-test p-value of 0.019 appears to indicate the contrary. This apparent contradiction arises due to the significant outlier at 0 for the labatorial group; the t-test is statistically powerful, but not robust to deviations from normality. Even though the Mann-Whitney U test does not indicate that the distributions are different, let us explore the outliers more thoroughly.

Upon identifying the five students who received a score of 0 on Question 8, it was discovered that three of them formed a team in Section 40 and the other two were members of a team of three in Section 44. All five of these students came from majors where the use of mathematics is light (including biology, environmental geography, and political science), and so their poor performance on this question is consistent with the mathematical ability correlation analysis of Section 5.3. In addition, these five students also all received a score of 0 on Questions 5 and 15. Since this phenomenon did not occur for any other students who came from majors that are not math-heavy, this suggests that these students consistently had difficulty as a group, which can be said for the two students in Section 44 as well as for the Section 40 group; while the third Section 44 group member excelled in the course, their first language was not English, which likely created some communication barriers (as I observed during class sessions). This may have limited the effectiveness of peer instruction within that team, effectively isolating the two struggling students along with their difficulties.

Considering the peculiar nature of these outliers, we re-examine the math-level correlation analysis, the overall performance analyses, and those for the aforementioned notable numerical questions (Questions 5, 8, and 15) to determine if the results change in any way. The new p-value for the t-test comparing the mean final exam scores of students from math-heavy majors and those not (now 79.36 and 66.97, respectively) across both lab groups is 0.008, and the η^2 value for the labatorial lab group (the only one affected by the outlier removal) is 0.326. These results differ negligibly from those in Table 5.2, and so the dependence of one's final exam performance on math ability in labatorials still stands.

For the post-test averages of the labatorial and traditional lab groups (now 70.87 and 73.42, respectively), the new t-test and Mann-Whitney U p-values are 0.364 and 0.741, respectively, and the η^2 value is 0.018. For the final exam scores of the labatorial and traditional lab groups (now 78.73 and 75.76, respectively), the new t-test and Mann-Whitney U p-values are 0.551 and 0.567, and the η^2 value is 0.008. For the final exam conceptual question averages of the labatorial and traditional lab groups (now 80.00 and 74.13, respectively), the new t-test and Mann-Whitney U p-values are 0.174 and 0.142, respectively, and the η^2 value is 0.039. These η^2 values correspond to small effect sizes, and the p-values are all insignificant. Therefore, we can still conclude that there is no significant difference between the labatorial and traditional lab groups overall.

As for Question 8, there is no indication of a significant difference in the means once the outliers are discarded, as expected. For Question 15, the distribution remains largely bimodal, and the Fisher exact test result reflects this fact, still strongly suggesting that the traditional lab students performed better than the labatorial students. On the other hand, while all the test results for Question 5 were originally significant, only the η^2 value currently indicates a significant difference with a medium effect size of 0.070. Therefore, we can no longer confidently conclude that the traditional group performed any differently than the labatorial group on this question.

Whether we consider the unmodified score analyses or those with the aforementioned outliers taken into account, the overall conclusions drawn do not change. Namely, based on the questions considered, labatorial students tend to perform better on conceptual questions while traditional lab students tend to perform better on short calculation questions. While the updated analysis of Question 5 may appear to contradict this statement, Question 5 involved no direct calculations (unlike the other such questions listed in Table 5.4), instead asking about data linearization based on the centripetal force equation. Therefore, we hypothesize that in general, labatorial students perform better on conceptual questions while traditional lab students perform better on short calculation questions. In order to pursue this hypothesis further, we shall next examine the eight statistically analyzed questions qualitatively.

5.5.2 Qualitative Analysis

In qualitatively analyzing students' post-test and final exam responses, we wish to gain a more nuanced understanding of the strong points and conceptual difficulties of labatorial and traditional lab students. This will allow us to begin formulating more general statements regarding the learning outcomes achieved by the students of each group and perform a meaningful comparison of their conceptual understanding. After establishing the sample of interest for the analysis, an overview of the results will be shown and discussed.

In order to limit the scope of this analysis, we concentrate on the eight selected questions discussed in Section 5.5.1 for the 12 student interviewees. This may also be useful if the students' responses reflect a way of thinking or an approach to problem solving that was mentioned in the interviews, leaving open the possibility of further analysis in a future work.

However, we cannot only analyze these students' post-test and final exam responses; these students volunteered to be interviewed, which could introduce an inherent bias in the ability level of these students. This is particularly true for the traditional lab interviewees; the interviews revealed that while the labatorial interviewees were of varying levels, the traditional lab interviewees were relatively strong students in physics overall. There exists the additional bias of an imbalance of student genders and majors in both sets of interviewed students.

In order to overcome this difficulty, we analyze the question responses of six additional students from each group together with those of the 12 interviewees. These students are selected with the aim of having a set of students from each group uniformly distributed across the associated course sections with equal gender representation that maximizes the diversity of final exam scores (and thus of possible levels of conceptual understanding) and student majors. We also ensure that at least one student from each labatorial working group in each section is included in the analysis in order to verify that the strong points or misconceptions of students are not isolated occurrences. The gender, class section, major, and final exam score of the selected students are summarized in Table 5.5.

To analyze question responses, we first separately compile all the responses of the appropriate students for labatorials and traditional labs, which have already been formally graded with feedback. Then for each student, we briefly summarize and comment on the key conceptual difficulty (when appropriate) and the reasoning process (or lack thereof) exhibited in their response. From here, we separately summarize the key points that arose for the labatorial students and the traditional lab students (also counting the number of students who understood correctly in each) and then finally synthesize the results of the two groups.

As an illustration of this approach, see Appendix M for a detailed analysis of the responses for Question 10 of the final exam, a conceptual question pertaining to centripetal force and acceleration. In brief, the analysis indicates that the labatorial students understand the direction of the centripetal force and acceleration overall, with 8/12 students understanding centripetal force and 9/12 students understanding centripetal acceleration. Among the

Pseudonym	Gender	Section	Major	Final Exam Score
	Student Characteristic			
Extra 1	F	40	Religion	39
Jessica	F	44	Exercise Science	59
Catherine	F	40	Biology	65
Emma	F	42	Exercise Science	66
Quincy	M	40	Environmental Science	69
Derek	M	44	Behavioural Neuroscience	69
Extra 5	F	42	Environmental Geography	78
Extra 6	M	44	Independent Studies	78
Extra 2	M	40	Science and Technology	86
Extra 4	M	42	Exercise Science	89
Stacy	F	44	Biochemistry	91
Extra 3	M	42	Physics	92
Extra 6	F	43	Biology	41
Extra 1	M	41	Marketing	44
Extra 2	F	41	Psychology	58
Extra 4	F	41	Psychology	79
Extra 3	F	41	Chemistry	80
Oscar	M	41	Biology	82
Adrian	M	41	Exercise Science	82
Evelyn	F	43	Behavioural Neuroscience	85
Zion	M	43	Aerospace Engineering	87
Lauren	F	43	Behavioural Neuroscience	89
Amir	M	43	Chemistry	91
Extra 5	M	43	Software Engineering	91

Table 5.5: Metadata of labatorial and traditional lab students whose post-test and final exam responses are qualitatively analyzed

traditional lab students, similar conceptual errors were made overall, with 6/12 students understanding centripetal force and 4/6 understanding centripetal acceleration. While there are some common lingering misconceptions in both groups, errors occurred more frequently in the traditional group. The issue of drawing a tangential acceleration component in particular appeared to be more prominent among traditional lab students. Therefore, it seems likely that a labatorial worksheet has the ability to improve students' understanding of the concepts of centripetal force and acceleration in general compared to traditional lab students, although there is likely still room for improvement in the worksheet. This is consistent with the statistical test results of Table 5.4.

A similar in-depth analysis was performed for each of the other questions in the table, the results of which are also summarized in Appendix M following the Question 10 discussion. The analyses revealed several interesting points, which we shall briefly discuss. There were several core concepts that labatorial students appeared to understand better than traditional lab students. For example, the responses to Question 14 of the final exam and Question 2 of the first post-test indicate that labatorial students may possess a stronger intuitive understanding of the meaning of the coefficient of restitution in collisions and the fluids concept of volume displacement, respectively. On the other hand, the traditional lab students perform better on Questions 9, 15, and 17, which all involve one-step, formula-based calculations that students could refer to in their lab notebooks (or labatorial worksheets) during the exam. Therefore, traditional lab students may be stronger at answering questions involving repetitive, template-based methods or tasks from the lab. However, based on Question 15, many labatorial students appear to have a better understanding of the concept underlying these methods and exhibit more efforts at reasoning conceptually in their solutions. Furthermore, the analysis of Question 8 indicates that students perform equally well on longer calculations, consistent with the statistical results. Finally, the result from Question 5 that the traditional lab students are more proficient at data linearization than labatorial students is unexpected since the labatorial worksheets were designed to scaffold students' intuition on linearization. This may be because traditional students needed to do this as part of their reports in a more formulaic way, whereas labatorial students often just talked about the idea or sketched the graph, which may have affected how they absorbed the concept. Refinements to the worksheets may also be necessary.

In summary, there is a tendency for labatorial students to possess a stronger intuitive understanding of conceptual questions. On the other hand, traditional lab students tend to perform better on questions where short, formulaic calculations are involved. Although the prior quantitative analyses suggest that labatorial students may not necessarily perform better than traditional lab students on every conceptual question, the questions that they do perform better on are always conceptual in nature. In addition, they may be attempting to think about the associated concepts more regardless of the question type, as suggested by the reasoning they exhibit in their solutions. There appears to be no difference in thought process or performance for the long (i.e. not template-based) calculation question considered, and so this may hold in general for all such questions. However, this analysis does not consider all the post-test and final exam questions, and so we will make a final conclusion regarding the learning outcomes of each group in Chapter 6 upon triangulation with all the relevant data sources.

Chapter 6

Triangulation

Recall from Table 3.3 that we were able to partition our research sub-questions into two categories: those that pertain to general characteristics of labatorials and traditional labs, and those that are directly tied to the content of the PHYS 224 curriculum. Furthermore, there are several data sources that can address each of those questions. However, by virtue of the structure observed in our research questions, we were able to specify precisely which sources can be associated with which questions, giving rise to the two regions in the table. Furthermore, within each of these sets of questions, one data source in particular provided the most information and thus could be considered the foundation of the data analysis addressing those questions: the student interviews for the general characteristics category, and the post-test and final exam responses for the content-specific category.

We can now triangulate across the data sources in a way that takes into consideration the inherent structure of the data: the TA interviews, class observations, and TA surveys will be used to triangulate with the student interviews, and the class observations, TA surveys, students' labatorial worksheets or lab reports, and the statistical analyses of students' scores will be used to triangulate with the final exam and post-test responses. However, before we can perform triangulation, we must introduce the technique used to analyze the sources of data that have not been considered so far.

6.1 Hierarchical Summarization

To begin analyzing the TA surveys, students' labatorial worksheets and lab reports, and the classroom observation records (and eventually triangulate with the primary data sources), we first devise a straightforward colour-coding scheme that can allow us to quickly identify the parts of a piece of data that are pertinent to answering our research questions. In particular, with regard to the student interviews triangulation, we highlight passages that reflect a key code or theme from the interviews in yellow and any contradictions to those codes or themes in blue. Furthermore, with regard to the examination responses triangulation, we highlight indications of conceptual gain or understanding in green and indications of conceptual difficulty in red.

Note that for the latter highlighting in students' labatorial worksheets or lab reports, we only consider a passage of the data to indicate a conceptual gain or difficulty if students provide a rationale complete enough for us to be reasonably confident in inferring that they do (or do not) understand. (For example, while simply performing a calculation correctly would not indicate understanding, a correct rationale utilizing the underlying concept would be highlighted in green.) In the case of the observations and the TA surveys, the comments must precisely state what the conceptual gain or difficulty was. (For example, while simply stating that students struggled with the theoretical computation parts of the lab would be too vague, stating that students understood where the kinetic energy goes in a collision would be highlighted in green.) This will be essential for performing each triangulation and thus deriving meaningful conclusions about the data. An example of this colour-coding scheme applied to the TA surveys is shown in Appendix N.

With the relevant data coded by colour, we can then perform what can be referred to as hierarchical summarization. This technique is an informal framework for extracting the essential ideas from multiple instances of a data type as well as across a diversity of data sources. The essence of the approach involves looking at each datum individually and then progressively synthesizing higher-level meaning across the data. Namely, one needs to:

1. Code all the data by colour.

2. Summarize the coding results and implications for each student or TA (depending on the source of data) for each lab.

3. Synthesize the results across all the students or TAs within each lab group.

4. Compare, contrast, and synthesize the results across each group (for each data type).

5. Triangulate across all the relevant data sources.

6. Synthesize across all the lab topics (if appropriate).

The hierarchical nature of this framework is visualized and summarized in Figure 6.1.

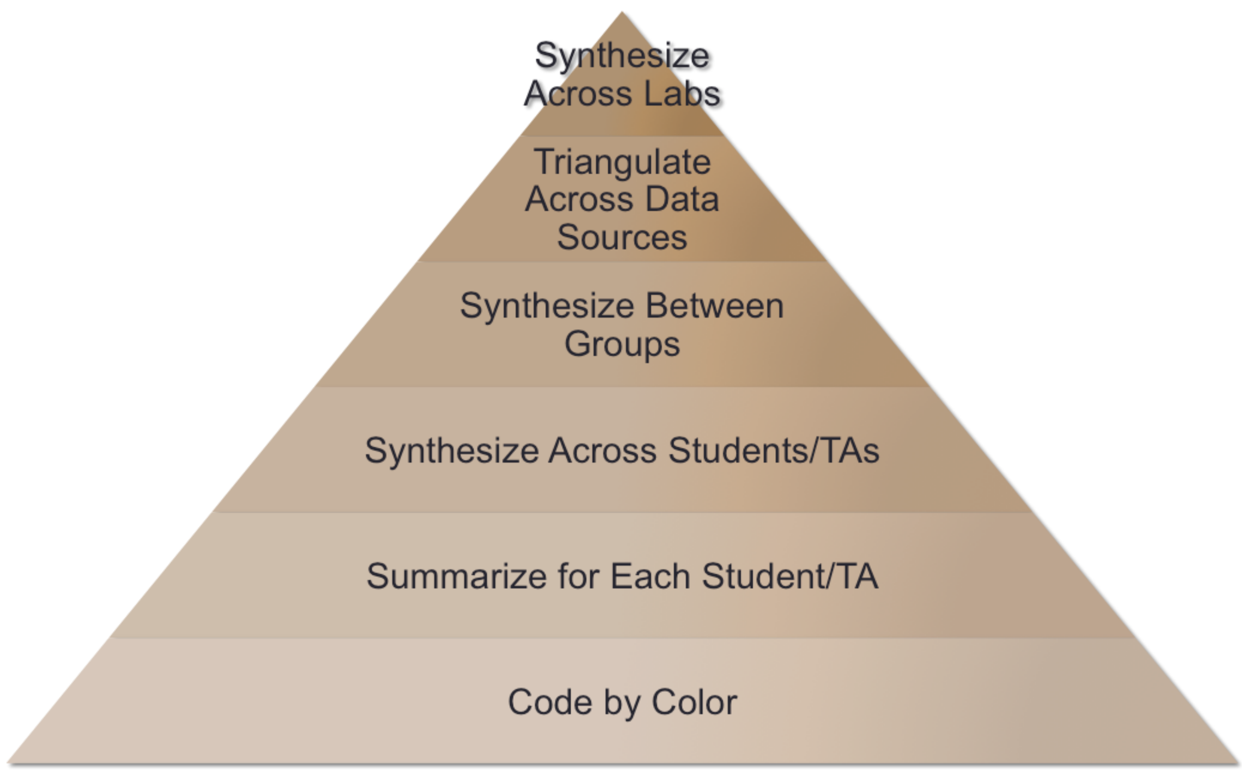

Figure 6.1: Schematic of hierarchical summarization framework

As a concrete example of the first three steps in this hierarchical summarization process, consider the free responses in the TA survey for Lab 4 (centripetal force), which are shown along with the responses for the other labs in Appendix N. After compiling the responses of the TAs into a separate document, I highlighted parts of their responses according to the aforementioned colour-coding scheme (Step 1). As for Step 2, Isaac's response for his labatorial section indicated that students had trouble understanding the relationship between centripetal force, velocity, and radius at first (highlighted in red), but that there was an improvement in their intuition of these parameters as the lab progressed (highlighted in green). In addition, Justin's response indicates that students did well in general (not highlighted due to the vagueness of the statement), and he points out that students are able to figure out problems through discussion (highlighted in yellow), which is consistent with the peer instruction and student support themes from the student interviews. Although Liam left his response blank for this lab, we see that the other TAs indicate a successful lab, albeit for different reasons. Had there been more in common between their responses, we would have synthesized their comments (Step 3). Then, after repeating the above for the traditional lab sections, we can compare and contrast the results for each group (Step 4).

Because the final two steps of the hierarchical summarization procedure will be manifested differently for each of our two triangulations, they will be presented separately in the following two sections.

6.2 Triangulation of the Student Interview Results

The student interview results will be triangulated with the TA interviews, classroom observations, and TA surveys. We begin by presenting the triangulation of the student interviews with the TA interviews, which were analyzed using an inductive coding scheme as was done for the student interviews. The triangulation with the student observations and TA surveys, which were both analyzed using the aforementioned hierarchical summarization scheme, will then be presented.

	Dimension of Research Questions		
Lab Type	Support Types	Learning Promoters	Learning Inhibitors
Labatorial	Peer scaffolding TA scaffolding	Peer instruction TA scaffolding Structure	Peer over-dependence
Traditional	Peer support TA support		TA over-dependence Frequent, direct intervention Understanding later

Table 6.1: Summary of themes from TA interviews

6.2.1 TA Interviews

Since the TA interviews will serve to triangulate with the student interviews, it would be beneficial to structure the discussion of the themes that emerged from them in the same way as for the student interviews. Therefore, we summarize the main themes in Table 6.1 and proceed with the analysis according to each primary research question.

The Student Learning Experience

TAs pointed out that peer and TA interactions served as an important form of affective scaffolding to the students in labatorials. Isaac noted that "it [took] more empathetic energy to understand what [students were] trying to do," which is consistent with students' comments about the TAs interactions with them feeing very supportive and involved. Additionally, Liam stated that "if they [didn't] know how to solve [a problem], they [could] talk with [their peers]," which they typically did before going to the TA for help. Isaac and Justin also felt that students' interactions in labatorials were overall very collaborative.

On the other hand, the traditional labs students appeared to meaningfully communicate less frequently since "a lot of them had difficulty sharing ideas and explaining things to each other and asking questions," according to Justin. As such, students would heavily rely on the TA for answering their questions. Isaac in particular noted this, saying that he had "way more interactions with the traditional [lab students] because they just [had] instructions" to follow. However, this is consistent with students' comments that the TAs were always very available and willing to help, which helped them feel at ease in the lab. He additionally suspected that an absence of group accountability could also be contributing to the lack of unity and the imbalances present in the teamwork in traditional labs; the former was identified in Isaac's interview:

> *They're not obliged to actually work well together [in traditional labs]. So you have more cases where there's this person who does everything, and the other ones are fine because there's no consequences to that.*

While this does not explicitly refer to students largely checking results with each other, which was a strong theme in the student interviews, it is not inconsistent with this prior result.

While the TAs did not explicitly comment on the students' affective response in traditional labs, they did note that the highly collaborative nature of labatorials helped create a positive learning experience for students. According to Isaac:

> *The majority saw that they really enjoyed working in teams, and for the traditional labs, they might not [always] be working in teams, but they're always interacting with each other. But I don't see that's actually helping them as much as the ones that are doing a single experiment in teams because they depend on each other for moving forward.*

Nevertheless, Justin observed that some labatorial students did at times over-depend on their peers, "not really understanding everything and [...] just copying from their teammates, just being carried by their team." This is consistent with the struggles of students like Emma as discussed in her interview.

In summary, the TA interviews are consistent with the student interviews overall regarding students' affective learning experience. While TA and peer support play a role in both labatorials and traditional labs, the nature of these forms of support is different in the two types of labs. The themes of grading support from the labatorial interviews and procedural support from the traditional interviews did not arise in the TA interviews, perhaps due to both involving highly subjective aspects of the lab experience that students were not likely to visibly express, and so we cannot triangulate for those themes.

Conceptual Learning in the Lab

Just as peer interactions were important for labatorial students on an affective level, they also played a large role in students' conceptual learning. Isaac indicated that peer instruction frequently occurred by saying that the way teammates in labatorials depended on each other "[pushed] them to also share the information that they [understood]," and that "by sharing, by putting what they know into words, they understand better." Both of the other TAs also shared this sentiment. Justin stated that he witnessed many light-bulb moments occur following involved student discussion, leading him to feel that the teamwork was the strongest aspect of labatorials. He also expressed that it was enhanced by the students being in heterogenous teams since they had different strengths and weaknesses, allowing students to "figure [their confusions] out between themselves" much of the time. On the other hand, he stated that while "some [traditional lab students] did talk with each other and did discuss a little bit," peer instruction did not usually occur in his PHYS 226 traditional labs.

As was also evident in the student interviews, all three TAs indicated that they took a scaffolding approach in the lab. Like Liam, all the TAs indicated that they always "[tried] to guide them about how to solve [a] problem." In particular, Isaac would begin by "first [...] asking questions about the concept that [they were] trying to understand, give them examples, and then leave them some time [to think]" before eventually following-up. This ensured that students "at least [...] went through the effort [of] trying to figure it out, even [if] they were wrong." Liam indicated that the fact that "they actually [thought] about the problem and then [tried] to [figure out] how to solve it" greatly helped students learn.

This aspect of labatorials was further enhanced by the peer instruction aspect. According to Justin:

The quality of their questions was better in labatorials because before they [asked] questions, they [had] already done some discussion between themselves. So they at least [came] up with one hypothesis or whatever and then [asked] me questions. But in the traditional labs, most of the time the questions they [asked were] very trivial and not always well thought through.

We see that the types of scaffolding put in place in labatorials mutually enhanced each other, as also determined from the student interviews; students were more engaged with each other and the material, allowing them to have more fruitful interactions with the TA who was himself encouraging students to collaborate. This was all supported by the structure of the labatorials by having the checkpoints and the gradual building-up of concepts integrated into the worksheets.

In contrast, as Justin's comment indicates, the traditional lab students were not as engaged in their learning. As a result, the TA served not to help students learn, but to check their results and their procedures, as with their peers. This over-dependence on the TA caused them to not think about the concepts deeply, which could have inhibited their learning. Isaac indicates that this was due in part to the recipe-like format of the labs:

With [traditional lab students], they have been given some instructions, they just follow mechanically, they do it, and then they ask if something is wrong. But they're not really understanding. I mean, not all of them, but most of them I would say they just approach it in this mechanical way, doing this and this and that and that, and at the end you get a couple of numbers.

Isaac additionally commented that he felt that he was "intervening all the time" in traditional labs in order to keep the students on track. In particular, he noted that "it's because [they] have to manipulate the instruments a lot more, and if [he doesn't] intervene, they never finish on time." As such, this type of frequent, direct intervention may also be deterring students from deeply thinking through the lab. Both of these behaviours are consistent with the theme of focusing on error-avoidance that emerged from the student interviews.

The TAs also indicated that because traditional lab students were not focused on their learning in the lab, but rather on simply following the instructions as correctly as possible, they may only have begun thinking about the concepts by the time they wrote their reports. According to Isaac:

> *They might start to grasp by the end in the conclusion, and that might be too late. Because it's kind of... It's all over right? I mean it's cool, because then for the final exam, 'Yeah, you understand what you actually just did. But you weren't understanding while you were doing it.'*

Because students waited until after the lab to make sure they understood the concepts and the lab as a whole, they will likely not have discovered any misconceptions they may have had about the concepts, making their learning less effective. This observation is consistent with labatorial students' comments on the matter with regard to their prior traditional labs.

In summary, the promoters and inhibitors of learning in labatorials identified from the student interviews were confirmed by the TAs. Students' interactions with their peers and the TA created an environment that promoted discussion and assisted students in resolving their conceptual difficulties. Contrariwise, the TAs did not refer to any particular promoters of learning in traditional labs, instead identifying inhibitors strongly related to those indicated by students. As such, all three TAs felt that labatorial students learned the concepts more deeply than the traditional lab students, with Isaac in particular stating that "[he] would actually put money that they [understood] better in labatorials because of the [lab report] conclusions that [he] read from the traditional lab [students]." However, they also indicated that due to the reduced focus on experimental techniques in labatorials, they may have become less proficient at these than the traditional labs students.

6.2.2 Classroom Observations

As with the previous triangulation, we will divide the discussion according to each research question. Furthermore, we will organize the discussion according to the main themes listed in Table 4.1 as we aim to triangulate with those themes. Any discrepancies with prior results will be explicitly noted.

The Student Learning Experience

In observing the labatorial sessions, it was evident that students were actively collaborating and supporting each other. Students in general appeared to be comfortable sharing with each other what they did not understand, just as all students expressed during the interviews. Students also got more comfortable with each other over time. However, there were some teams that were relatively quiet and whose members tended to work by themselves. Therefore, although the students that were interviewed were not all high-performers in physics, they were likely more outgoing students, and so other student perspectives of labatorials may be yet unexplored. In addition, I noticed that stronger students would sometimes dominate the pace of the group and that students would not always check in with their struggling teammates. Therefore, while the peer support as described in the interviews was confirmed, the observations showed that the teamwork was not always ideal, as was to be expected.

However, there were no discrepancies between the labatorial interviews and my observations regarding the TA support theme. Typically, the TA of each section regularly checked in with students, which corresponds with students' sentiments of feeling supported. Students also appeared to become more comfortable with the TA as the course went on, which was also mentioned in the interviews. However, I did observe the frustration that the advanced students like Stacy would sometimes experience due to having to wait for the TA at checkpoints in the worksheet. Finally, aside from a generally relaxed atmosphere, I did not observe anything regarding the support that students felt due to the grading scheme of the course, and so this theme cannot be triangulated via the observations.

My observations from the traditional lab sections also corroborate the themes from the corresponding interviews overall. The support that students provided each other with was of a more practical nature, as I often saw teammates subdivide tasks among and check results with each other. There was also one instance in particular of a student (whom I did not interview) dictating to his peers what they should do. Such behaviour corroborates the theme of some students wanting to be in control of the results they get. However, there were some instances of more involved support that do not correspond exactly to the themes from the interviews, such as a more advanced student giving one of his peers some pointers about the lab and another student encouraging his teammate to speak up more. Therefore, while the interview themes may attempt to capture typical occurrences in the lab, there may certainly be exceptions depending on the students. Regardless of the type of support, I observed that students do indeed rely on each other to a degree.

The TA interactions that I observed were also exactly as identified in the interviews for the most part. The questions for the TA mostly involved clarifying instructions or how to use a formula. I also noted that they would ask the TA as soon as something seemed amiss, often resulting in a constant stream of questions for him. However, there were occasionally labs where students did not ask the TA many questions (although the questions they did ask were typically as described above), but rather kept to themselves. In these situations in particular as well as among others, both TAs (especially Isaac) regularly checked in to make sure that students were performing the experiment properly and immediately corrected them if there was an issue. Therefore, both the students' way of approaching the TAs as well as their frequent checking-in with the students corroborate students' general comfort with interacting with them. This is further corroborated by my observation of Zion laughing with Liam about a silly mistake that he had made. Finally, I did not observe anything in particular that could be used to triangulate with the procedural support theme regarding their stress about grades. However, students were often engrossed in reading the manual, which could suggest that they saw it as a source of support that—like the peer and TA support—could help them get the best grade possible.

Conceptual Learning in the Lab

As with the themes related to the first research question, I was able to confirm most of the themes pertaining to conceptual learning that emerged from the labatorial interviews. There were many instances of peer instruction, often allowing groups to resolve their own difficulties. As a result, I observed several instances of students discussing together and only rarely asking the TA questions. Furthermore, whenever they did ask questions, they often asked more subtle questions, which was mentioned in the TA interviews. I sometimes also noticed apparent light-bulb moments from students after participating in a discussion, indicating along with the prior point that students did indeed get deeply engaged in their interactions with each other and with the material through peer discussion. However, I also observed at times a possible limitation of peer instruction; when the levels of understanding of teammates were too unequal, the instruction was usually unidirectional and the students on the receiving end often did not understand, which is consistent with the theme of over-dependence on peers identified in the interviews. Nevertheless, this form of scaffolding did appear to be valuable to students in general.

The TAs' scaffolding as identified in the interviews, facilitated by the worksheet structure, was also apparent in my observations. The TAs all typically tried to answer students in such a way so as to guide their thinking in the right direction. This was sometimes in the form of giving a hint or encouraging them to further explore an idea they had, albeit they began to give more direct hints if they saw that a group's pace was too slow due to the time constraints of the lab. This appeared to promote the regular group discussion and engagement with the concepts that I observed. However, there was one instance where Justin accidentally overlooked a group's error in an equation until later in the lab. Additionally, I did notice one team continue to move past a checkpoint before the TA arrived. Whether or not overlooking the error was because of this, these observation show that the TA scaffolding will not always be perfect due to mistakes that can be made. However, a scaffolding approach did generally appear to be valuable to students' conceptual learning.

On the other hand, while some students seemed comfortable designing the required experiments themselves, there were also cases of students subsequently having trouble setting up the experiments, additionally not performing the experimental procedures completely rigorously. This was noted by the TAs in their interviews, and so the observations also do indicate the possible disadvantage of labatorials focusing on concepts over experimental skills. However, this may also simply indicate that changes to the worksheets are required. Finally, the benefit of the worksheets and experiments being relevant to students' lives for their learning could not be corroborated with the observations.

Similarly to labatorials, the traditional lab observations generally corroborated the students' interviews. I did not observe many instances of students discussing concepts with each other or asking the TA conceptual questions; rather, they usually asked many questions about the experiment. This is consistent with the TAs' comments about students depending on them too much for checking their progress. I also observed an instance of two students who would regularly copy results from each other. While it did not occur to this degree for all students, this is consistent with the theme that traditional lab students often rely on each other for checking their results. Furthermore, I noticed that in most labs, students would mostly stop discussing with each other as soon as all the data was collected, stopping entirely once they began writing their lab report (despite doing so in the lab). Therefore, while there were often opportunities for students to help each other learn in the lab, the ways in which such collaboration occurred were limited.

As for the introductory theory explanation, I did observe the TAs explain the concepts to the students and the occasional student groups that temporarily formed after hearing the explanation. In those cases, the introduction did indeed encourage students to begin thinking about the concepts more deeply. However, at every lab most of the class time was spent with students absorbed in the lab instructions, whether the students worked in teams or individually. This appeared to make them no longer think about the concepts or ask questions about them, instead only focusing on performing all of the steps correctly. This likely contributed to students overthinking the lab and frequently checking with the TA, a poignant instance of this being when a student asked Liam a trivial question about using the weight equation $F = mg$. This type of behaviour is consistent both with the theme of the recipe-like format of traditional labs acting as an inhibitor to learning as well as that of the tendency for students to focus on avoiding errors.

However, there was an instance of a more advanced student thinking about the role of air resistance in the experiment even though it was not mentioned in the manual. This indicates that some students do try to think about concepts, albeit the inhibitors of learning present make this less likely. Aside from seeing students write their lab report discussions at the end of the lab, there were no observations in particular to triangulate with the theme of understanding after the lab is over nor with that of the effect that the tangibility of the concepts through the experiments had on students' learning.

6.2.3 TA Surveys

The TA surveys focused largely on the key concepts of the lab, and so there is little mention of themes that pertain to students' conceptual learning in the lab and none that pertain to their learning experience. However, the relevant themes that emerged will be briefly discussed.

For labatorials, all the TAs mentioned peer instruction in some form of another. In particular, Liam noted that students tried to think deeply about the concepts, and that by struggling with the theory in this way, they were often able to figure out a problem through discussion amongst themselves. Liam also explicitly mentioned that students appear to discuss more in labatorials than in traditional labs, but that it may depend on the type of student. Regarding Lab 6 (the period of a pendulum), Liam said that they knew how to design the experiment and collected good data. This is in slight opposition to the TA interview comments that labatorial students may not be performing their experiments rigorously, and so a lack of proficiency in experimental skills may only apply to some students rather than be a side-effect of labatorials. Furthermore, as a result of the conceptually driven approach of this lab, Isaac said that conceptualizing the period of the pendulum on their own as opposed to simply verifying the formula helped students go through the process that a physicist uses, which may have potentially had a large impact on students' perspectives about physics.

For traditional labs, Isaac indicated that when he took the time to explain the theory behind an experimental procedure the students used, the students were able to understand the experimental design better. This suggests that a proper theory explanation at the beginning of the lab can be helpful both for understanding concepts as well as for doing experimental physics. Furthermore, Isaac said that when he demonstrated one of the experiments to students in conjunction with an explanation, they were able to better understand the associated concept. This is consistent with the real-world connection theme wherein being able to see the concepts more tangibly was helpful for their learning. However, Isaac also said regarding some labs that students did not have any major problems in conceptual understanding since the labs were more about taking good measurements. This is consistent with the theme that traditional lab students tend to focus on the instructions of the lab without deeply thinking through the concepts.

6.3 Triangulation of the Conceptual Outcomes

Despite having implemented the colour-coding scheme described in Section 6.1 for each of the qualitative data sources pertinent to examining students' learning outcomes (i.e. class observations, TA surveys, and student writing products), it is not immediately clear how they can best be triangulated with the examination responses. To this end, we derive a heuristic for triangulation that can be used to synthesize all the analyses (both qualitative and quantitative) and begin extracting general results about students' learning of the concepts.

6.3.1 Developing a Triangulation Heuristic

As there are several important dimensions to consider in this problem (lab type, learning outcome, data source, and concept), we structure the results of the colour-coding as a multilayered cross-tabulation between these dimensions. In particular, in order to visualize the prominence of the key conceptual gains and difficulties experienced by students and any patterns therein, we count the number of occurrences of gain or difficulty for each concept (denoted respectively by the green and red highlights of the colour-coding scheme) indicated by each data source and enter this count into the appropriate region of the table, denoted labatorial-gain, labatorial-difficulty, traditional-gain, or traditional-difficulty. As can be seen in Table 6.2, this effectively results in a quadrant system (whose dimensions are the lab type and the overall learning outcome) superimposed with the table, dividing it into four-subtables recording the occurrences (whose dimensions are the data type and the identified concept). Note that the colours used in the table are arbitrary, not bearing any relation to the aforementioned colour-coding scheme; they are simply used to allow patterns to be more easily identified across the quadrants.

In counting the occurrences of conceptual gain or difficulty across each data source, certain considerations had to be taken into account for such a heuristic to be functional. Firstly, because we examined final exam and post-test responses for 24 students in total, there would certainly be more counts in the "Final/Post" column than in any of the other data type columns. An additional complication is that the concepts present in the table may be pertinent to more than one question that we examined, which could inflate the number of occurrences and thus skew students' apparent level of understanding from lab to lab. To counteract these difficulties, thereby keeping the table balanced, we divide the actual number of counts by two (since only 12 of the aforementioned students, i.e. the interviewees, were also examined through the other qualitative data sources) and then divide by the number of analyzed final exam or post-test questions that pertained to the given concept.

Furthermore, in order to also take into account the whole class's performance on a topic,

		Labatorial					Traditional				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*Relationship between Fc and v, r*		*			P2(94)		*			P2(90)
	Fc direction			*	****	P1(83) F10(80)					P1(72)
	a direction			******	****	F10(80)					
	v direction			****							
	T = Fc + Fg			****							
	Inertia			*							
	Linearization				**				**	****	F5(62)
	Line of best fit				***					****	F17(82)
	Sources of error								**		
Conceptual Difficulty	*Inertia*		*	**							
	T = Fc + Fg	*	*	**							
	F direction	*		*	*					*	F10(61)
	a direction			*	*					**	F10(61)
	Line of best fit				**	F17(59)	*	*		**	
	Sources of error								***		
	Focused on formula verification								[redacted]		
	Linearization				****	F5(41)	*		*	**	

Table 6.2: Raw compilation of occurrences of conceptual gain and difficulty for labatorial and traditional lab students in Lab 4

we include a column containing the post-test (P) and final exam (F) scores (XX%) for each question (whose number is appended to P or F) related to the given concept, not only those that were analyzed qualitatively. (Since there is only one post-test for each lab, the post-test number is the same as the lab number. As such, P2(94) in Table 6.2, which is for Lab 4, should be interpreted as a score of 94% on Question 2 of Post-Test 4.) This column functions under its own heuristic; if the scores are significantly different between the two groups, then the scores are entered into diagonally opposite quadrants of the appropriate groups (i.e. labatorial-gain and traditional-difficulty or labatorial-difficulty and traditional-gain). On the other hand, if there is no statistically significant difference, then because all the final exam averages range from approximately 40% to 100%, we choose 70% as a reasonable (albeit quasi-arbitrary) threshold for placing each group's performance into a conceptual gain or conceptual difficulty quadrant.

In order to now derive meaningful information from this table, we must discuss how such a table should be interpreted. First and foremost, since we are trying to make comparisons between labatorials and traditional labs, entries in Table 6.2 will only be meaningful if they allow us to conclude that the two student groups are the same (in terms of their average understanding) or different. In order for one to draw the former conclusion from the table, there must be occurrences uniformly distributed across all quadrants of the table. This is because while both groups only having occurrences in their respective "gain" or "difficulty" quadrants may imply that they both understand (or do not understand) the concept, the lack of occurrences in the opposite quadrants may simply be coincidental (e.g. faults in understanding may simply not have been detected in our data). Therefore, in order for one to draw the latter conclusion from the table, there must be an overdensity of occurrences in diagonally opposite quadrants, with the most conclusive case being that the occurrences of a concept are strictly in diagonally opposite quadrants.

Two comments should be made the reliability of this heuristic. Firstly, we expect the reliability of the conclusions drawn from the table regarding a conceptual learning outcome to be higher if it appears across more data sources. Additionally, if the ideal density distribution is not met for either of the aforementioned scenarios but it is close (e.g. there is a strong overdensity of occurrences in diagonally opposite quadrants, but a third quadrant also contains a non-negligible amount of occurrences), then the interpretation may be based on our impressions of the examination responses (albeit taken with a grain of salt). With these considerations in mind, we refine the triangulation table so as to only include concepts from which some conclusion can be drawn, resulting in the reduced quadrant representation shown in Table 6.3.

6.3.2 An Example of Analyzing Students' Learning Outcomes

Now that our triangulation heuristic has been thoroughly discussed, we may now discuss more precisely the similarities and differences between students' learning outcomes in labatorials

		Labatorial					Traditional				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*F direction*			*	****	P1(83) F10(80)				***	P1(72)
	a direction			******	****	F10(80)				**	
	Linearization				**				**	****	F5(62)
	Line of best fit				***					****	F17(82)
Conceptual Difficulty	*F direction*	*		*	**					***	F10(61)
	a direction			*	*					****	F10(61)
	Linearization				****	F5(41)	*		*	*	
	Line of best fit				**	F17(59)	*	*		**	

Table 6.3: Refined compilation of occurrences of conceptual gain and difficulty for labatorial and traditional lab students in Lab 4

and traditional labs. To exemplify the process of deriving the final results, we only discuss the concepts shown in Table 6.3. However, a similar triangulation analysis can be done for each of the other labs, whose respective raw quadrant representations of the conceptual gains and difficulties of each group are shown in Appendix O.

Firstly, let us consider the direction of the centripetal force. While the occurrences of this concept are spread across the four quadrants, we see that the highest density is in labatorial-gain and traditional-difficulty. While there were certain conceptual difficulties in the final exam responses for both groups (e.g. gravity pointing absolutely “downward” or along the direction of motion), the deciding factors here are their overall performance on the post-test and final exam questions related to it. We can see that the labatorial students performed better on average for both of those questions (even if the difference was not significant for Question 1 of the post-test). However, we should err on the side of caution in forming this interpretation since the labatorial worksheet did indeed focus more on the direction of the centripetal force than the traditional lab equivalent.

The results for the acceleration direction in uniform circular motion are similar to that for the force, with the highest density along the main diagonal quadrants. While there are some occurrences under labatorial-difficulty, there are none under traditional-gain. As for labatorial-difficulty, they were both occurrences of different people thinking that there was a tangential component to the acceleration. The same is true for traditional-difficulty, except that there were additional errors such as drawing the centripetal acceleration inward toward the orbiting planet for Question 10 of the final exam rather than toward the centre of rotation or simply not drawing anything at all (a possible indication of total non-understanding). Therefore, we argue that students were able to learn the concept better in labatorials.

Contrariwise, the results for linearization suggest that traditional lab students understood the linearization process better for similar reasons. Originally, we did not expect a difference at all since both groups did similar graphing activities, and the labatorial worksheets additionally encouraged labatorial students to think about the rationale for figuring out how to linearize as opposed to just applying it. Perhaps if—similarly to other topics in the course—the traditional lab students mastered doing those specific graph linearizations or simply memorized them, then they may indeed have performed better (or at least not worse) than the labatorial students, who always did such activities in a slightly broader way. Note that the final exam responses do not make it clear if the traditional lab students simply understood how to do it for those specific cases (i.e. the particular process) or if they truly understood the interpretation of the linearized graph that they got (i.e. the slope, intercept, etc.) Not many of the students verbalized the process in either group, and the question as written may not test for this this type of understanding. However, at least to first-order, the traditional lab students likely understood this concept better than the labatorial students.

Finally, for the line of best fit concept we also see an overdensity in the off-diagonal quadrants, indicating that the traditional lab students have the better understanding. The most poignant difference lies in the score for the pertinent final exam question. This may be due to the fact that traditional lab students have their graphs individually checked and graded directly by the TA via their lab reports. This gives them concrete feedback once the lab report is returned since the TA will have corrected even minor mistakes made in drawing the line of best fit or calculating its slope. On the other hand, while the TA does look over labatorial students' plots at checkpoints, it may be more likely for them to accidentally

	Lab Type		
Lab Topic	Labatorials	Equivalent	Traditional Labs
1. Density	Volume displacement	Density equation Sources of error	
2. Force Addition		Graphical methods Component method Equilibrant force	
3. Springs	Spring mass fraction	Period equation Hooke's law	Mass fraction graph
4. Circular Motion	Force direction Acceleration direction	Centripetal equation	Linearization Line of best fit
5. Restitution	Interpretation of e KE loss in collisions	Free-fall math	KE loss math
6. Pendulums	Period intuition	Period equation	Linearization

Table 6.4: Concepts best learned by labatorial and traditional students

overlook a minor procedural error (even if their overall understanding is correct), which the students would then carry forward into the following week. However, it is worth mentioning that a TA indicated in their survey for the very last traditional lab that students still did not truly understand what the line of best fit means and how it is related to experimental error. Therefore, while the contrast between the two groups may again be based on their ability to correctly do the process and not their understanding of the meaning of the process, the results certainly do indicate a stronger performance at the level under consideration.

6.3.3 Notable Student Learning Outcomes

Compiling these results with that of all the other labs, we can finally synthesize across all the data sources, achieving Step 5 of our hierarchical summarization framework. The results are summarized in Table 6.4.

Upon examining these results further, a pattern emerges in terms of the types of concepts that students of each group tend to perform well across all labs (Step 6 of the hierarchical summarization procedure): the labatorial group exhibits mastery of the core concepts of the lab, while the traditional group exhibits mastery of standardized procedures and memorization-based calculations. These results both make sense considering the focus of each type of lab; labatorials are designed to reinforce concepts, while traditional labs involve recipe-like work.

Although all students had access to resources during the final exam (i.e. the worksheets for the labatorial students and the lab notebooks for the traditional lab students) with all the same essential information and equations, the labatorial students did not seem to be as proficient at the questions about linearization or plotting a line of best fit, for example. In addition to the aforementioned possible cause of labatorial students' minor graphing errors not always getting caught by the TA, there is also the possibility that due to the nature of the questions in the worksheet, they would try and explain more than needed or overthink somehow and thus make a mistake. This also occurred quite often in the one-step, formula-based exam questions, and so the underlying cause of the discrepancy may be the same.

However, it does make sense that despite this, both groups perform equally well on the longer calculation questions. Since they cannot be solved by simple memorization (e.g. Questions 3 and 8 of the final exam) and both groups performed similar amounts of such calculations during the lab sessions, we would not expect a difference.

While we would have expected labatorial students to perform better than traditional lab students on all of the conceptual questions, there could be a multitude of reasons pertaining to the design of the course or the questions themselves that could have rendered this implementation of the course suboptimal. The results nevertheless suggest a general trend for the types of questions, i.e. conceptual vs. memorization-based numerical, that labatorials and traditional labs respectively teach students how to solve, which is a valuable result since it may hold generally for the two lab approaches regardless of the specific course content. However, additional research would be required to confirm this trend in student performance in different courses.

Chapter 7

Conclusion

In this study, we explored how the experience of learning differs between labatorials and traditional labs. In particular, we were interested in the ways in which students' affective learning experience could differ between the two types of labs as well as the ways in which they each promoted the development of conceptual understanding. It was found that students' learning experience as well as the quality of their conceptual learning was generally better in labatorials than in traditional labs by virtue of the various forms of scaffolding present in labatorials.

7.1 Summary of Key Results

The highly collaborative nature of labatorials allowed peers to support each other in the lab. Students felt a sense of camaraderie in working with their peers, feeling like it was always a team effort toward understanding. This helped them feel more comfortable sharing doubts about their knowledge and have a more positive overall experience. This sentiment was reinforced by the interactions with the TA, which—through his regular guidance at check-points and general involvement with the students—allowed students to feel more confident in working through the worksheet since they knew he was there to scaffold their understanding. Moreover, because of the low-stakes grading of labatorials, students were able to not worry about making mistakes, instead focusing on the learning experience and feeling more fulfilled upon completing the lab. This, in conjunction with the students' perceived relevance of the content beyond the lecture course, lead many students to express an improved outlook on physics in general, indicative of a highly positive affective transformation.

By virtue of this peer, TA, and graded-related scaffolding, labatorial students were also able to get more engaged in the learning process in the lab, regularly getting involved in discussions with their peers and making an effort to understand the concepts. While there was the possibility of weaker students sometimes depending on the stronger students for progressing, the peer instruction was valuable to students not only for figuring out problems, but also—by virtue of the structure of the labatorial worksheets—for effectively dealing with the cognitive dissonance involved in overcoming misconceptions. The worksheet elicited their prior ideas, the experiments performed challenged those preconceptions, and then peers worked together to resolve their conceptual inconsistencies. The strategically located checkpoints of the labatorials also ensured that the TA could verify their state of understanding and then guide their thinking at key parts of the worksheet. By virtue of these various forms of scaffolding, labatorial students exhibited a deeper conceptual understanding of the core lab concepts than the traditional lab students, typically performing better on the conceptual questions of the final exam (albeit the overall exam averages exhibited no statistically significant differences). Interviewees also all expressed a strong general preference for labatorials over the traditional approach.

In traditional labs, while there were mechanisms of support in place that helped improve students' learning experience, scaffolding was less prominent than in labatorials in all respects. The peer support in traditional labs typically involved verifying for correctness of each other's results and did not result in true collaboration. The TA played a similar role for students, being available whenever they had procedural questions about the experiment. The TA would also occasionally check in on students to see if they were doing things correctly, and so their role was largely managerial as opposed to one of guidance. These types of relatively shallow interactions, although reassuring for students, were incurred by a pressure to follow the instructions correctly in order to get a good grade. As such, for some students the recipe-like instructions themselves served as a source of support. While most students did not express having a particularly negative lab experience by virtue of these forms of support, there were no unprompted statements of satisfaction, and the overall experience of working in the lab was strongly influenced by the recipe-like lab format.

This focus on the lab instructions and error avoidance also had adverse effects on their learning. Rather than thinking about the concepts behind the experiments, traditional lab students were largely engrossed in their instructions, typically not engaging in any meaningful discussion with their peers or the TA and only trying to understand the experiment once they began writing their lab reports. Many students felt that the introductory theory explanation at the beginning of the lab helped them to begin thinking about the concepts and that seeing the concepts in a more tangible way via the experiments helped reinforce their prior understanding. However, misconceptions were less likely to be elicited and confronted in this framework, and so cognitive dissonance would not have been resolved. This absence of the conditions for conceptual change effectively encouraged students to simply follow instructions and proceed through the lab without thinking about what they were doing. The effect of this repetitive, procedural nature of traditional labs on students' learning was also apparent in the final exam of the course; the traditional lab students always performed better on questions that involved short, template-based calculations or formulaic procedures.

Upon considering these results as a whole, there are clear dichotomies between labatorials and traditional labs that emerge regarding the forms of support in the lab, the pedagogical approaches taken, and the resultant impact of these on students' conceptual learning. These dichotomies are summarized in Table 7.1.

	Lab Type	
Dimension	Labatorials	Traditional Labs
Lab Focus	Conceptual	Experimental
Student Focus	Learning	Error Avoidance
Teamwork Style	Collaborative	Independent
Accountability	Group	Individual
TA Involvement	Guidance/Collaborative	Managerial
Real-World Connection	Relevance	Tangibility
Lab Structure	Scaffolding	Instructions
In-Lab	Understanding While Doing	Doing Without Understanding
Learning Outcomes	Conceptual Understanding	Formulaic Procedures

Table 7.1: Dichotomies between labatorials and traditional labs

7.2 Recommendations for Practitioners

Due to institutional constraints, we were incapable of implementing labatorials in a fashion that fully optimizes conceptual learning. Nevertheless, there were several important things that we learned about labatorial implementation and design throughout the study that we believe are essential for one to consider should one wish to design a labatorial course within their own institutional setting.

- **TA training**: Whether a labatorial is taught by one or more TAs or the main course instructor, one must ensure that there is appropriate pedagogical training available, as the lab instructor's role as a scaffolder of knowledge is paramount to assisting students in constructing an understanding of concepts. Based on my observations of interactions in the lab, my conversations with the course TAs, and a two-month sojourn with the Physics Education Group at the University of Washington during which I had an opportunity to extensively observe their Tutorial system, I believe that training should consist of the following key elements:

    1. *A labatorial simulation together with other TAs with the trainer playing the role of the instructor for each lab.* This would allow TAs to not only familiarize themselves with the labatorial content, but also reflect on what the experience might be like

for a student (both in terms of concepts and interactions), which would help them perform their role more effectively.

2. *A discussion of strategies for eliciting student participation at checkpoints.* By design of labatorials, students should all come to the same conclusion or understanding by the time they reach each checkpoint. However, although the interviews suggested that students were comfortable interacting in the lab, some students may still not be as vocal with the TA or their peers about the things that they do not understand. Furthermore, students may think that they understand the concept, but may in fact still be lacking in some respects. As such, the TA needs to be prepared with ways of getting every student in a group to share their understanding without asking redundant questions as well as means to ensure that the questions they ask can meaningfully assess student' understanding.

3. *A discussion of strategies for dealing with student questions.* A TA teaching a labatorial for the first time may likely not be familiar with a Socratic approach to responding to questions, i.e. answering a question with another question. While responses need not always be fully Socratic, knowing ways of promoting deeper thought in responding to students' questions all the while displaying empathy would be an asset since the TA's role is to guide students' thinking.

4. *Promoting awareness of key student pitfalls and misconceptions.* Because the purpose of labatorials is to assist students in dealing with misconceptions and/or understanding a concept more deeply, a labatorial TA should be as aware as possible of the types of issues that students may have and where they stem from. This would allow them to be more prepared to deal with these issues as they arise, thereby increasing the effectiveness of their interactions with students.

- **Course alignment**: In order for students to get the most out of a labatorial, the concepts should be recently covered in a lecture section. As such, labatorials can be most ideally implemented in a setting where students must take a lecture course and its associated lab concurrently. While assigning pre-readings—as implemented in our case—is one way of countering the absence of this condition, students need sufficiently meaningful prior exposure to and experience with a topic before aiming to address the associated conceptual difficulties in the lab. Inconsistent ordering of the topics between the lecture and lab courses, even if taken concurrently, would also likely make it more frustrating for students who may already be struggling with a given concept.

- **Labatorial design**: Ideally, labatorials should be designed to only target one key misconception and such that students have ample time to discuss with their peers and work through the worksheet. While this was generally not an issue in our labatorials, students did occasionally feel time pressure in the lab that may have led them to not be able to fully grasp all parts of the worksheet. Therefore, when adapting traditional lab experiments to a labatorial format, one should not feel obliged to include every single aspect of the lab, instead distilling out the essence of the content. If necessary, one may also consider designing new experiments that allow the concept (and associated misconceptions) of interest to be more easily targeted, or perhaps changing the conceptual focus of the lab so as to make the experiment itself more fruitful. While the concept under investigation must be sufficiently challenging so as to encourage meaningful peer and TA interactions, unnecessary use of mathematics should be avoided, as this will take away from students' focus on the concepts.

In addition to these recommendations for optimizing labatorials, we can also apply the results of this study to improve the implementations of traditional labs. Namely, some simple changes to the format of a traditional lab could help avoid the inhibitors to learning identified in Section 4.3 and improve the quality of students' learning, albeit it would likely still not attain the degree of scaffolding and thus the quality of learning in labatorials. Note that these recommendations are based primarily on the specific type of traditional lab of PHYS 224. As such, they may be more or less pertinent to a different lab setting.

For example, applying a grading scheme that does not emphasize numerical correctness, but instead prioritizes evaluating students' understanding of the experiment and the concepts involved (i.e. focusing evaluation on the process rather than on the result) could help deter students' focus on error avoidance. This would not only help alleviate additional stress, but also likely encourage students to take time to think about and discuss the ideas of the lab with others more meaningfully, simultaneously helping them avoid a "do now, understand later" mindset. Another possibility that could have similar benefits (supposing that the labs must be verification experiments) would be to integrate some conceptual questions at key locations in the instructions. Framing the experiments in terms of real-life applications (or, better yet, basing them on real-life applications) would additionally assist students in perceiving the relevance of their work in the lab, improving their overall affective experience.

7.3 Contributions and Future Outlook

In addition to the aforementioned suggested recommendations for educators teaching both labatorials and traditional labs, there are also several avenues for exploration and furthering the results of this work that may be of interest to the greater research community.

As indicated in Section 5.3, there was a strong correlation between the degree of mathematics typically utilized in a student's major and their performance on the final exam in the labatorial group, but not in the traditional lab group. In a future study, the repeatability of this phenomenon could be verified for different course contexts and worksheets, from which points its cause could be investigated. This could potentially allow for the further characterization of labatorials as well as contribute to the development of more standardized design criteria for labatorial worksheets. Additionally, it was indicated in Section 5.5.2 and Appendix M that labatorial students appeared to exhibit more sophisticated reasoning in their exam question responses as well as attempt to explain their thought process more often than traditional lab students. One traditional lab student's response in particular also suggested that traditional lab students may be less willing to think through new situations, perhaps due to a template-seeking mindset incurred by their lab experiences. These interesting trends in students' thinking as well as others as yet not considered could be more deeply explored in a future work, perhaps designing interview questions that explicitly elicit students' reasoning abilities as well as their views toward problem solving in physics for each type of lab.

An additional promising avenue for future research would be to examine in greater detail the contextual codes that emerged from the interview analysis, e.g. academic background, prior lab experiences, concurrence of lab and lecture, perceived purpose of physics lab courses, etc. This would allow us to better understand the types of external factors that affect students' experience and learning in labatorials and traditional labs. Some other interesting possibilities include examining labatorials and traditional labs in the context of other physics sub-disciplines in order to see if the general conceptual learning trends posited in this work still hold for other topics. There may also exist several topic-specific nuances that may affect the way one considers the design of labatorials. While labatorials show much promise for any sub-discipline (and possibly any discipline), all currently existing work on labatorials has focused on the introductory level. Therefore, the range of applicability of labatorials could be investigated by implementing them in, for example, mid- and upper-undergraduate physics lab courses.

Despite the suboptimality of this study's implementation of labatorials, we were able to explicitly show for the first time that students learn concepts more meaningfully and deeply in labatorials than in traditional labs, all the while genuinely enjoying the experience. By explicit comparison of two different groups within a same course, the conditions for conceptual change in labatorials were identified while simultaneously confirming the absence of these conditions in traditional labs. In the future, we hope that this comparative study will serve as a source of inspiration for physics educators who wish to make simple but powerful changes in their classrooms as well as a foundation for further exploration in conceptually driven physics lab pedagogy, which has the potential not only to deepen our understanding of students' learning in a lab setting, but also to impart to students a superior education in an aspect of physics fundamental to the nature of the discipline.

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Appendices

Appendix A

Sample Labatorial Worksheet

The following is the labatorial worksheet for the fourth lab, which addressed the topics of centripetal force and acceleration. The content of this particular labatorial was adapted from the work of Sobhanzadeh (2015).

Labatorial 4: Centripetal Force
PHYS 224 – Introduction to Experimental Mechanics
CONCORDIA UNIVERSITY

Pre-Reading:

- *Physics for Scientists and Engineers* by Serway and Jewett (10^{th} ed.), Section:
    - 4.4 – A.M. : Particle in Uniform Circular Motion
    - 6.1 – Extending the Particle in Uniform Circular Motion Model (see in particular Examples 6.1 and 6.3)

Equipment: Ruler, fixed-length string, mass, photogate timer, PASCO force sensor, caliper

Learning Goals:

- Understanding the relationship between centripetal force, radius, and velocity
- Understanding the nature of the centripetal force in a simple pendulum
- Understanding some applications of centripetal force in the real world

Activity 1: The Merry-Go-Round (30-40 min.)

Problem: We wish to model the physics of a merry-go-round to understand what kind of forces act on the riders from the perspective of an observer on the ground. If a ladybug happens to be on board when the merry-go-round starts, they will also be in for quite the ride.

Question 1:
Suppose the bug is on the merry-go-round and moves around to various locations. Assume it is turning counter clockwise.

a. Draw what you think the **velocity** and **acceleration** vectors would look like at the locations shown in Figures 1 and 2. Indicate higher velocity and acceleration with longer arrows.

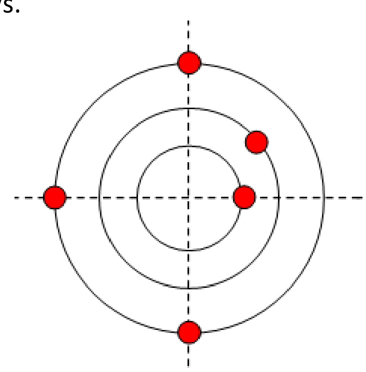


Figure 1 – Velocity vectors (expectations).

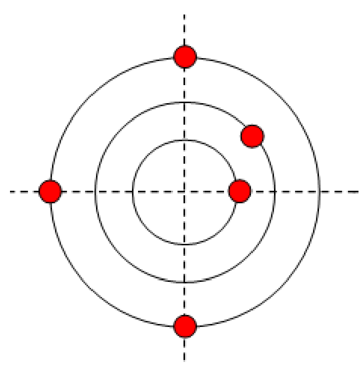


Figure 2 – Acceleration vectors (expectations).

b. Using the **Ladybug Revolution** simulation (rotation_en.jar) to check your ideas and make corrections on Figure 3 and 4. Start the simulation by clicking on the plate and spinning it or setting an angular velocity. If there were any discrepancies with your expectations, discuss why you think your intuition went wrong.

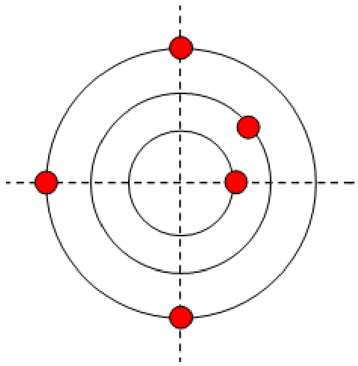


Figure 3 – Velocity vectors from the simulation.

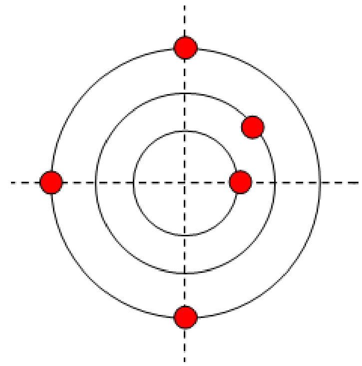


Figure 4 – Acceleration vectors from the simulation.

Question 2:

What is the nature of the centripetal force that keeps the ladybug from sliding off the merry-go-round? Draw a free-body-diagram of all the forces in the plane of rotation acting on the bug shown below. Now assume that the ladybug has a mass of 2 g and that air resistance can be ignored. By playing with the simulation, determine the maximum possible magnitude of this force. (Hint: The ladybug will get flung off if moving too quickly.)

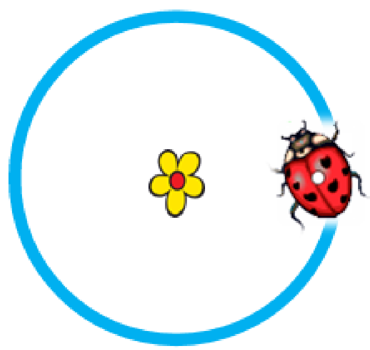


Figure 5 – Ladybug free-body diagram.

Question 3:

We know from our intuition (and the fact that the ladybug gets flung off the merry-go-round if spinning too quickly) that the ladybug would feel as though it is being pushed outward as the merry-go-round spins, just like we feel ourselves pushed toward the right in a car as it turns left around a bank. But from the free-body diagram, there should be no forces acting outward in centripetal motion according to an observer on the ground. Then why do you think we feel that outward push?

Checkpoint 1: Before moving on to the next part, have your instructor check the results you obtained so far.

Activity 2: The Simple Pendulum (70-80 min.)

Question 4:
In this part of the experiment we will have a cylinder hanging from a string tied to a force sensor (Figure 6). The cylinder will move like a pendulum. There is a photogate that measures the velocity of the cylinder at the lowest point of the swing.

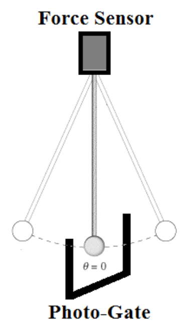


Figure 6 – An object hanging from a string exhibiting periodic motion.

a. Draw a free-body diagram for the hanging cylinder when it is not moving.

b. If the cylinder were moving, what would the free-body diagram look like at the lowest point?

Checkpoint 2: Before moving on to the next part, have your instructor check the results you obtained so far.

c. Make sure photogate is directly below the hanging cylinder. Connect the photogate to the PASCO black box (Digital Input 1). Open PASCO Capstone and click on “Hardware Setup”. An image of the PASCO black box will appear. Click on Channel 1 and choose the “Photogate” option. Click on “Hardware Setup” to make the PASCO black box image disappear. Use the caliper to measure the diameter of the cylinder. Click on the “Timer Setup” tab and click “Next” until step 3. At this step, select the type “One Photogate (Single Flag)” option and click “Next”. At step 4, ensure that “Speed” is selected and then select “Next”. At step 5, enter the measured diameter of the cylinder as the “Flag Width”, and then click on “Next” and “Finish”. Now you can click on the “Timer Setup” to close the setup window.

   d = ______________________

d. Connect the force sensor to Port 1. On PASCO Capstone, click on “Hardware Setup”. An image of the PASCO black box will appear. The “Force Sensor” icon should have appeared in Port 1. Click on “Hardware Setup” again to make the PASCO black box image disappear.

e. Remove the pendulum mass from the force sensor, hit “Record”, and drag “Digits” from the icons on the right hand side to the main page. Click on “Select Measurement” and choose the “Force (N)” option. When there is nothing attached to the force sensor (not including the string), it should read zero. To set the reading to zero, press the “ZERO” button on the force sensor. When the force sensor shows zero, stop recording data and delete the digits box by right-clicking it and selecting “Delete”.

f. Choose the “Two Displays” option and select the “Graph” options in the middle icon on both displays to create speed-versus-time and force-versus-time graphs. Add a coordinates tool (which is the approximately “+” shaped icon 8th from the left on the toolbar above each display) on each graph. Then for each graph, right-click the icon that appears and select “Tool Properties.” Open the drop down menu for “Numerical Format” and then “Vertical Coordinate”. Select “Override default number format” and set the number of decimal places to 3. Select “OK” to close the window.

g. Re-attach the pendulum. Start the cylinder swinging and hit the “Record” button on the PASCO Capstone software. Record about 15 seconds of data. Choose seven speed data points from the bottom of the motion and note the force at those data points. Enter your data into Table 1. (You may play with different starting angles if you want.)

h. Measure the length of the pendulum from the pivot point of the pendulum to the center of the cylinder.

   l = ______________________

i. What type of force does the force sensor measure in this experiment?

j. Calculate the net force for each speed and record your data in Table 1. Show a sample calculation below.

Table 1 – Measured and calculated data for the circular motion experiment.

	Speed of the Cylinder (m/s)	**Force Sensor Force** (N)	**Calculated Net Force** (N)
Point #1			
Point #2			
Point #3			
Point #4			
Point #5			
Point #6			
Point #7			

k. If you wanted to repeat the experiment again, what could you do to get better results?

l. How does the net force you have calculated compare with the force that the force sensor has measured?

m. Try to come up with a possible explanation if your calculated values are far from your experimental results. Call your lab instructor.

Checkpoint 3: Before moving on to the next part, have your instructor check the results you obtained so far.

Activity 3: Centrifuges (20-30 min.)

Question 5:
The idea of centripetal force has numerous applications, two of which are two types of centrifuge (i.e. a spinning chamber). Scientists can use large centrifuges to create artificial gravity for astronauts inside in order to prepare them for the high *g* forces experienced during a rocket launch. They can also use smaller ones to separate a heterogeneous fluid in a flask into its constituents, such as separating the plasma and red blood cells from a blood sample, or oil and water; in the centrifuge shown in the image shown in Figure 7, the denser fluid will end up at the bottom of the flask, and the less dense fluid on top. Using what you have learned so far (in particular, your answer to Question 3), try to explain how these applications work. Feel free to draw any free body diagrams if it helps with your explanation. (Hint for the fluid centrifuge part: Think about what causes oil and water in an upright flask to separate. How does rapid spinning accentuate this process?)

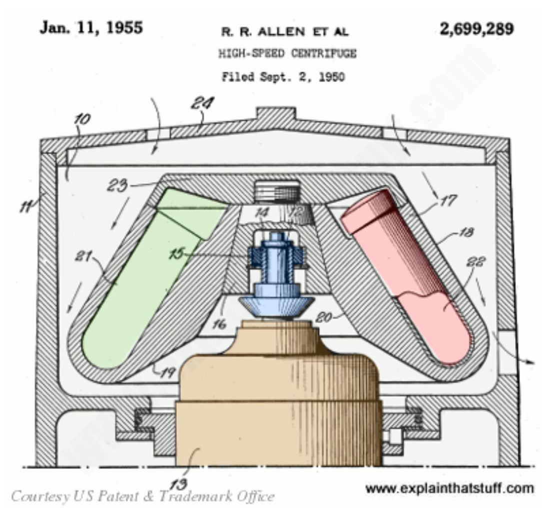


Figure 7 – A diagram of a fluid centrifuge.

Checkpoint 4: Put the equipment away and have your instructor check your work before leaving the lab.

Component	**Explanations**	**Points**	**Mark**
Worksheet	• If you finish all checkpoints, you will get 4 points.	4	
Group	• All students must be engaged in the lab activity. • All students must work, discuss, and share their information in the lab. • Interaction with group members and TA is mandatory. • All students must obtain answers to the questions that are the same as the other group members.	3	
Individual	• All appropriate data must be collected. • Data must be well organized and neatly displayed, including graphs. • The results of calculations must be presented with appropriate units. • Related physics concepts must be stated correctly.	3	

Please note that:

- Not properly cleaning the worktable or not putting away equipment that was taken out will result in a 1-point deduction from the “group” component of all members’ grades.
- As of Labatorial 2 onward, not bringing your labatorial manual (in which case, a separately printed worksheet will be provided) or pre-reading summary to the lab will result in a 1-point deduction from the “individual” component of your grade.
- Progressing as a group is critical to the success of the labatorial, and so being more than 15 minutes late will result in a 1-point deduction from the “individual” component of your grade. Being more than 20 minutes late means you cannot perform the labatorial and you will receive a 0.

Appendix B

Peer Evaluation Sheet

The following peer evaluation sheet is completed by students at the end of each labatorial session. It serves to instill a sense of accountability as well as promote constructive practices of collaboration.

NAME: ________________________ EXPERIMENT #: __________

ID: ___________________________ DATE: ___________________

Please individually complete the first two sections of this sheet after completing the labatorial worksheet and submit this to the TA. Once your grade for the labatorial is assigned, you may leave the lab.

List below the members of your team and indicate what rating you recommend for ***yourself*** *and for each other team member ("good," "incredible," or "lacking"). If you have given a rating other than "good", please indicate underneath the evaluations an explanation for the evaluation. For example, "group member X always helped those who had trouble understanding, or "group member X generally did not contribute and just copied things down."*

Name	Rating
1. __________________________________	__________________________________
2. __________________________________	__________________________________
3. __________________________________	__________________________________
4. __________________________________	__________________________________

Component	Explanations	Points	Mark
Worksheet	• If you finish all checkpoints, you will get 4 points.	4	
Group	• All students must be engaged in the lab activity. • All students must work, discuss, and share their information in the lab. • Interaction with group members and TA is mandatory. • All students must obtain answers to the questions that are the same as the other group members.	3	
Individual	• All appropriate data must be collected. • Data must be well organized and neatly displayed, including graphs. • The results of calculations must be presented with appropriate units. • Related physics concepts must be stated correctly.	3	

Please note that:

- Not properly cleaning the worktable or not putting away equipment that was taken out will result in a 1-point deduction from the "group" component of all members' grades.
- As of Labatorial 2 onward, not bringing your labatorial manual (in which case, a separately printed worksheet will be provided) or pre-reading summary to the lab will result in a 1-point deduction from the "individual" component of your grade.
- Progressing as a group is critical to the success of the labatorial, and so being more than 15 minutes late will result in a 1-point deduction from the "individual" component of your grade. Being more than 20 minutes late means you cannot perform the labatorial and you will receive a 0.

Appendix C

Labatorial Pre- and Post-Interview Guides

These are the lists of questions used as guides during the pre- and post-interviews with students from the labatorial group. The guides are designed to include corresponding pairs of questions so as to enable pre-post comparison of students' perspectives. The post-interview also contains additional questions, going into greater depth than the pre-interview.

Pre-Interview Questions
(Time Limit: 30 min.)

Section 1: General Aspects of Labs

1. Could you give me a brief overview of your academic background until now?
   - Did you come straight from high school?
   - Did you have any other educational experience before coming to Concordia?

2. As a _______ major, why do you think you need to take a physics lab course?
   - What made you take this course?
   - How do you feel about studying physics?

3. What do you think is the purpose of having lab reports in a course?
   - How useful are lab reports?

4. What do you expect out of a lab course like this?
   - Does the labatorial activity seem to help you meet your expectations of the course? If so, how (in which way)? If not, why not?

Section 2: The New Style

5. From your prior experience, can you tell me a little bit about which aspects of traditional labs you enjoy the most and the least?
   - Are there any other ideas that come to mind?
   - If they never had labs, ask: When you think of typical physics labs, what kinds of images come to mind?

6. In contrast, what aspects of labatorials do you enjoy the least so far? How about the most?
   - Did anything else in particular stand out to you?

7. Walk me through your team's process for working on the labatorial worksheets.
   - What do you think about the labatorials' checkpoint system?

8. Try and think back on your time in the lab. Can you describe how you felt about your interactions with your partners and the TA throughout the session?
   - How do these interactions compare to labs you've had in the past?
   - Were you comfortable participating and asking questions?
   - What was the atmosphere like during the labatorial?
   - What was most special to you about the team aspect of labatorials?

Section 3: Understanding

9. Just to provide some context for the next question, let me give you the definition of pre-understanding. You may already have some ideas about physics concepts such as force, velocity, mass and so on. These ideas may come from your former educational

experience, or from your experience of the real world. Let's call all those ideas in your mind before you entered this course your pre-understanding. How do you think this pre-understanding helps you learn new things?

- Do you bring your pre-understanding into studying for this course?
- If they have trouble answering: What goes through your mind when trying to learn something new? What role does your pre-understanding play in all that?
- What role does your *physics* pre-understanding play in doing labatorials?

10. In what ways do you think labatorials might allow you use your pre-understanding?
    - What kind of role did your prediction from early on in the lab play in your overall labatorial experience?
    - Were there times when you felt like your pre-understanding was not valued?
    - How do you think labatorials can help you use your pre-understanding to deal with misconceptions?

11. You probably noticed that labatorials do not give you a fixed experimental protocol to follow, but instead ask you, as a group, to figure more things out on your own. In as much detail as possible, could you tell me what it felt like doing a lab like this for the first time?
    - Do you think that the labatorials are asking for too much?
    - Does your pre-understanding ever come into play in this more independent process?

12. Can you tell me about how you felt about the conceptual questions in the worksheets?
    - How about in relation to your understanding before taking this course?
    - Did these questions play any particular role for you in progressing through the worksheet?

13. How did your understanding of the core concepts evolve throughout the lab, if at all?
    - Were there any details about the concept that were less clear before?

Post-Interview Questions
(Time Limit: 45 min.)

Section 1: General Aspects of Labs

1. If at all, how are your ideas about physics different now compared to before you took this course?
    - What about the course helped you shape your ideas?

2. Having completed the course, how do you feel about there having been no lab reports required for the course?
    - Is there a reason why you would prefer having lab reports?
    - Did the workload feel balanced with summary writing instead?
    - How much time did you spend on various aspects of the course?

3. Did the way you would prepare for the labatorial sessions change throughout the semester?
    - Did you find that summary writing was helpful for understanding the material and actually doing the labatorials?

4. What did you expect from labatorials when you were first introduced to the idea, and did labatorials meet those expectations? Please explain why or why not.
    - At first, did you think the labatorial style was weird compared to the traditional style in any particular ways?
    - In terms of what you thought you would learn, time commitment, your experiences in the lab, etc.

Section 2: The New Style

5. What aspects of labatorials did you enjoy the most and the least?
    - Did anything else in particular stand out to you?

6. Could you describe any ways in which your team's process for working on the labatorial worksheets changed over the course of the semester?
    - How important was the checkpoint system to you?

7. Try and think back on your time in the lab. If at all, how have your feelings about your interactions with your partners and the TA changed over the semester?
    - How do these interactions compare to labs you've had in the past?
    - Compare your feelings about expressing your own scientific ideas at the beginning of the course vs. at the end.
    - What kind of impact did working in teams have on solving problems?
    - What was most special to you about the team aspect of labatorials?

8. Do you feel any more or less confident in thinking independently and solving problems than you did at the beginning of the course?

Section 3: Understanding

9. Just to provide some context for the next question, let me once again give you the definition of pre-understanding. You may already have some ideas about physics concepts such as force, velocity, mass and so on. These ideas may come from your former educational experience, or from your experience of the real world. Let's call all those ideas in your mind before you entered this course your pre-understanding. How do you think this pre-understanding helped you learn?
    - Did you bring your pre-understanding into studying for this course?
    - If they have trouble answering: What went through your mind when trying to learn something new? What role did your pre-understanding play in all that?
    - What role did your *physics* pre-understanding play in doing labatorials?

10. In what ways do you think labatorials might allow you use your pre-understanding?
    - What kind of role did your predictions from early on in the labs play in your overall labatorial experience?
    - Were there times when you felt like your pre-understanding was not valued?
    - How do you think labatorials can help you use your pre-understanding to deal with misconceptions?

11. You have surely noticed that labatorials do not give you a fixed experimental recipe to follow, but instead ask you, as a group, to figure more things out on your own. Ultimately, how do you feel about this aspect of labatorials?
    - How did you find the difficulty of the labatorial questions?
    - Did you get better at answering the labatorial questions?
    - Does your pre-understanding ever come into play in this more independent process?

12. Can you tell me about how you felt about the conceptual questions in the worksheets?
    - How about in relation to your understanding before taking this course?
    - Did these questions play any particular role for you in progressing through the worksheet?

13. Having now completed the course, how does your current understanding of the concepts covered in the labs compare with your pre-understanding?
    - On a lab-by-lab basis? Overall?
    - How do you think that your understanding of core concepts has evolved in doing labatorials?

14. What could be improved in the course or the labatorials themselves to further the improvement of students' conceptual understanding?
    - Are there any other ways in which they could be improved?

15. What is your biggest take-away idea from the course (whether it be specific to the labatorial content, or something in general)?

16. If you had to take more lab courses, what format would you prefer for them?

Appendix D

Traditional Pre- and Post-Interview Guides

These are the lists of questions used as guides during the pre- and post-interviews with students from the traditional lab group. The guides are designed to include corresponding pairs of questions so as to enable pre-post comparison of students' perspectives. The post-interview also contains additional questions, going into greater depth than the pre-interview.

Pre-Interview Questions
(Time Limit: 30 min.)

Section 1: General Aspects of Labs

1. Could you give me a brief overview of your academic background until now?
    - Did you come straight from high school?
    - Did you have any other educational experience before coming to Concordia?

2. As a _______ major, why do you think you need to take a physics lab course?
    - What made you take this course?
    - How do you feel about studying physics?

3. What do you think is the purpose of having lab reports in a course?
    - How useful are lab reports?

4. What do you expect out of a lab course like this?
    - Does the lab activity seem to help you meet your expectations of the course? If so, how (in which way)? If not, why not?

Section 2: The Traditional Style

5. From your prior experience, can you tell me a little bit about which aspects of labs you enjoy the most and the least?
    - Are there any other ideas that come to mind?
    - If they never had labs, ask: When you think of typical physics labs, what kinds of images come to mind?

6. What would you want in your ideal lab course?

7. Walk me through your team's process for working on the lab.

8. Try and think back on your time in the lab. Can you describe how you felt about your interactions with your partners and the TA throughout the session?
    - How do these interactions compare to labs you've had in the past?
    - Were you comfortable participating and asking questions?
    - What was the atmosphere like during the lab?

Section 3: Understanding

9. Just to provide some context for the next question, let me give you the definition of pre-understanding. You may already have some ideas about physics concepts such as force, velocity, mass and so on. These ideas may come from your former educational experience, or from your experience of the real world. Let's call all those ideas in your mind before you entered this course your pre-understanding. How do you think this pre-understanding helps you learn new things?
    - Do you bring your pre-understanding into studying for this course?

- If they have trouble answering: What goes through your mind when trying to learn something new? What role does your pre-understanding play in all that?
- What role does your *physics* pre-understanding play in doing the labs?

10. In what ways do you think labs might allow you use your pre-understanding?
    - Were there times when you felt like your pre-understanding was not valued?
    - How do you think labs can help you use your pre-understanding to deal with misconceptions?

11. What do you think about the protocol format of labs?
    - If there are things that you do not like, what would you prefer instead?

12. From your experience, how do you feel about conceptual physics questions?
    - What if labs included conceptual questions?

13. How did your understanding of the core concepts evolve throughout the lab, if at all?
    - Were there any details about the concept that were less clear before?

Post-Interview Questions
(Time Limit: 45 min.)

Section 1: General Aspects of Labs

1. If at all, how are your ideas about physics different now compared to before you took this course?
    - What about the course helped you shape your ideas?

2. Having completed the course, how do you feel about the required lab reports?
    - How much time did you spend on various aspects of the course?

3. Did the way you would prepare for the lab sessions change throughout the semester?
    - Did you find that reading the manual was helpful for understanding the material and actually doing the labs?

4. What did you expect from this lab course at the start of the semester, and did the labs meet your expectations? Please explain why or why not.
    - In terms of what you thought what you thought you would learn, time commitment, your experiences in the lab, etc.

Section 2: The Traditional Style

5. What aspects of the labs did you enjoy the most and the least?
    - Did anything else in particular stand out to you?

6. Could you describe any ways in which you or your team's process for working on the labs changed over the course of the semester?

7. Try and think back on your time in the lab. If at all, how have your feelings about your interactions with your partners and the TA changed over the semester?
    - In that regards, how does this course compare to labs you've had in the past?
    - Compare your feelings about expressing your own scientific ideas at the beginning of the course vs. at the end.
    - Did you prefer working in teams or alone? Why?

8. Do you feel any more or less confident in thinking independently and solving problems than you did at the beginning of the course?

Section 3: Understanding

9. Just to provide some context for the next question, let me once again give you the definition of pre-understanding. You may already have some ideas about physics concepts such as force, velocity, mass and so on. These ideas may come from your former educational experience, or from your experience of the real world. Let's call all those ideas in your mind before you entered this course your pre-understanding. How do you think this pre-understanding helped you learn?
    - Did you bring your pre-understanding into studying for this course?

- If they have trouble answering: What went through your mind when trying to learn something new? What role did your pre-understanding play in all that?
- What role did your *physics* pre-understanding play in doing the labs?

10. In what ways do you think labs might allow you use your pre-understanding?
    - Were there times when you felt like your pre-understanding was not valued?
    - How do you think labs can help you use your pre-understanding to deal with misconceptions?

11. Could you share some thoughts again on how you feel about the protocol format of the labs?

12. From your experience, could you remind me of how you feel about conceptual physics questions?
    - What if labs included conceptual questions?

13. Having now completed the course, how does your current understanding of the concepts covered in the labs compare with your pre-understanding?
    - On a lab-by-lab basis? Overall?
    - How do you think that your understanding has evolved in doing the labs?

14. What could be improved in the course or the labs themselves to further the improvement of students' conceptual understanding?

15. What is your biggest take-away idea from the course (whether it be specific to the lab content, or something in general)?

16. If you had to take another lab course, what kind of lab course would you want it to be?

Appendix E

Sample Post-Test and Rubrics

The following is an example of a conceptual post-test administered to the labatorial students. The associated lab was about centripetal force and acceleration, and so the questions aimed to evaluate students' understanding of the directions of these vectors and the factors that affect them. Sample solutions and grading rubrics are shown for each question.

POST-TEST 4 (Sec. 40, 42, 44) – CENTRIPETAL FORCE

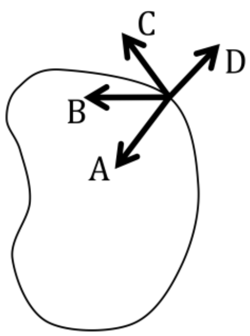
NAME: ________________________ COURSE SECTION: _____________

ID: ____________________________ DATE: ________________________

NOTE:

- No materials are allowed.
- Time allowed is 5 minutes.
- Answer in the space provided below. Use only as much space as you need.
- This post-test does not carry negative marks, so please try your best to answer. *Even if an answer is incorrect or incomplete, part marks will be given for signs of effort and for your thought process.*

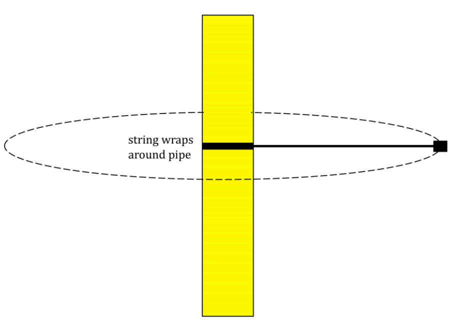
A car travels counter clockwise with *constant speed* around the track shown below. Which of the vectors (A, B, C, or D) depicts the direction of the net force acting on the car at the point shown? Explain your answer.



Sample solution: The net force points along A. Because the car is moving at constant speed, there is no acceleration (and thus no force) along the direction of the track. But since the car is turning counter clockwise around the track, there will be a force pointing towards its centre.

Grading rubric (assuming appropriate justification provided):
1.00/1.00 —> A. The student understands that the force points radially inward.
0.75/1.00 —> D. The student acknowledges that the force is radial, but confuses the centripetal and centrifugal forces.
0.50/1.00 —> B. The student understands that centripetal force points toward the centre but thinks that there is also a tangential component.
0.25/1.00 —> C. The student thinks the force points tangentially along the track.
0.00/1.00 —> The student answers without justification or makes no selection.

A string wraps around a fat pipe as a bob attached to the string is made to move in a circular path in the horizontal plane as shown below. Assuming the speed is somehow held constant as the radius decreases due to the wrapping, how will the centripetal force change? Explain your answer.



Sample solution: The centripetal force will increase since F_c = mv^2/r and the radius of the wire is shrinking as it wraps around. So if the speed (and mass) are constant, radius decreasing means that the force increases.

Grading rubric:
1.00/1.00 —> The student answers correctly and fully justifies their answer.
0.75/1.00 —> The student answers correctly and shows intuitive understanding but does not refer to the centripetal force equation.
0.50/1.00 —> The student answers incorrectly but shows some understanding.
0.25/1.00 —> The student answers incorrectly with mostly incorrect justification or just repeats information from the problem statement.
0.00/1.00 —> The student answers incorrectly with no justification or leaves the question blank.

Appendix F

Labatorial Grading Scheme

The following multiple choice quiz is a compilation of six questions from the Force Concept Inventory (Hestenes et al., 1992). The questions were selected so as to include one question from each of the main concepts tested for in the original inventory (e.g. Newton's first law, Newton's second law, gravitation, etc.).

Conceptual Quiz on Classical Mechanics

NAME: _______________________________

COURSE SECTION: ____________________

Question 1

Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:

(A) about half as long for the heavier ball as for the lighter one.

(B) about half as long for the lighter ball as for the heavier one.

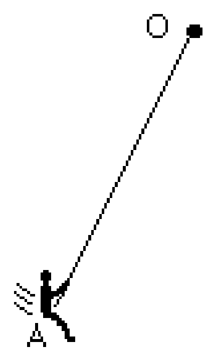
(C) about the same for both balls.

(D) considerably less for the heavier ball, but not necessarily half as long.

(E) considerably less for the lighter ball, but not necessarily half as long.

Question 2

The figure below shows a boy swinging on a rope, starting at a point higher than A.



Consider the following distinct forces:

1. A downward force of gravity.
2. A force exerted by the rope pointing from A to O.
3. A force in the direction of the boy's motion.
4. A force pointing from O to A.

Which of the above forces is (are) acting on the boy when he is at position A?

(A) 1 only.

(B) 1 and 2.

(C) 1 and 3.

(D) 1, 2, and 3.

(E) 1, 3, and 4.

Question 3

A large truck breaks down out on the road and receives a push back into town by a small compact car as shown in the figure below.

While the car, still pushing the truck, is speeding up to get up to cruising speed:

(A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.

(B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.

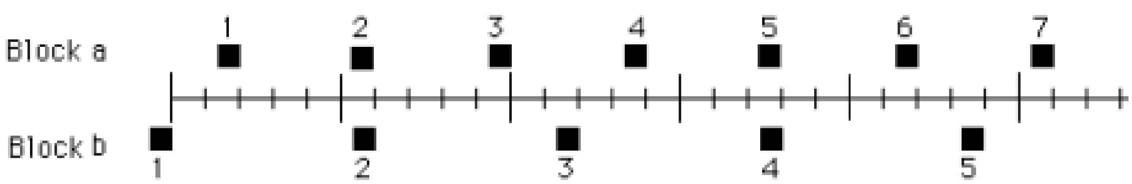
(C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.

(D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.

(E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

Question 4

The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



The accelerations of the blocks are related as follows:

(A) The acceleration of "a" is greater than the acceleration of " b".

(B) The acceleration of "a" equals the acceleration of "b". Both accelerations are greater than zero.

(C) The acceleration of "b" is greater than the acceleration of "a".

(D) The acceleration of "a" equals the acceleration of "b". Both accelerations are zero.

(E) Not enough information is given to answer the question.

Question 5

An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure below. All frictional effects are negligible. In this situation, forces on the elevator are such that:

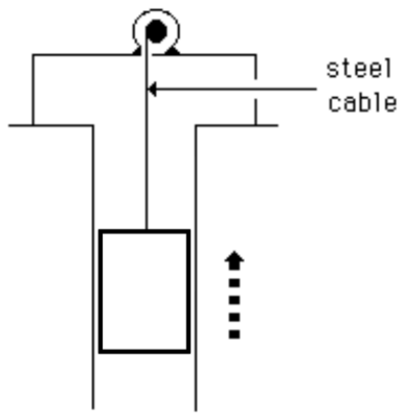
(A) the upward force by the cable is greater than the downward force of gravity.

(B) the upward force by the cable is equal to the downward force of gravity.

(C) the upward force by the cable is smaller than the downward force of gravity.

(D) the upward force by the cable is greater than the sum of the downward force of gravity and a downward force due to the air.

(E) none of the above. (The elevator goes up because the cable is being shortened, not because an upward force is exerted on the elevator by the cable).



Elevator going up
at constant speed

Question 6

A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed "v_o". The constant horizontal force applied by the woman:

(A) has the same magnitude as the weight of the box.

(B) is greater than the weight of the box.

(C) has the same magnitude as the total force which resists the motion of the box.

(D) is greater than the total force which resists the motion of the box.

(E) is greater than either the weight of the box or the total force which resists its motion.

Appendix G

Sample Class Observations

The following tables are a sample of the labatorial and traditional lab observations made during the study. Each begins with a rough description of the layout of the student groups and records each observation along with a time stamp and any personal impressions at that moment.

Labatorial 4 Observations (Section 44)

Date: May 28, 2019
Mapping: 4 students in first row, 4 in second row, 3 in fourth row

Time	Event/Details	Impressions
5:10 PM	All groups begin talking amongst themselves quite soon.	This is definitely faster than it was at the beginning of the term, though this may also have to do with the fact that the first questions of the labatorial are a little bit less wordy and theoretical.
5:15 PM	Students sketch the acceleration and velocity vectors without the simulation, and they get it a bit wrong. Namely, the length of the velocity vectors aren't longer for the larger radii.	This is a common thing that students may forget about, along the magnitude of the centripetal acceleration.
5:16 PM	Students have fun with playing with the ladybug/friction question.	Sometimes a computer can act as a source of exclusion if everyone is doing all the work, but in this case everyone seems quite entertained with the simulation, so everyone is focused.
5:23 PM	One student notes the need to convert the simulation's units to radians to keep things consistent.	This is a small detail, but it is an important one in any situation.
5:31 PM	Students have a long discussion about the nature and direction of the force keeping the ladybug on the turntable, as well as the cause for the ladybug getting flung off. Some explanations heard were "it gets flung off when the acceleration overcomes the friction," and "when the angular velocity is fast enough," and "the friction points opposite to the direction of the velocity." Another student also mentioned that because of inertia, it's when the centrifugal force exceeds the frictional force.	These are some typical examples of ideas students have about the concept of centripetal force, acceleration, and related things. Mixing up ideas between the stationary and rotating frames is common, as well as mixing up the force direction and velocity direction. But I'm hoping that with a bit of guidance from the TA, they'll get it.
5:40 PM	A student discusses with the TA about the direction that the bug gets flung off in when the friction gets overcome.	She came to realize that because the velocity points tangentially when the ladybug gets flung off, that's the way it'll keep moving when the forces stop.
5:44 PM	The guy in the middle group is a little bit less involved than usual, sitting on the rightmost side while the three girls talk.	It's hard to pinpoint exactly what the cause might be. It could be his particular state of mind for the day, the fact that they're all girls, or the fact that he might be a little bit more advanced than the others and not wanting to interfere in their discussion.
5:47 PM	A student draws the components of the tension vector in the moving pendulum	I think she understands the concept, but maybe just misunderstood the question.

	diagram as though it has an x-component. It seems like she drew it at the extreme of its motion, not at the lowest point.	
5:48 PM	Students ask me if they can proceed since they just got to a checkpoint, but I told them I couldn't do to my role as researcher. So they have to wait some more for Linxiang.	He's not being slow or anything. Rather, he's quite involved going around answering people's questions. But this is the unfortunate drawback sometimes, wherein people get delayed at checkpoints sometimes when the TA isn't available.
5:52 PM	Linxiang gets a question about centrifugal force. Linxiang explains that there's no actual force outward in the reference frame of someone on the ground.	A common misconception is about this, since there is technically a force in the rotating reference frame.
5:55 PM	A student mentions an issue where the threshold velocity is a little different depending on if the velocity was set after the bug was already moving or if it was set after being at rest.	This is something I need to maybe mention to TAs next time (or put it in the manual) so they know how to deal with it properly.
6:09 PM	Students are all already at the data recording part of the experiment.	I know that this lab is shorter than the others, but the teams are going exceptionally fast on this one.
6:11 PM	Two students debate the nature of the force being measured by the force sensor. One thinks that it's centripetal force, while the other thinks that it has nothing to do with it since simple harmonic motion is involved.	Both students have a slight misconception here; one where she is forgetting the effect of gravity, and the other that centripetal motion and SHM are always two separate phenomena in physics.
6:50 PM	The first group finished.	Way faster than last semester, but I guess it's not so bad to have one lab that's a little bit lower pressure. Though maybe a bit more could be added in the future.

Lab 6 Observations (Section 43)

Mapping: 2 students per row (except 3 in middle one)

Time	Event/Details	Impressions
1:35 PM	Linxiang begins lab explanation.	All the students are gathered around the board, which is a rather rare sight for this course.
1:41 PM	I remember that there were generally larger teams for the first lab (around 3 people).	I'm not sure why the groups have become smaller here. It may just be coincidence, in particular due to there being 10 people and 5 stations.
1:45 PM	Linxiang goes around helping people with troubleshooting their setup.	For sure this is the most complicated setup that they had to use so far, so it's understandable that they need more time for that.
1:53 PM	I chat casually with Amiel about the end of classes and the niceness of the campus.	I know he's an interviewee so he knows me better, but he's always very open and pleasant to talk to. It would be nice if I could build that kind of rapport with all students.
1:54 PM	It's hard to hear specific conversations since everyone is about equally medium-loud (and Zean and the girl he's with are not speaking English).	It looks like I'll really need to go near a station and listen closely for a couple of minutes to get proper observations.
1:55 PM	The clamp of the 4th setup gives and the force sensor falls into the apparatus with a thud.	Maybe the equipment is older, or something wasn't set up properly. I just hope nothing broke.
2:12 PM	Linxiang talks with two students about university fees for international students.	It'll cool that students seem to feel comfortable enough with him to just casually talk about things in general.
2:15 PM	A pair of students is about to finish the experiment. Linxiang was saying how it's due to the old in-class exam, but then the student said that in 225 the last experiment was much harder and that they had to stay after the exam to finish it.	This is feedback similar to what I received from Adam in the interview earlier today. It sounds like it's due to the greater complexity of the topics involved in 225, as well as of the setups. (That is, it takes longer to get things set up, so it takes longer to see the TA for help.)
2:18 PM	Eden checks with the TA about the graph she got, namely which points to use to measure the slope of the line.	She didn't seem particularly confused about it, but I've noticed in general that people tend to have trouble with properly drawing graphs.
2:19 PM	She and Lara ask about the style of the final exam after Linxiang makes a comment about something.	It's natural that they'd ask, even though everything is in the syllabus (which it seems nobody reads).
2:23 PM	I caught a peek at Amiel's lab manual, and he has almost everything in it highlighted. Others have more moderate highlighting, while some have none.	This all comes down to people's personal work styles, which is totally fine. But highlighting too much just makes everything blur together, not

		allowing what matters to stand out. It's similar when people do summary writing since it's up to them to decide what to write. But in both cases, some more specific guidance could help with this process.
2:31 PM	Zean is a little bit confused about how to interpret the slope in the F vs. v^2 graph.	This is an issue that occurs in labatorials sections too. Despite all the labs, students still have trouble. It might be that just because the equation looks different than usual, they are intimidated by it.
2:35 PM	Eden and Lara try to rationalize how to perform the different parts of their experiment, i.e. what remains constant, what they have to vary, etc.	It's only a bit surprising since I thought each of the subsections are titled such that you know what remains fixed and what changes. Though it might be the subtle thing confusing them.
2:50 PM	The lab has gotten mostly quiet since people seem to be focusing on their reports.	Makes sense since the lab is so short.
3:11 PM	The first student finishes the lab.	This is quite ahead of schedule, even for the traditional labs.
3:13 PM	Amiel's group discusses with Linxiang about the interpretation of the point (0,0) of the F vs. 1/r graph, noting how that would mean infinite radius.	This isn't a point I expected to come up, but it's a fair question actually. Not super intuitive, since when r = infinity, the force vanishes since the curvature is effectively 0.
3:16 PM	I overhear Lara and Eden notice a mistake with their graphs, meaning they have to redraw them. (I think it was plotting the wrong x-axis.)	I seem to remember them having straight lines though, so I wonder what the problem is (and I hope it's not a false alarm).
3:31 PM	One of the more advanced students helps Eden and Lara figure out their issue.	Having a third opinion proved to be quite helpful. Although it's not required, it's good to see that students will watch out for each other even if not in the same team.
3:36 PM	Amiel tells Linxiang about how he finds the TAs in other departments don't always care as much, but that he appreciates what he's doing here in physics.	I feel like it's rare for a student to give direct feedback, so I'm glad to hear that students really like Linxiang.

Appendix H

Sample Post-Lab Survey for TAs

The following is an example of a survey administered to the TAs after each of their labs. The structure and content of the surveys differ slightly depending on whether they are for a labatorial or traditional lab section. In the labatorial case, the concepts or competencies of interest are organized according to the worksheet activity they pertain to.

Labatorial 4 – TA Feedback Survey

NAME: ______________________________

This is a brief questionnaire designed to help understand your perspectives on the progress and level of understanding of students after they have performed the fourth labatorial. It will contain questions about each activity, as well as one general question. Check the box that most accurately captures your perspective for each statement. Comments are welcome.

Activity 1: The Merry-Go-Round

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Students understand that the acceleration of a body in uniform circular motion points toward the center of the motion.					
Students understand how changing the radius and speed in uniform circular motion affects the centripetal acceleration.					
Students understand the role of inertia in explaining the centrifugal force that we feel in circular motion.					

Comments (optional):

Activity 2: The Simple Pendulum

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Students understand how the tension in a simple pendulum at $\theta = 0$ varies between stationary and swinging pendulums.					
Students can explain the discrepancy between the force sensor reading and the calculated centripetal force.					

Comments (optional):

Activity 3: Centrifuges

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Students can adequately explain in terms of centripetal force how a centrifuge can simulate artificial gravity.					
Students can adequately explain in terms of centripetal force how a fluid centrifuge can separate fluids of different densities.					

Comments (optional):

Conclusion: Please briefly describe your view of how students' conceptual understanding developed as they performed the labatorial.

Appendix I

Labatorial Pre- and Post-Interview Transcripts: Catherine

These are the full transcripts of the interviews with Catherine, a student from the labatorial group. The transcripts are verbatim on the part of both the interviewer and the interviewee.

Pre-Interview Transcript – Catherine

Franco
So anyway, thanks again for coming.

Catherine
No problem.

Franco
I really appreciate it. This is my classic intro.

Catherine
It's perfect, it's great.

Franco
[laughs] So you were saying you haven't taken a physics class in a while. Was it a physics class or a lab?

Catherine
A lab. I haven't taken a physics lab since high school. I've actually already taken 204. But unfortunately, my professor passed away, so he left mid-semester. It was a stressful semester. But I feel that I learned more in the one lab than I picked up in the class, which says something good about the way it's structured and says something sad about 224.

Franco
You mean 204?

Catherine
Yes that's right.

Franco
So up until now, what was your academic background like?

Catherine
I'm from California, so I did community college there, which is kind of like CEGEP here. I'm much older; I started back at school 2 years ago now, maybe a year and a half. Really, I'm working toward nursing, so I'm in a biology program here. That's pretty much that. I graduated high school in 2008, so that ages me [laughs]. But it's okay.

Franco
It doesn't matter! And it doesn't show, so don't worry about it.

Catherine
[laughs] Thanks.

Franco
So I guess as a biology major, as somebody who wants to study nursing, why do you think you have to take a physics lab course in your program?

Catherine
I think because they want you to have a well-rounded science background. And I guess maybe if I were to go into research, there are elements of physics that are important to understand for biological processes. But I would love to have it related more, you know? Like in the way that it's taught. Because it's hard to care about why the ball is falling off the table, you know? It's just very hard to find that passion to want to understand why.

Franco
That's totally understandable. And actually, I totally agree. And I do want to try and incorporate that one day into my teaching. It's just hard sometimes to find meaningful applications. Like, "Oh, a cell can do this too," but why does it really matter?

Catherine
Right, right. And I know for engineering students, you can talk about why and how the vehicle moves, and things like that. And that probably, well for certain engineers, interests them. But for someone like me…

Franco
That's totally reasonable. A balance would be nice.

Catherine
Yeah, a balance would be great to be able to make it more interesting for the life science crowd.

Franco
[2:57] Absolutely. Your rationale makes sense, like why it matters in principle. But how do you feel about physics in your heart?

Catherine
It's my least favourite science [laughs]. And the thing is, I feel like I could enjoy it. But every time I've taken it, it's been very difficult and hard for me to understand. And even when I study a lot, I still have a hard time. And yet, seeing it practically applied made it make a lot more sense than just… Like I didn't even know what the r in the equation was, and I've taken the course. That's embarrassing. Like I don't know how I passed. You know what I mean? I didn't have that base. Yes… Physics is my least favourite, but I'm hoping to be able to embrace it more in the future [laughs].

Franco
I hope so too.

Catherine
I'm actually in California (this summer); I'm going back for the summer. And I'm gonna take a baby algebra-based physics course not for credit there just to try and get… Like I went into the class, and it felt like they were speaking another language.

Franco
Which class now?

Catherine
204.

Franco
Ok, very recently then.

Catherine
Yeah I took it here. And I felt like I didn't understand. So I'm gonna go and just take kind of an overview, general course in order to feel like I'm in a better place since I need to take 205 and 206 for my major. And I don't want to hate my life two semesters in a row [laughs]. I'd like to feel like I can understand. So I'm trying to help myself enjoy it more. So I'm kind of going back to the basics.

Franco
That's totally fine. To a degree it (the next course) builds off of that, some of the core concepts. Energy, forces, whatever.

Catherine
Yeah, and diagrams. Like I kind of just want to go back to baby steps and work up.

Franco
Well that's partly what we're doing next week, so it'll tie in [laughs].

Catherine
Ok perfect.

Franco
Now I know we don't have lab reports in our class, but what do you think the purpose of lab reports is in general?

Catherine
Well I think that being from a scientific background, it's important to be able to present your scientific ideas in a way that the scientific community (can understand)… Plus, if you're doing research down the road and you're reading somebody's scientific research, you want to have it laid out that way and understand how it's laid out so you can use it. So I think it's good to use. But we do that in chemistry, we do it in biology. So it's kind of nice to have a course that's more focused on the practical applications of understanding what we're doing when we're in the classroom setting than just writing reports. I mean, I know how to write a report; I've done it. But half the time, I'm rushing a bit at the end, maybe not even understanding what my data is. Like I have these numbers, I'm gonna put them in these things, and I'm gonna follow the example, and hope that it works out. Whereas I do feel that this is… I'm seeing step-by-step kind of what's happening, and the fact that he would come over and check in with us each time, and kind of affirm, "Yes, you're doing this right," or, "Actually, why don't we think about it this way instead?" is very helpful. It makes me feel like, "Yeah ok, this makes a lot of sense."

Franco
Ok great. Pedagogically though, do you think lab reports serve any purpose? Or is it really more in terms of scientific presentation and presenting your ideas?

Catherine
I mean, there have been times when it clarified a concept for me. But I think that's because it wasn't presented well to begin with. So then I had to go home and be like, "Ohh that's what I was doing." I didn't know even though I read the lab and did a pre-lab. I actually had no idea what I was doing or why. Like it happened in organic chemistry last semester. I was like, "Ohhh the reason why I'm

seeing this glow on this piece of paper is because these things are blocking it like a shadow." But I had to go home and write a report. Like the TAs, no one is sharing this information with you. Yes, I'm sure there are some pieces of information [7:19] you pick up from writing a report. I think if it's taught in a way, presented in a way where it gives you the information, maybe you wouldn't need to have that to learn what you're doing. Maybe you should know what you're doing before you do it.

Franco
[7:34] That's true. I mean I've heard different opinions about these (lab reports). Some people like being able to put your thoughts into words.

Catherine
Yeah like process it.

Franco
But I mean at the very least, labatorials kind of make you do all the thinking in the lab. So in principle, if all goes well, you should at least be able to have a decent grasp by the end. It won't be perfect but…

Catherine
No of course, but still… And I feel like it uses the time, right? We've set this time aside, we have this course, whereas in some of my chemistry labs, I'm done in an hour. But that doesn't mean I go home and write my lab report. For that, I wait until the day before it's due, and then I don't (remember much)… But to sit there and use the time that is set aside for this class I think is nice, to spend more time going through it rather than having to kind of stay on task on your own. I can do that, but it's nice to take advantage of the time that has been set-aside for that purpose.

Franco
[8:27] Sure, cool. I feel the same. Though I haven't taken this kind of lab class, but…

Catherine
[laughs] Of course, but it's neat.

Franco
That's very kind of you to say. I know it's only been one class so far, but what are you expecting from the class in terms of what you're gonna learn, maybe? Or in general?

Catherine
Probably just the practical applications of the things that I studied in the class. But it's also neat to also have those social experiences where we're all… Like psychologically, they say you learn best by teaching someone else. So when we're working in a group and you know, each of us are giving ideas. I think we're all learning more than we would in (the lectures)… I don't know, more than you would otherwise. And what do I expect?... Hopefully more of the same because I enjoyed the lab [laughs].

Franco
[9:22] Great to hear that. The content, the styles of some of them are different, but the underlying philosophy of them will be the same, so that should stay all throughout.

Catherine
Perfect.

Franco
Actually I do wanna talk more about your teamwork in a second, but first just to contrast with what you've done in the past… You've already mentioned many pieces of this, but could you just summarize for me, if you haven't said it already, what are your least and most favourite things about the traditional approaches?

Catherine
For the traditional approaches… That they weren't physics? [laughs] That's not fair, that's not fair! It's horrible.

Franco
[10:08] It's ok I'm not offended [laughs].

Catherine
I guess in other ones I've worked only with one person. So it's neat to have more… Even though I'm not a super social, like I am more introverted, but it's neat to kind of pushed into that social (situation), to be with more than one person, and to have different personalities. Cause sometimes when it's just one person, it's like… You're (the partner) great, or you're not.

Franco
So it sounds like a negative thing about the traditional (labs), maybe.

Catherine
Yeah, like only working with one person. Maybe not having so much, not feeling the support of the TAs or whoever is in the lab with you. Actually, I've had that a lot, where a lot of lab professors in California and some of the TAs here, either they're split too many ways and can't actually get around to everyone, or they just don't care, you know? [laughs] Not so much TAs here, more my lab professor in California. He was very dry. Hilarious, but didn't care.

Franco
That's unfortunate.

Catherine
Yes… The good thing about traditional (labs)…

Franco
[11:36] It doesn't have to be an extremely amazing thing, just something positive.

Catherine
No I mean, I always enjoy like the practical application, but I think that's the same in both, right? I like to get to see something or get to go deeper into something that's in front of you rather than reading about it in the textbook. I think labs are important, but… [pause]

Franco
But I mean, your silence speaks for itself I think, so…

Catherine
Sorry!

Franco
[12:00] No no, that's totally ok. Even though this is kind of like my whole project and method or whatever, I don't want to be biased, and want to explore all the angles. But now on the other end of things, what is you least and most favourite thing about labatorials?

Catherine
I really liked the groups. I really feel supported by the TA. I like that we pause and have him come over and check what we're doing to make sure we're on the right track so we're not (going down the wrong path)... We don't have to wait until we're actually stuck. I mean he'll help you if you're stuck, but then he also comes and checks to make sure that what you're doing is correct. [12:43] Actually, that's one of the things I don't like about regular labs, that you go all the way through the lab, you turn in the lab report, and *then* you find out what you did or did not do correctly. If you don't know to ask the questions leading up to that moment, you're docked a bunch of points, and you don't really understand what you're doing because nobody's guiding you. You're kind of just given a lab manual and told to go, and if you have a practical question like, "Is this what I'm supposed to do with this solution? Is this what I'm supposed to put here?" you can get very lost very fast, whereas this is more structured, which is nice. [13:22] Least favourite… I do like that it uses the whole lab time, but it also uses the whole lab time, you know? But I would be, in a practical lab, spending that time, probably even more time outside writing a lab report or figuring out what on Earth we did. So it's a double-edged sword, but I'm willing to fall on one side. I prefer staying in the lab to work through it, and then feeling like, "Oh I finished!" It's neat to have that, "Ah! I worked through it and worked hard, and I'm done now" (feeling) until next time. But the readings are fine. It's different to have to do readings, but I'd rather have to do readings than pre-labs.

Franco
[14:03] Ok. It's meant to be pretty balanced. I agree it's usually an intense lab session, because you're working hard and hopefully learning a lot during that period, but you can kind of feel at ease afterword.

Catherine
Yes, and process it, and you feel good about walking out. "Ok, I did something. I accomplished it." Not like "Now I have to do this. Now I have to remember to write the report. I have to remember exactly what I did. Did I write enough notes. Did I get the data?" All that stuff. So it's the essence of, "Ah, I applied something! How neat. I can move on with my life." So, yes…

Franco
[14:40] Actually, speaking of the time spent in the lab, could you describe a bit you and your team's process for actually working through the worksheet?

Catherine
Yeah, so what we did this last time? You just kind of work in order no?

Franco
Yeah sure. I mean I suppose, say on a given question, how do you and your team go about solving the question and moving forward?

Catherine
I think we (first) all read the question… One of our guys was late coming into the class, so we kept trying to catch (him) up.

Franco
Yeah, he had car troubles apparently…

Catherine
Yeah, poor guy, I mean he was fine, but he was always a little behind us, and we were trying to catch up him. But then he'd go off to the bathroom, neither here nor there… But we'd read the question, and each kind of discuss the idea on how to approach it. Like, "We've got this number, and we know the density, so we should use the density to find this." So we'd talk it through and then we'd start. And then we'd check with each other to make sure we're on the same page. And when we got to a point when we'd finish the math, we'd discuss it again. Yeah, I think that's basically what we did. And then we'd confer. And if we didn't know what to do, we'd ask the TA [laughs].

Franco
[15:57] Right, that's perfect. So you discuss, kind of do your own thing, bring your answers together, discuss if there's any inconsistencies, and then when you agree, you proceed.

Catherine
Which we actually found (happened) a lot since when you're talking about your… What's that, not the error, but…

Franco
The uncertainty?

Catherine
Yeah. We didn't convert it initially, so he (our teammate) got a different number and was like, "Wait, why did you get a different number?" and we realized, "Ohh you need to convert." So we were all coming together and fixing it. I wish you could take an exam like that. That would be great [laughs]. (For) things where you may be going in the right direction, but forget to switch something over. So it was a good team. I think we have a great team.

Franco
Well I'm glad things are going well so far. It's often a bit variable on the people.

Catherine
It is, it always is.

Franco
But I've seen all 3 of the sections that have labatorials this semester, and I'd say there's about 9 or 10 groups, and only 2 of them are bit shyer or don't interact as much as the rest. But it's going pretty well.

Catherine
Well hopefully once you get up to this level of education, you can get past differences or shyness and just enjoy yourself. Because you're all in it together.

Franco
[17:15] That's exactly what it is, yeah. So you're describing overall a lot of positive interactions between your partners and the TA. But how did you feel about everything compared to prior labs you've had? How did those interactions compare?

Catherine
I actually think we're working together more (in this lab), cause I think we're working on the same thing. And I know we've all read the same lab in previous labs. But you kind of come at it with a different approach, or you don't know who's gonna do what, whereas with this, for whatever reason, it kind of just flowed better. I don't know if that's the people, or if it's because it's structured and there's the questions and we all work on that and then we all move on to the next thing. I grab this, you grab this… What was the question? [laughs]

Franco
Just how your interactions in this lab compared to those in labs in the past?

Catherine
Yeah and you're with a larger group. I think I've had a lab with 4 people maybe, but it wasn't structured this way. I like that we're moving linearly.

Franco
[18:27] And actually, you mentioned 4 people. I know you were saying 2 was kind of iffy depending on who you get since you get stuck with them.

Catherine
I think 3 is a good number, but I think 4 would be fine. The good thing about 3 is that there's one (person) on either side, so you have the ability to converse better than if you had a 4th person. I mean of course we could all huddle together, so we would be fine. But I love that this lab has benches to sit on. It's the best!

Franco
Is that not a thing you usually got?

Catherine
Yeah, like in chemistry.

Franco
Oh, you have a table and stand at a table, I guess?

Catherine
Or the fume hood. So it's very nice to sit. Maybe that's the lazy human in me [laughs]. But it's nice.

Franco
[19:20] Even more ideally a lot of active learning classrooms have these roundish tables. So this way, everybody's engaged with each other. In this lab, 3 (people) is tolerable, but with 4 people they inevitably kind of get segmented into two halves. Not really their fault.

Catherine
No, but it's probably just a natural inclination. There's probably some study on that [laughs]. I think 3 is great, and you'd be fine with 2 if you were stuck being in a group of 2. But ideally, 3 is nice.

Franco
[19:56] For sure. And this may be a little redundant, but was the most special thing to you about the team aspect of the labatorials?

Catherine
The sharing of ideas, and the ability to learn from someone else. I think that principle, that you learn so much better yourself when you're teaching someone else. And then when you're presenting something and somebody else points out it that it's wrong, they're pointing it out so they're learning, but you're also learning. So I think that is the best part of it. The ability to all come together, apply those ideas, and… Yeah, it's great. I like the team aspect. It's good.

Franco
I'm loving the positive energy! Of course, if there's anything negative, feel free to be as honest as possible.

Catherine
I would, since I know you need that feedback. But I'm a bit of an idealist. Maybe by the end I'll have some negative things. But I have a lot of hope [laughs]. I'm coming into it with a very good attitude, and I'm enjoying it thus far, so I can't complain.

Franco
[21:03] So glad to hear that. Now the last few questions are gonna be a bit more specifically related to understanding, since that's kind of the underlying motive or goal of this approach. I'm just gonna give a quick little definition of sorts so that we're on the same page. It's about this idea of "pre-understanding". It's pretty much what it sounds like. It just includes all the ideas about physics you have before coming into the class, which may be from your prior education, or from your prior experience in the world just interacting with things. So how do you think that pre-understanding you take to the class helps you learn new things?

Catherine
I actually think it probably limited me [laughs]. I need to come into it with a better pre-understanding. I think because I came in with such a negative feeling about physics, I'm always looking for the opportunity to be excited about it. But I haven't found that in the majority of courses in physics that I've taken. So… How does it help me? It would create the opportunity to care about the subject matter. And even after taking 204, and you see certain things happening, and you see how something falls off, or how some things fly… You know, you then wonder about it, you think about it, even though I didn't want to care [laughs]. I cared just a little bit. Just curious about what makes that do that, or that I have an idea about this elevator I'm getting in now. Kind of like the practical applications. It does expand what you think about it. But the pre-understanding, I mean, yes it makes you interested in learning, and it does kind of give you a basis. But part of my problem is that I don't have enough of that. So that's why I want to go back and get that, because I want to love this, well, not love it, but like it. I want to enjoy taking the courses.

Franco
I mean if you do love it, it wouldn't be the worst outcome [laughs].

Catherine
Of course, it would be great! [laughs] I'm just having reasonable expectations.

Franco
[23:16] Understandable. Actually it's funny you mentioned how it (pre-understanding) can act as an inhibitor. Do you think that there are any other ways that prior understanding could inhibit you trying to learn new concepts? Let's say you have a misconception about something, right? And

you're trying to learn the proper conception. How do you think that knowledge could make it harder for you?

Catherine
I think across the board, as a human being, if you've got pre-distinguished ideas about something, it's going to make you less open to accepting new ideas, or wanting to learn something new about it. I try and not to be that person, like I think across the board; in physics, life, in general, people need to be more open to accepting and learning and processing new things because people are so closed off. "We know what we know. I know what I'm good at. I like biology. I like writing. And physics is very difficult for me." I try to look at that as a challenge. I can't say it's always easy. I can't say every day I come at it and feel like, "I'm ready!" Sometimes I just want to dig a hole, get in it, pull the dirt on top [laughs]. But no, an ideal world would be one where people are open-minded because it's not that way. So many people, myself included, you look at something, and… I'm dreading 205. Dreading it, dreading it. And I'm trying not to, but yeah… I ended up dropping it actually last semester because I had a death in my family. I walked in to take the midterm. I walked up to the door. I knew I didn't know enough to pass the midterm, so I turned around and dropped it. It's one of those things where… [ughs]. I will take it again, and I will pass it and be fine. But I do now even more go into it with this fear, so yes… It does make you more closed off or more wary of that because I don't think any of us wanna fail or be wrong, or… Yeah. So accepting that my ideas about it may actually be incorrect, I think it's a hard thing for anyone to process.

Franco
[25:43] Especially when the idea is so intuitive to you, then something that seems so unintuitive is like, "What you mean that's the right way to think about it?"

Catherine
Right, exatly.

Franco
How do you think labatorials can help you overcome that kind of wall?

Catherine
Looking at a formula, applying it to what I'm doing, and understanding what that formula means, what I'm using it for. Cause part of my problem with physics problems is I don't know what formula to use. Like sure, I can pull out what I have. But I was so far from having ever taken a physics class when I took 204. He would write like v, and then (inaudible), you know? And I didn't know what he was talking about. Like I know it's velocity, and there was an acceleration or something like that. And he never presented it because to him, that's such basic knowledge that I should have come into the class having a background in that, but (I had) no idea. It was a rough, rough road. I think using labatorials to have a practical application for these formulas, and understanding what the math is that we're doing, why are we doing this math, how to apply it…

Franco
Also what it means.

Catherine
Yeah what it means. Like I can look at a picture I drew, but it doesn't mean I have any idea about what's going on, honestly. So I think it can help a lot.

Franco
You've already said a lot of things that I agree with, things that come up with a lot of people, a big point in education theory in general. Like what makes productive learning and understanding. I think really getting your hands dirty with the things and seeing it for yourself helps solidify (the concepts).

Catherine
[27:42] Especially for someone like me that… Listen, I've watched every nature documentary on the planet, my parents are dentists, I've looked at teeth, I've looked at microscopes… I've seen this stuff. So for biology, taking a lab is second nature, I know what I'm doing, whereas in physics, I look at a formula and think, "Wait, how do I use this?" and then I have to process how to use it. So it's different for me because I have no background. It's giving me a physical chance to see what's happening on paper, in the math, in all of that.

Franco
[28:22] And you've probably noticed that the approach is non-traditional in the sense that there's no fixed recipe. Like there are steps roughly, but you have to figure out a lot as you go more independently. Having done a lab like this for the first time, and given your uncertainties with physics, how would you say that went for you? How did you feel about that?

Catherine
It was good. It started off because I've done chemistry, I knew how to convert units. So it started off simple, but then it brought in all the physics of it. So she (my partner) would remind me density is just this over of this, and I was like, "Oh, of course it is, I remember that!" But it was beneficial. Like… Sorry, what was the question again?

Franco
It's ok you basically answered it. Just how was your experience doing this more self-driven kind of lab like for the first time?

Catherine
No it was great. I really feel like I learned, or confirmed what I knew. And I showed myself that I actually knew more than I thought I did, which was a great feeling. It was like, "Ok, I may not know the same amount for the next lab, but I have now kind of solidified that I know that kind of basic (material), so now I can look at something else." So it's good.

Franco
[29:51] Was it the same for the conceptual questions? Cause those are kind of unconventional as far as labs go. Not numerical in any way, just asking you to think about the underlying ideas. How did you feel about those questions?

Catherine
Were those the post-test questions?

Franco
Those were examples of such questions, but let's say question 5, where (it said), "You put a 1 cm^3 block of lead inside this thing, what's the difference of mass?" It's not really calculations, more thinking about what's happening physically.

Catherine
It helped. We had to sit there and think about it. We had to determine (an answer), and we worked (on it) and did some math that we didn't need until the next problem, which was great that we had already done it. No it's good, because that's how they're asking you to think in the class. And I had no basis for that. So I think that to not only have it applied in what you're doing in front of you, but to continue applying similar concepts to more, not abstract, but analytical, conceptual ideas was helpful. Can you tell me the answers? Is it the same with the beads and the chunk?

Franco
Yeah it's the same.

Catherine
Ok that's what I thought. I felt pretty sure, cause like there was the surface area, but also the volume…

Franco
I Think you did super awesome on the post-test, so don't worry about it.

Catherine
Ok I'm glad to hear that.

Franco
[31:19] Just one last little thing before we close off. I know you've been mentioning it here and there quite a lot. You said there were many things that confirmed your understanding. Were there any things that were clarified for you by the end of the lab?

Catherine
Yes, like what these things stand for… What was it again? The 0.1… Like when you had the difference… The uncertainty! Like he was telling us what the x and what the delta x means and what the delta r means. I didn't know how to use that. And so to now know how to use it going forward… I don't know if we'll use it in the future, but I love to know what I'm looking at. What does this stand for, what are we plugging in here. Now I know, because I didn't know. And I've taken the class, which is scary, you know? It's a little scary. But I hope for more educators who care about the learning experience in physics in general, and I hope that somehow, principles like this can be applied to a lecture level, or maybe require that you take the lab if you take the lecture, because I feel like I would have understood and been much better suited to do well in the lecture if I was concurrently taking the lab. It really helped me feel like, "Ok, this is what I'm doing. This is why this is important. This is why this matters," cause otherwise it's just a bunch of numbers on a piece of paper, and a word problem, and I can't really think of anyone who loves a word problem. I mean maybe you love a word problem [laughs].

Franco
I mean it depends [laughs]. They're there to make you think.

Catherine
[33:30] For sure. I need to learn to think. And that's what I said to the professor who came on after (the incident): I just don't know. Thinking for biology comes naturally to me. This thinking does not, and so I feel like this is a way to build it into something physical, into something that you're working together (on) in a group. You don't feel isolated, (not) like it's just me and my book trying to figure out what any of this means. This man is up there speaking to me, and I don't really know what he's

saying. He's writing a bunch of stuff on the board, and I'm copying it, but I don't really know what it means. So I think this is great. And having that peer aspect and then the TA on top to really make sure that we're all understanding, I'm very excited to continue. I'm glad that I was in this lab, in one of these sections.

Franco
I'm super happy to hear that. Well we're about done, so thank you for all your points.

Catherine
No absolutely!

Post-Interview Transcript – Catherine

Franco
My official thank you once again. There'll be a lot of questions that kind of mirror what we talked about last time, but also some extra things for the post-interview. So if at all, how would you say that your ideas about physics are any different now compared to before you took this class?

Catherine
I think I have a stronger understanding of it being applied to things. There are definitely still areas that were difficult or confusing, but it's doable, working through it. I found that I liked doing it with a group more than on my own, or just reading. And the pre-reading leading into it was helpful too. But I'm still nervous about taking the next class, and I would like to have a lab like this for my next class as opposed to what I saw the people on the other side of the class doing [laughs]. I would much rather do this, but alas…

Franco
It's very hard for me to know that, since unfortunately I don't really control that. Actually, that was gonna be my last question.

Catherine
Well we'll come back to it! [laughs]

Franco
[laughs] [1:24] It's ok, we're already good. And I mean this is maybe related to that point, actually, but now that you've done everything, how did you feel about the fact that there were no lab reports for the course?

Catherine
It was very nice, since you were able to kind of put in your time during the lab, learn, and then kind of process (it) without (leaving it for later)… I always had a hard time with reports since I felt like I didn't understand the lab enough since we would either rush through it, or it was all written there and you followed certain steps, and you didn't know what you actually did by the time you were done. And to go home and try to write a report on it when you didn't really understand is difficult. This was more working through the understanding so that when you finish, even if you were to write a report, it would be much easier than it would have been to do it otherwise. [door opens, participant says "hello"]

Franco
[2:22] I see. I mean to be fair, in this course the lab reports are in class right at the end. They're really short. But it's still kind of a separate thing from the actual lab itself, so you grapple with it at the end.

Catherine
Yeah, which is how a lot of other science labs are. You then just have to figure out what you did and why you did what you did, since you don't know going into it why you were doing half the steps, so… It's nice to work with the theory, and then do something, and then process that. It's a good flow.

Franco
As you go, you mean?

Catherine
Right, right.

Franco
[3:00] Is there any reason why you might want to have lab reports? Why you think it could be a good thing? [door closes]

Catherine
If we were at an education level where we'd never written a lab report before, maybe it would be good because I think people should know (about it), especially if they're going into sciency fields. But I mean I wrote lab reports in high school, so… I prefer it without lab reports. But there may be people who have traveled, like international students who haven't had to write one. Then learning how to write one could be good. But there are plenty of other classes to learn to write lab reports.

Franco
So all in all, would you say that the workflow of the course was okay? Balanced and everything?

Catherine
Yeah. Like I said, it was really nice to use the lab time that was set aside for the lab to do the work. And yes, then there's the outside reading, but none of that was excessively long or anything. Though some parts of it, and I don't think it had anything to do with you, I'm just not understanding what it's saying. But I think that's more a book problem than (anything)… I'm sure it's a fine book, but some of the maths stuff, I would be like, "What? What are you even talking about?" Nonetheless, physics just doesn't come as easy to me as I wish it did. But I think this class helped it be a little less scary [laughs].

Franco
That's good then. Even if not all of the readings were so clear at the beginning, that's totally fine. Part of the purpose of labatorials is to come in with what you know, understanding as much as you could, and then you refine what you were unsure about in the lab. But I don't wanna spoil my later questions, so we'll come back to this.

Catherine
[laughs] Ok no problem.

Franco
[4:50] Did the way you would prep for the labs change at all throughout the semester?

Catherine
I should have changed… I should have read through the lab. But I didn't do that only because I've been so busy, and then, "Oh, we'll get to that!" And we did. I mean I think it was the same as everyone else in the class, but I think if I had looked into it, maybe I would have been thinking, "Oh, this question's coming up, I remember!" or maybe it wouldn't have made a difference, I don't know. But it's one of those things where I was sitting in the lab I was like, "I probably should have read through this before I started so I would know what I needed." But that was on me, not anything (on you). But I think everyone's in the same boat, and we were able to finish for the most part in time. There were some things where we got tripped up on, but that's ok too.

Franco
I think you all got to like 95% in most cases, so…

Catherine
Yeah the grading was very fair, all things considered. I don't know if we're gonna get into that later, I'll rewind.

Franco
Actually I don't think that's planned anywhere, but the whole being able to finish on time things, the grading itself is something I'm thinking about quite a bit. Actually, we're here now, and I don't think it's gonna come up later so…

Catherine
Sure, we can talk about it.

Franco
Sorry about that.

Catherine
No it's fine. I just thought it was very fair. I don't know, I should have asked this at the beginning. When it says there are negative marks, maybe explaining that a little bit. (It says), "Don't guess." Students are there like, "I have an educated thought on this, and I'm gonna answer because it feels wrong not to answer it." But I guess I haven't really taken a quiz or anything like that before, so I was kind of like, "What does this mean for my grade? Should I make a guess that's based on something I think I know? If I don't know it 100%, should I leave it blank?" I should have asked this forever ago, but…

Franco
It's ok. I haven't seen your pre-test, to be honest, but you can still see them at the information desk. I think it's like if you answer nothing, you get a 0. But if you answer something wrong, you get a small deduction. I don't think it's the full weight of the question, but some small amount. So I don't think you can get -100% or anything.

Catherine
[laughs] That would be so sad!

Franco
Yeah like 0 is the lowest, if you get half right and half wrong.

Catherine
Okay, that makes sense. I should have asked that before. But like I said, I think the grading throughout the labatorials was very fair, and the questions were fair. And it was nice to work through it with the TA because you didn't get to the end and then have him be like, "Oh, you did step 1 wrong, so step 10 is (wrong)… You just screwed up all the way along." So that was nice. But I think that's all I have to say about that.

Franco
[7:59] That's okay. I do wanna come back to the TA later actually. But regarding grading, I realized the challenge more in doing it this semester; I didn't really catch on last semester. But it's really difficult to evaluate students for this kind of lab. Since students almost always get 100% or close to 100%, and I think everybody is doing what they're supposed to in principle. It's just that compared to the traditional lab students, it's (the grade) a little bit inflated, even though it wasn't last semester for other reasons, so that's why I didn't realize it until now. I think we need a more proper way to

evaluate students (inaudible 8:38), which maybe is a good thing since it's less stress since you're not worried about the grades.

Catherine
You're focusing on the learning instead. It's not so much, "Oh my goodness, I didn't write my definitions in the lab reports, and I got my grades 4 weeks now the road. So now I'm missing 25% of my lab report grade and didn't even know it." It takes those minimal mistakes and makes them a non-issue. Cause that's actually one of the most difficult things in university. Even if you're putting in a lot of effort, if you don't get your grades right away, you will continue to make those errors without being directed or having the bumpers put up. And then it's very hard to get (back on track)… Even though the grade scales are shifted down, it's still hard to do as well as I was at the community college level. And I'm sure that the education is different, but… I wanna do well, you know what I mean? We all want to do well! So it's very disheartening to feel nitpicked at. And especially when these are students who are doing your grading, it's like, "No, I didn't do a definition. But when you told me to write this, you can't have 4 areas telling me what you want, and when I follow what you wrote, it's not on this itemized list of things you wanted." It just feels like, "I had a hard time in my labs, I had hard graders in my labs. Therefore, I'm gonna be hard on you." Isn't the point to learn? Isn't the point to look into this and actually understand and not feel (put down) by those… It is what it is.

Franco
I see.

Catherine
The nice thing about this is that even with the TAs, even with you, it felt like a team effort toward understanding. Even when he'd be like, "No, think about it." You know, he wouldn't help you right away. It was still the classroom working toward understanding instead of, "I'm bigger and know more than you, so you just figure it out since I had to figure it out when I took this class." "I don't know what's going on!!" Anyways… This was a better experience.

Franco
[11:01] Nice. And I just wanna check a thing you may have mentioned earlier. In previous labs, you may not have gotten feedback until way later. So I guess that's why you must have appreciated you were basically getting feedback all the time.

Catherine
No it was great. And by the end of class you would know… Not only at the end of class, but throughout the class, stopping at the sections, having him go over it, making sure that you know what you did up to that point.

Franco
The checkpoints, you mean?

Catherine
Yeah the checkpoints. It was really really great. So I appreciated that. It just felt like you were being supported throughout instead of annoying to ask questions. I mean I still felt a little bit annoying, but those are my own personal issues. "Sorry!"

Franco
You're never annoying, so that's a non-issue.

Catherine
[laughs] Thanks!

Franco
So compared to your expectations of the course at the beginning, did you think that labatorials met those expectations?

Catherine
Yes. I think there were a couple (of labs) that were harder than I expected them to be in terms of understanding. But given that I come from a place of not understanding physics [door opens], I don't know why I thought they would be easier. Maybe from the first one, since it was just very straightforward. But I think that they were fair, and that they went over the material that we were learning in the class, and the math [door slams]… I think it was actually only 1 that I thought was difficult. Maybe not in the experiment itself, but in the mathematical understanding. But I mean, I would choose to take a labatorial again 10/10 times over a regular lab. It was a much better experience, and it did live up to the expectations I had going into it.

Franco
I'm always very pleased to hear that! But I'm also happy for you.

Catherine
Yes, I'm happy for me too! I'm happy that I got into one of these even (numbered) labs without even knowing it.

Franco
It's like you won the lottery!

Catherine
Yes I did, the physics lottery!

Franco
[13:31] You mentioned it a lot already, but if you had to pick one, what would say your most and least favourite thing about the labatorials was?

Catherine
I would say the support throughout. The least… Maybe, and this was very rare, but… No, my least favourite was that my group kept changing. And that's not your fault at all since you have no control over that. But we were also supported through that by you and Israel, and we always… And by the end, we had our core group and stuck with it, which was nice. But there were a few thrown in there at the beginning that were a little rough. But again, not your fault. It's a lottery, again [laughs], that I maybe didn't win at first. But the girl in my group was amazing. We jived and dealt with whoever came along. And when Franco joined us, it was smooth sailing from then on.

Franco
Nice. I don't know how the first guy you were with was, but even if he was ok, it's more just the instability and all. It's hard to work with.

Catherine
The first guy was fine, but then he didn't come back.

Franco
Yeah so it was like, “Oh… ok.”

Catherine
Yeah exactly. And then the next, I think there were two, and Israel was like, “What are you doing here man? You’ve missed so many at this point. I don't think this is your semester for this,” which was nice for our group cause we were the people continuing to show up. So it was nice to have that support. But yeah, you can’t guarantee that with a group [door slams].

Franco
[15:24] Well at least you had one solid, nice partner from the beginning.

Catherine
Exactly, it was great. We had each other.

Franco
Did the way you would work together on the worksheets change throughout the semester?

Catherine
Did it change?

Franco
I mean, I’m asking if it did or not.

Catherine
I think it was pretty much the same throughout. We would still talk about it, read over the questions. We maybe had more time to just sit and stare at it as it got harder, and maybe critiquing what the other person thought. Not in a negative way, but just, “Are you sure about that? Because I have a question about how you did this, cause this doesn’t seem correct.” But it maybe changed too since the people were changing, you know? And Franco, who we ended up with, was much more analytical and was like, “This is just how I do it.” But how do you get there, you know? F: “I’m gonna go ask him.” C: “Ok, you go ask him.” You know, one of these types. But we didn’t find he was (inaudible, 16:47), yeah maybe just a bit more time sitting and staring at a question wondering, “What does it want from me? How do I answer this?” But that’s only because it was getting increasingly more difficult. It kind of ramped up and then dropped at the last lab, it wasn’t so bad. Not that it was bad, but just in terms of confusion…

Franco
Like mathematical confusion?

Catherine
Yes exactly. So I’d say it was about the same.

Franco
[17:11] Alright, that’s okay. And you mentioned that you liked the checkpoint system.

Catherine
Yes, I very much liked the checkpoint system. I don’t wanna work through something all the way to the end and then be wrong. I’d rather be caught at step 1, you know? You don’t wanna raise a kid to 18, “Well, I screwed up at 3 so…”

Franco
Just wasting your time.

Catherine
Exactly, now he's (inaudible). That's terrible [laughs]. Re-track!

Franco
[laughs] It's ok, I like dark humour so it's fine!

Catherine
[laughs more]

Franco
[17:58] This may be a little redundant, but to confirm, you said you had overall positive interactions with Israel and your stable partners, so that was pretty ok. How would you say the labs compared with labs you've had in the past?

Catherine
With labs I've had in the past, it was never the professor or the TA, in this case, feeling like they were on your side. It felt much more like it's me against you, which I didn't realize until I had this lab. Or I had a chemistry lab, where I felt like the professor didn't really want to be there, whereas Israel was always on time, always in a decent mood as I far as I could tell, he was always nice, always willing to answer questions. He was just really nice. And again, my partners were great, and I felt like we all gave what we had to give. They never didn't do their summaries. I had people who were keeping up with the class, which was nice, other than those two people.

Franco
Things happen I guess, so whatever.

Catherine
Yeah, I hope that whatever is going on in their lives that's stopping them from achieving corrects itself for them. But it felt like… And I said the grading was fair, so it felt like, "Even if I don't 100% understand this right now, not only is he gonna help me learn it, but the grade is gonna reflect the learning I had after, not the confusion I had before."

Franco
It made it less stressful probably while actually doing it.

Catherine
Yeah.

Franco
Mistakes are, well, not encouraged, but are welcome. If it happens, it's totally fine.

Catherine
It's a springboard to learning, instead of being like, "Oh, well, -10."

Franco
[laughs] Yeah like, "Sucks to be you." Well that's (style) on purpose, so…

Catherine
That's nice. Having less stress in university, I'm a bit older and have experienced many stressful things. But then there are some of these kids coming in. University is stressful, life is stressful. But university is I think one of the most stressful times in life since you feel like so much rides on this. Plus, you're having so much given to you for finals and things like this. It's a wonder that it doesn't throw people more off the sides of buildings. Not literally, but emotionally. So to have something, especially physics, not feel like it's causing so much stress that I can't function is very nice, to say the least.

Franco
[20:37] Well I'm happy to hear that. Just going back to the team stuff for a quick second. You've already hinted at this a lot, but what would you say was the most special to you about the team aspect of labatorials?

Catherine
Working through, not feeling alone in your confusion or your knowledge, feeling like you had 3 minds working together toward a common understanding. And so much in life is like that anyway, that it could build those team interactions, and especially on things that you don't know about. And to feel like you're in a safe enough space that it's like, "Hey, I actually don't know what I'm doing. Could you explain to me why you understand this?" We all had moments like that, where one of us was the one who knew more, and the other was the one who knew less. We were even, but we all came out of more knowledgeable. It kind of makes me wish we could take the final together, since we spend the whole labatorial doing three minds are better than just my one, and then we've gotta go and (do the exam alone)… But hopefully the learning that we all did will aid us in the final.

Franco
That reminds me of a side note that I'll come back to at the end, but there's actually a model for such two-stage exams. I wanna tell you more about it cause it's cool, but I'll tell you after.

Catherine
Oh ok!

Franco
[22:13] But basically it must have helped, like you said, with solving problems and just doing the stuff, right?

Catherine
Yeah.

Franco
Ok I see. Given all that, could you try to compare your feelings about expressing your own ideas about physics at the beginning vs. at the end of the course?

Catherine
With the group or just in general?

Franco
Sure, with the group, maybe with the TA also. Just in the class (in general).

Catherine
I mean, I think I came into it much more… I come into situations like that socially, and then kind of become more myself. It's a defense mechanism. I felt comfortable speaking to both Israel and my group members. And then that only grew throughout, instead of me feeling like, "Oh, I've gotta pull back because I feel like I look stupid," it was more of a, "Ok, it's ok for me to not know everything. It's not looked at as me being stupid. And she doesn't know everything either. And Israel is willing to help us figure this out, so this is a safe space." It felt much safer than some traditional labs do. It could also be my partners, since I've had partners in other labs where even though I probably have a better understanding, whatever's going on in their life, like the texting or the this or the that, sometimes it's hard to… Anyway, I don't know exactly where I was going with that, but it was nice to have the group that I had.

Franco
Right, it would be distracting and I guess not very conducive to learning. I'm assuming that's what you're kind of leaning toward…

Catherine
Yeah exactly.

Franco
[23:55] Would you say the same in terms of problem solving and independent thinking now that you've taken the course? Was there any improvement on that?

Catherine
Yeah, I mean, I didn't feel like I went in with very much understanding of how to problem solve in physics, and it did help. I learned some things that like to… It was nice to have the group aspect. I am very appreciative to that because it was… I didn't feel so alone in my misunderstanding or whatever, as I keep saying. But probably… Yeah, I would say that it helped my personal problem solving, and that I don't feel quite as unsure moving forward.

Franco
Ok I see. I know you haven't really had much time to test that out for yourself at this point, but there is a final next week.

Catherine
Yup, there is a final next week!

Franco
I'm sure you'll be okay, I believe!

Catherine
Thanks! Keep my fingers crossed.

Franco
[25:01] Yeah, thanks for sharing all that. Really interesting points for me to learn about. And now like last time, we're gonna shift gears a little bit and move to the more understanding and learning-centric part of the talk since that's kind of what my project is all about. So I'm just gonna recap the definition of pre-understanding from last time. Again, it's what it sounds like. It's this collection of ideas of physics you might have before coming to the class, whether from your prior schooling or

your physical intuition about stuff. So how do you think this physics pre-understanding helped you learn in the course? [pause] Take your time.

Catherine
Like I said the last time when I answered this question, I think that it kind of hindered me since it made me kind of afraid, and so I didn't go into it feeling like, "Oh I can do this, I'll be able to figure this out!" Instead it was, "Can I do this? Will I be able to figure this out?" Because of my experience, and I kind of have an interesting experience with physics. I was kind of just pushed through the class in high school because of some personal issues going on, and my teacher wanted me to graduate and helped me out. But I didn't end up picking anything up. Then I hadn't taken it until I had taken 204, and my professor ended up passing away mid-semester, and it was like very topsy-turvy, and I didn't understand very much going through that class. So I kind of feel like my pre-whatever was, "I don't actually know if I can do this at all. I have no idea." I feel much stronger now that I can, but it may not come as easily as other subjects do. So…

Franco
I also wanna just maybe… Like that's totally important I think, but I actually meant, on top of that, more like… Let's say, we know that when you try to open a door, you shouldn't push it near the hinges, but instead near the edges. You just know that from your everyday interactions with the world. Not so much say personal experiences with physics, but physical intuition and stuff. Like if I stand too much to the side, I'm gonna fall over or something. Just stupid things.

Catherine
Oh ok, so for things like that, I think that did help. But I also had pre-conceived misinformation. Like for one of the big questions we answered I was like, "It seems intuitively that there should be a force going outward, since why do I feel it when I spin?" So I mean it helped, but it also made you question it. But your physical experiences being on those rides, having done those things, watching the pendulum, how long should the pendulum be if it's long or if it's (short)… It solidifies knowledge that you think about in your daily, physical life. Like stopping on cement versus on wet pavement. I ended up thinking about these things a lot more than I did before because now you have a kind of wondering. And it's not just, "How long did the ball take to fall from here to there?" which is a question I don't really care about, but it was other things that made it more interesting because it is applied to your life.

Franco
[28:40] Nice. It's always a nice thing.

Catherine
But I think, yes, to come back to the question since I often go on tangents, I do think the pre-understanding of just your physical experience does help in this lab because this lab is applying it. So instead of it just being reading and math, it's looking at your physical experiences and applying your reasoning in math to it…

Franco
Like connecting it together?

Catherine
Yeah, connecting your physical experience with your educational experience.

Franco
Yeah I get it. It's like connecting the theory perhaps with your prior knowledge, with the base of knowledge you have or your intuition or whatever.

Catherine
Yeah you're tying them together, making those connections that weren't there before.

Franco
[29:37] Sure, and before you mentioned an interesting point about having the possibility of having a misconception sometimes. So how do you think the labatorials could help you use that understanding as a starting point to then deal with the misconception itself?

Catherine
Well that situation, I understood then what it was that… Cause the force is actually… Anyways, it helps explain why you feel that, even though that's not the force that's happening to you. And even sometimes on the pendulum questions, or something like this, we thought it would be take longer or shorter, I can't remember what, but we were wrong. And I think realizing that you're wrong is a place to start with learning. If you're just confirming that you know everything, are you learning? It's applying… I can't remember the question, I'm sorry.

Franco
It's fine. Just how labatorials help you deal with misconceptions.

Catherine
Cause you're seeing it. You're seeing it, so, "Obviously what I originally thought isn't correct, and in fact it's this and this is why." So you're answering your misconceptions, and it makes you wonder how many other misconceptions do you have [laughs].

Franco
[31:05] We all have some so don't worry. I actually have a funny story related to that related to lab 5, but I'll come back to that after as well. Some of the labs, not all, but some had these sort of prediction type questions at the beginning making you think about what might happen in this situation or this experiment. What kind of role did those play for you in the overall lab experience?

Catherine
I really liked those again since it's a way to channel your pre-existing knowledge since you're thinking about this certain thing occurring, and how do you think that would be… And then either you're concluding with something that affirms that, or you're realizing, "Hey, I was wrong! And this is why." It just goes back to the previous question. It either affirms with you knew or thought you knew, or (contradicts it)… I liked the pre-questions since it helps you think about the scenario before you get into the (lab)…

Franco
Not the pre-quiz, but the questions in the lab?

Catherine
No no, the questions in the lab, not the pre-quiz.

Franco
Ok just wanted to be clear.

Catherine
Of course, that's fair.

Franco
[32:35] Ok so, I'm sure you obviously know at this point, but you don't have much of a recipe to follow in the labatorials. Like yeah you have questions, but they're a bit more of a guide than anything. You're figuring out a lot on your own, or as a group. How did you feel about this more open-ended aspect of labatorials?

Catherine
I liked *most* of that. Though sometimes it would be nice with the actual physical part of the experiment to say, "Ok, we need to do this…" Like with the pendulum, and we had to do 3 different weights and 3 different lengths. But we did like 3 different lengths and then came to sit down and were like, "Oh wait, we needed to do 3!" Sometimes, we didn't think about the entire picture and would do part of it, and realize that we had to go back. Or that we didn't do one with a lower length so it didn't look right and we had to redo the results. But that was that one lab. And again, I think it's good to have to think it through, but sometimes when you're going to apply it, a little bit clearer direction… I don't know, I don't know what I needed.

Franco
A little bit more guidance, maybe?

Catherine
A little bit, but not much. I liked the thought questions. I liked that once you're applying and using that data, but maybe to make sure that you're getting good data that's going to help show the results… But again, in doing that we learned that, "Of course you need to take this string down much shorter. If you do it 95, 90, and 95, your results are going to look like that, while if you do one at 30, you results will look more like this." But you know, it was one of those things where we maybe weren't 100% sure on what we were testing for or didn't have an understanding, so we only shortened the string a little bit since it was the easier route, instead of moving that (noisy) thing up and down the wall [laughs].

Franco
The sweet sound of physics [laughs].

Catherine
Oh it was a great sound, that metal scraping [laughs].

Franco
Though you have a good point. They were a little bit more open ended on purpose, especially near the end. It tried to be more guided at the beginning and let you develop more yourself near the end. So maybe some things could have been a little more guided.

Catherine
Maybe a *little* clearer. But again, I would choose this over a traditional lab every time.

Franco
[35:00] Ok great. Well none of these things are fixed. They're updated and made better for the next time, so these are all valuable things to hear. And how would you say the overall difficult of the labatorial questions were?

Catherine
Like I said at the beginning, they did get increasingly more difficult maybe up to lab 5, and then lab 6 (wasn't so bad)… For lab 6, the thing that was difficult was simply that when you were combining the units, it said to have a common denominator, but then there wasn't a denominator or something…

Franco
A common base, I think.

Catherine
Ok, a common base. So maybe I took that as meaning denominator and I was confused. And it was more straightforward than we expected it to be, so we spent a lot more time than maybe was necessary. I mean it's not… It was an interesting aspect of that one labatorial. But I think lab 5 was very difficult. But leading up to that it was very manageable. And for lab 6, other than a couple of those concept questions, it was reasonable. Reasonably difficult.

Franco
(Inaudible, 26:18)

Catherine
Yes exactly.

Franco
That's what counts at least. Ultimately, how did you feel about the more conceptual questions? Not the math ones, just the ones that ask you to think.

Catherine
Like the theory?

Franco
Yeah, like the post-test questions were like that also, but there were a lot in the actual lab as well.

Catherine
Yeah there were a lot. I think it helps make your understanding a lot more concrete. Cause if it's just the math, what am I actually finding? Like, "Ok, I got the right number, but what does the right number mean? What is the theory behind the right number? It helps to have those leading questions so that when you do the mathematical parts, you understand what you're looking at.

Franco
[37:04] Ah ok, makes sense. So all in all, how would you say your current understanding of the concepts covered compares to your pre-understanding of the concepts?

Catherine
I think a lot better. I still need to review for my final, but I think that my understanding is much greater after the fact than it was before.

Franco
Would you say that even on a lab-to-lab basis? Or more in retrospect now?

Catherine
No, I think on a lab-to-lab basis since we were, even though it didn't go in a (linear fashion)… Like when I had to read from chapter 1 for lab 6, I was like, "What?!" But you're still… I think the extra stuff you put in for pre-reading was really good and helpful too. Like the little websites and things like that. That clarified a lot. And I feel like those are always better said than it is in the book, for whatever reason. But the question though was…

Franco
It was how your current understanding to your pre-understanding.

Catherine
I think it was lab-to-lab. You kind of picked up understanding *and* understood how the labs were gonna ask the questions, and how you needed to think in order to work through the labs.

Franco
[38:35] Ok that's good, cause this class' structure is really suboptimal. Ideally, it should be integrated with the theory course so that you'd see it to reinforce the theory. But it's just like, isolated labs. So if we could do something in an isolated setting, it could be even better when done properly. So already if it did something good, I'm happy to hear that.

Catherine
[laughs] Yes.

Franco
I was also hoping for a bit of your feedback or ideas. What do you think could be improved about the labatorials to further students' conceptual understanding and conceptual learning?

Catherine
I think maybe making, like I said, some of those things that aren't as theory-based a little more straightforward. Or I mean, I don't know if you could find a pre-reading for that damn math question in labatorial 5. Like he (Israel) said to focus on the math, and I tried. But I don't know if the book reading (was sufficient)… And it's not your fault, but if there's something out there that would better prepare your for that lab, it would be nice to have read that, because I kind of just sat there being spoon fed since I don't really know what's going on here. But I mean physics is a hard class, and there are (inaudible, 40:08) class. Except I don't think you wanna make it so easy that students are just skating through. You want a challenge, and you want to think, and you want all of those things. But if I could have come in to that more prepared, more than him just telling me, "There's a lot of math." Like there's a lot of math in the world, so what math do I need to focus on? I know there was the pre-reading, but sometimes I had trouble applying the mathematical parts of the pre-reading to the mathematical parts of the labatorial, and that was mainly in lab 5. The rest of it really did seem to go along with… I felt like I was doing the pre-reading for a purpose, and that I used it, and that I used my notes during the labs. So that was the one thing… [40:57] There's nothing you can do about teams, there really isn't. But if somehow there's a way to like, chain everyone together so they have to live their lives together for the next 6 weeks that would have been nice [laughs]. But I mean, I think from what I observed over all of the labs, it was pretty well divided up. Like the teams seemed to work well together, they seemed to be on a level playing field. And it's not like there was one time that was always finishing 4 times as fast as the rest of us. And the questions that we were confused about, it seems the other teams were confused too. It's not like anyone got the whiz or the genius. We were all working from a relatively similar level of…

Franco
Yeah, coming into the class.

Catherine
Yes.

Franco
[41:54] Alright I get it. All important things, which I do want to keep in mind.

Catherine
And make sure that you have to have a TA that's super supportive like Israel was for us. He was awesome. Cause if we had had any of the people that I've had from other labs, I don't think it would have been the same experience. He really elevated (the experience) and made us all feel like we were supported in the class. And I think the class size is nice too, like the fact that we didn't have 150 people or whatever, since he had the time. But I guess the class could be bigger if we had more than 1 TA, but then we're not all getting the same information because then you have (many TAs)… That's what I had in one of my organic chemistry classes, and you have two different people grading. And it was like, "She said it was ok, but you're not…" So continuing to make sure you have really supportive TAs like him, or like you, you helped too. But you were more observing.

Franco
I would have really loved too, but I had to hold back as a researcher [laughs].

Catherine
Yes, observe and report [laughs]. But yeah, he really did a great job.

Franco
Awesome, I'm glad to hear that. He's a really nice guy.

Catherine
Yeah he is, he's a nice guy.

Franco
[43:17] And all in all, just the last little question. What would you say your biggest takeaway idea from the course is? Either specific to a lab, or something in general?

Catherine
I think that I feel better about moving forward in physics in general. But, I wish that these were more readily available for the upcoming classes that I'm going to take, since I may not be as prepared for that style of physics lab, and I'm just gonna be sad for 2 semesters. And it's all your fault! [laughs]

Franco
Gosh I'm sorry! [laughs]

Catherine
No no [laughs]. Again, they say it's better to have loved and lost than to have never loved at all, right? We can apply that here. So my hope is that students in the future will have this kind of opportunity and this kind of learning, because university is hard, and this wasn't such a terrible experience.

Franco
Then we did our job well.

Catherine
You did, you did your job, it was good. So my takeaway is that physics is doable, and it is interesting, and it is applied to daily life, and it's not just found in an amusement park or… It kind of has to do with waking up in the morning. Everything that you do follows these rules and these principles, and there is a reason why this learning is important.

Franco
Ok, thanks for sharing. Is there anything else you'd like to mention in closing? I'm good.

Catherine
I think we're good.

Franco
Alright, right on time as well!

Catherine
Look at that!

Franco
Awesome, thank you very much.

Catherine
You're so welcome.

Appendix J

Traditional Pre- and Post-Interview Transcripts: Lauren

These are the full transcripts of the interviews with Lauren, a student from the traditional lab group. The transcripts are verbatim on the part of both the interviewer and the interviewee.

Pre-Interview Transcript – Lauren

Franco
Thank you so much for coming. I do honestly appreciate you taking time out of your day for this.

Lauren
Oh no problem.

Franco
We haven't had much time to talk much yet. Could you give me an overview of your background so far?

Lauren
Well I studied in… I did up to 7th grade in high school in Egypt, and then I came here to the German system, in the German school in Baie D'Urfe. And then I did 12th grade, so I have a German diploma, which makes me skip CEGEP. So this is my year 0 of university, I just finished my year 0. And now I'm starting my year 1 next year.

Franco
Oh cool. Actually I didn't even realize they had those kinds of schools here. It's helpful for those who wanna transfer in, for sure. What are you gonna study again next year?

Lauren
Behavioural neuroscience and psychology.

Franco
Sounds fun. And given that you're interested in that, why do you think you have to take this kind of physics lab course? Besides the fact that it's a prerequisite.

Lauren
Actually my friend and I were just talking about that, how I might not really need it. But I guess it's good to have that science background. Since I'm going into a science program, it might help me with other courses I'm taking such a chemistry and things like that.

Franco
Maybe. So just like background kind of knowledge.

Lauren
Exactly.

Franco
Yeah I get that. Although that does make perfect logical sense, how do you feel in your heart about physics?

Lauren
[laughs] I don't enjoy it.

Franco
That's fair.

Lauren
I don't enjoy doing physics, but I was generally really good at it in high school. But I wouldn't go out of my way to do physics.

Franco
I'm not offended in the slightest, it's totally understandable I think. Everybody has their own strengths regardless. But as somebody who wants to teach physics, I expect these kinds of reactions [laughs]. But it's ok. But I hope I'll be able to change that through my teaching, hopefully. At least give an appreciation for it.

Lauren
Yeah, it's just that I liked physics so much, and then I had physics last semester. And the professor was really really bad. So it's not really going well.

Franco
Almost every single person I've interviewed who's taken 204 said it's not good. I don't know who it is. I'd rather you don't tell me to not bias anything, but it's unfortunate.

Lauren
It's an intro course, so no one really cares about it, so it's kind of like floating.

Franco
And that's the weird thing! In my opinion, it should be the opposite. It takes more carefully designed teaching when you're at an introductory level I think, personally. But they treat it like a punishment, "Welp, you don't get to teach these cool, quantum whatever classes. You just teach mechanics." I'd love to. Just hire me instead! [laughs] Well one day. So, I was wondering what you think the purpose of lab reports is? Cause nobody really likes them, but they're usually a part of a lab course right? [3:06]

Lauren
I think it's important to get used to that structure of having things organized while you do your experiments, whether it's in physics or biology. It's just having that structure after so you can go back to your notes. Because if you come up with something important that you want for yourself, it's important to come back to it again. So lab reports are important.

Franco
Right, like organizing, communicating your ideas I guess. Do you think there's any learning benefits to lab reports?

Lauren
Yeah for sure. With me, it helps better to write stuff, so I think writing stuff while doing an experiment or something helps me keep, retain it better.

Franco
I see. That's handy then. And I guess, just given what you've seen so far, even though it's only 1 class, what are you expecting to get out of this class by the end of it?

Lauren
I think I will learn to use new equipment and for sure see how a physics lab goes since I've never had a physics lab before. And yeah, just learn how a lab is in something other than biology or chemistry.

Franco
Nice. So broaden your knowledge and your skills a little bit.

Lauren
For sure.

Franco
Makes perfect sense. So you said you haven't had physics labs before right? But have you done other kinds of labs? Bio, chem, anything?

Lauren
Yeah, I've done biology labs and chemistry labs at Concordia and other places.

Franco
Ok perfect. So based on that prior experience, which aspects of those would you say is your favourite and least favourite?

Lauren
I definitely enjoyed the experiments.

Franco
How so?

Lauren
The new experiments I've never done before. But things I haven't enjoyed is the very number-specific corrections that we had, or like the way things were structured, that if you don't get this specific value it's wrong. Like there's always an error that's gonna happen, and it could be more or it could be the equipment. So it shouldn't be very strict following…

Franco
I see. And during those experiments, you didn't have to like cite what your error was or something? Cause often you understand that it's not gonna be exact, but your error can kind of justify for that or something.

Lauren
I had intro courses here, so it wasn't really that I just had to find what my error was exactly for some reason. It was just, "This is the number I got and this is it."

Franco
Ok, so too inflexible for that.

Lauren
Exactly.

Franco
That's unfortunate. It's experimental right? So it's normal that you're gonna have errors. It's more important I think that you analyze what you got and be like, "Ok it's a bit wrong, but why?" But anyways… Is there anything else that comes to mind as far as likes or dislikes that stand out?

Lauren
Honestly I can't think of anything else. I'll probably remember everything later, but [laughs].

Franco
Ok, well we can come back to it if something comes to mind, no problem. I suppose then with those in mind, besides those points, what would you want in your ideal lab course? So if you had to design a course, take your dream lab course for physics, what do you think that would involve? [6:17]

Lauren
I think it would involve something like me coming up with my own idea and then actually coming up with my own research instead of having to follow everything step-by-step, but at the same time having the support of someone who actually knows what they're doing. Cause I still don't know what I'm doing.

Franco
Well you're learning.

Lauren
Exactly.

Franco
So beyond just, let's say, having a hypothesis and making a prediction for a given experiment, you want to have more of a say in the design, like the entire process of designing the experiment and doing it and…

Lauren
But I understand that to get to that part, I have to do things where I follow a specific hypothesis to learn the feel of things and how things work for…

Franco
Yeah of course. It's just cause I was wondering like… I think that's a great idea. But I'm wondering how you could do that and at the same time have TA's kind of guide you… I guess they would be more supervisors. They wouldn't know the experiment since you'd be the one designing it. But I think there would be some kind of compromise made there. Cool idea. Is there anything for out-of-lab things, by any chance? Like for the course as a whole. Or is it really that in-lab activity that would make it for you?

Lauren
Can you rephrase that?

Franco
Sorry, I was unclear. Like for a lab course, there's often an in-lab part and an at-home part, like reports. Is there anything else you would prefer instead of reports? Or just not have reports at all? What would you like in your ideal course?

Lauren
I think it's a good idea to write the reports in class and not take them home, especially cause when we take reports home, if it's a bigger experiment or project it should be taken home, but if it's a small things, doing it in class is more fresh and helps with remembering everything I just did, just writing it down again.

Franco
Makes sense. That's cool, I was just curious so I can make things as good for students as possible in the future. So I think today we're gonna be doing a lab alone since that's just how the course is for some reason, but based on the first lab, could you give me a description of what your team's process was like for working on the experiment, moving through the lab? [8:39]

Lauren
So we just decided, my friend and I, that we're going to read every step and do every step individually. Since we didn't know our teammates very well, we decided to kind of go alone but share with them. So we'd do things on our own and share the process. So we'd do every step, write the results next to it, and then keep going, and then ask if everyone's ok with it.

Franco
Ok, as you go?

Lauren
Yeah. Cause there are always some people who won't join the experiment completely and are basically sitting on the side. So we're like, "Are you ok with this result? Is that ok with you?" And then after that, we wrote our lab reports. We compared our results to see if we were all in the same area, and yeah.

Franco
So yeah, I guess you kind of worked on in simultaneously, but individually since you were checking with your partners as you go.

Lauren
Exactly. It's like checking with your partner, but still working individually.

Franco
Got it. I guess besides… The thing that sticks out there is the person who doesn't do anything, which is kind of annoying I think but… But at least it was you and the other…

Lauren
There were two others.

Franco
So you two were kind of doing your own thing and the others were also individual?

Lauren
Like we were all trying to help each other, but when it came to actually measuring things, it was mainly Eden and I… It has to do with me that I like to be in control of the things we do. So I measure it, and then I would be like, "Is everyone ok with that?" Someone would be like, "Oh no there's a mistake here," and we'd fix it. But I like to be in control of the results I get. [laughs]

Franco
[laughs] That's a normal feeling. So that way if something goes wrong, you can just blame yourself and you don't have to depend on people. I understand that feeling. Though the working together could have some benefits too in some contexts, I think, even though it might take a bit more personal effort to do so. Actually, how about things with the TA? How were interactions with the TA like during that lab?

Lauren
I think it was helpful to have the TA there since at some point we didn't really understand what the lab manual was telling us. So asking the TA was good since he told us what was expected of us about, and about the calculation errors that we were getting maybe just because we were overthinking the process. So the interactions with the TA were very helpful since… Yeah, it was good.

Franco
You were checking with him as you were going?

Lauren
Yeah. At times where I wasn't really sure, so I asked the TA. But other than that, it was a very individual process.

Franco
How did that kind of entire, the interactions with the TA like that and with your peers, how did that compare with your previous lab experiences? Was it kind of similar or were there differences?

Lauren
It was definitely not as strict as my other labs. My other labs were very strict all the time, like, "You can't talk to these people. You have to follow what you're doing. You have to finish in very…" It was very time-stressful in other labs. In this lab it was like, "We're done and can give in the things." It wasn't very time-sensitive. Maybe it had to do with the fact that it was a very easy lab last time, so it was very straightforward. My other labs were very time-sensitive and we had to get this done… We were working with chemicals and everything, so we had to have our lab coat on and… This was more relaxed.

Franco
Ok, so a more relaxed atmosphere, I guess overall…

Lauren
Yeah.

Franco
That's kind of nice at least. Less stressful for you.

Lauren
For sure.

Franco
Sounds like if every you needed help, you sounded pretty comfortable asking questions to the TA or whatever.

Lauren
Yeah.

Franco
Would you also be comfortable asking your teammates for help if you needed help? [12:36]

Lauren
For sure. When I wasn't sure about something, I didn't need to ask the TA. I would ask the people next to me to see, "Am I thinking in the right zone or am I completely off?"

Franco
Ok that's good. Ultimately, even if you're doing things individually, you're kind of team anyways, so it's good if you can help each other out. That's why they're teammates ultimately.

Lauren
Yup.

Franco
Those were a lot a good points, thanks for all that. So now we're entering our last subsection, which will deal with conceptual understanding of physics concepts since that's really what my research is trying to investigate, how students learn concepts in labs. So I just have to get a really quick definition so we can be on the same page, namely the definition of pre-understanding. So it's kind of what it sounds like. Before coming into a physics class, you probably have a bunch of ideas about physics concepts like force, motion, velocity, mass, whatever that could have come from your prior educational experiences, your prior courses or something, or even just your everyday experiences in the world, everyday interactions. You kind of have a feeling for how the world works, like, things fall. You know how the world works. So everything you had in your mind before you came into this physics class we'll call your pre-understanding. So how do you think this pre-understanding helps you learn new things?

Lauren
Honestly, since I come from a German background with the German education system, I feel like I did things a little bit differently. So I have this basis of knowing stuff, but somehow doing it here was completely different. Although it's the same thing, but it's just a different language and it's a different way of looking at things, for some reason. That pre-understanding I have helped me with some stuff, but doing it again solidified things, especially since I'm doing it now in English, it helped me understand things better than I did before.

Franco
What role do you think that pre-understanding actually played in that? Cause you said you were solidifying old ideas. So… It's a bit of a hard question, but how do you think that pre-understanding was actually relevant in making you understand new things?

Lauren
I think it helped me have a basis to understanding concepts that we're doing now. But at the same time, it also confused me a little since I feel like I understood things in some way, and now I'm understanding them in another way. And I was like, "Which way is right?" It shouldn't be like that, it's just that the high school understanding I had was very basic, I guess. And now that we're doing it more in depth, it should have helped me, but it didn't help me that much for some reason.

Franco
So it acted almost like an inhibitor, making it harder for you in a way.

Lauren
You think you know things but then you don't, so…

Franco
Yeah I get it. Often, you would call that a misconception sometimes. It's almost always unintentional since we understand what we think is right, and when we see something different we're like, "Why is it different?" We have to try and sort that out, you know? How do you think that labs can allow you kind of try and reconcile this maybe false pre-understanding with the accepted, correct idea? [16:10]

Lauren
I think the lab actually helps with that since you're actually in contact with these experiments and these ideas that you're having. So it helps me solidify what I actually just learned and what I learned before. So the top layer of everything I learned before this solidifies everything else.

Franco
Ok. And you think actually manipulating and seeing things makes a big difference?

Lauren
For sure.

Franco
Ok so I guess, you think that's the things that allow you to maybe try and replace the wrong understanding with the right understanding?

Lauren
Yeah.

Franco
By seeing it I guess you're more likely, not believe it, but it becomes plausible to you when you see it.

Lauren
But of course without that pre-understanding, I wouldn't really understand the lab enough, but yeah.

Franco
So it's a dual role. You need the base, even if there's cracks in it it's ok. It's just kind of cycling until you get the right… That's not the right word but…

Lauren
It's kind of back and forth.

Franco
Yeah, between your pre-understanding and the class content. I like the back-and-forth analogy, that's nice. I think I already asked what I wanted for here… Actually, were there any times in the lab where you thought your pre-understanding was irrelevant or didn't matter?

Lauren
For this lab specifically?

Franco
Yeah the one we had last week.

Lauren
I mean for this specific lab, I think it was very basic, so I think to generalize it to my pre-understanding and helping me understand something in that lab was… I don't know, like it didn't hinder me.

Franco
Ok, the pre-understanding didn't hinder you, you're saying.

Lauren
Yeah. But it like helped, there was a lot of help in converting things, like it helped… But yeah.

Franco
That's perfect, that makes sense. It's only been one lab so I know you can't say much yet. But if you're still able and willing to talk with me later in the semester, we can discuss any differences there might be later.

Lauren
Yeah sure.

Franco
Actually speaking of labs, what do you think of the protocol format of labs? You know, the step-by-step, follow the instructions style of labs.

Lauren
I actually like that since I had another lab where it was just like, "This is the procedure. Just like…" It was very vague. It was just a paragraph of, "This is what you'll be doing." It was very vague, so you might miss steps. But a very recipe-like lab is very good I think since you won't miss something and you'll follow the steps very well, which helps you actually understand, and helps you understand before the lab that you know what's happening step by step, rather then when it's just like a vague text where you have to pick out the steps for the procedure.

Franco
I get it. Is there anything you don't like about that approach by any chance?

Lauren
Sometimes it's not explained enough. Sometimes it's… It's usually straightforward, but sometimes it's so vague like, "Which device or equipment do you want me to use? Do you want me to use the previous one or the one before?" That's why the TA usually helps when it comes to these things.

Franco
Ok, so even though there's instructions, they may not be clear at times and you need to ask for help.

Lauren
Yeah. But there's only so much that can be written in a manual of how detailed things could be [laughs].

Franco
I get it. So it's kind of two extremes, I guess. There's having every detail and step vs. not having enough guidance.

Lauren
Yeah for sure.

Franco
But ultimately, I think if it was clear enough and you could follow what you're doing, that's the most important thing. Even if it's less explicit at every step, if you know where you were going with it, it would be ok.

Lauren
For sure.

Franco
There's many ways of trying to accomplish this [laughs].

Lauren
I like in the manual that it says at the top what the purpose of the lab is. So you're like, "Ok this is what we're doing today, makes sense." Rather than just having the title and you just have to read it out of the text what's happening.

Franco
Of course. I mean the context of what's going on is super important. And it wasn't in this lab or anything, but just in general from your experience, how do you feel about conceptual physics questions? [20:32]

Lauren
I think that it's nice to have a challenge to answer questions. It makes you think and have all the ideas that you learned from everywhere to put it in the same question. But usually, conceptually questions, just physics is not something I really enjoy. So doing these questions is a challenge for me. I like a challenge, it's just that I don't enjoy doing them.

Franco
That's fair. So you don't like them that much, but they still make you think a little bit.

Lauren
Exactly. That's the challenge. It's good to have at the end of an exam or something to have that question that will make you think and challenge (you), and… Yeah.

Franco
So I imagine you probably learn something by doing them, but it's probably hard, I imagine.

Lauren
[laughs] Yeah exactly. Like some people enjoy that challenge cause they're like, "Oh I just learned everything about that, and I'm gonna put everything I learned in that question." But in the context of physics necessarily, it's not nearly my most enjoyable part for me.

Franco
I understand. What if, hypothetically, labs like you're doing now included conceptual questions kind of like, not just at the end, but kind of interspersed throughout the lab between the measurements, making you think about things as you go?

Lauren
I think it would be important for labs not only to have that. But I think since it's like an intro course level lab, for a beginning lab like this, it would be a little bit hard, especially because it's a prerequisite for most people. It's something people wanna just get through, and that would be like a little bump for people.

Franco
For sure. But you said you thought it was important, right? Why did you say it was important?

Lauren
Because it makes sure we understand what we're actually doing and not just blindly following the steps. It makes sure that I understand what I just did and that I can apply it somewhere where I need to think. Yeah I actually think that towards the end as a total result, it would actually help me since I would have understood everything so much in depth by answering each question, if I get the answers before the end though [laughs]. Because I could be guessing wrong.

Franco
Right. But if the TA checks with you as you go then it's probably ok.

Lauren
For sure.

Franco
And I feel like even in a lab like this, maybe… Like I understand there's these big kind of questions that synthesize a lot of your knowledge, and those are very difficult. But I feel like you can probably find easier, small kinds of questions that are just pertinent to the thing you're doing right now, so it probably could still be appropriate for the intro level. It would just need to be designed properly.

Lauren
Exactly.

Franco
It can't be super hard for sure. [23:23] So just the last little thing I wanted to ask you and then we'll be good I think. Based on the first lab, do you find that your understanding of the core concepts kind of evolved throughout the lab in any way? Were there any points that were clearer for you at the end than at the beginning?

Lauren
Yeah I guess just reading the lab before actually going to the lab, I understand things. But going to the lab and writing the results and calculations and everything, it makes me understand the concept

more, which helps me understand what the main purpose of the lab is. So after the lab, I understand more than when I went into the lab. If that was the question…

Franco
Yeah that was perfect. Was there anything specific from last week's lab for you personally?

Lauren
I honestly can't think of something specific. But I know that when I was calculating the error and calculating things, I was aware of the error that could have happened. And the results I had… Yeah, but I can't think of something specific, sorry.

Franco
But I guess the general calculations of the densities and the errors involved, once you did the experiment you had a better idea of what they represented, maybe. How to interpret them, I guess.

Lauren
Yeah for sure.

Franco
I'm just hypothesizing also here [laughs]. But overall, you felt that you learned something by the end at least.

Lauren
Yeah.

Franco
That's what counts.

Lauren
It solidified things, yeah.

Franco
Ok perfect. And there'll probably be a question or something on that on the final, so you'll probably have to review it anyways, but that at least is a good start. Well I'm about done, so did you have any other questions or points you wanted to raise about the things we talked about so far?

Lauren
Not really [laughs].

Franco
You said everything you had to say?

Lauren
Yup, we're good. Though I wanted to ask about your research actually.

Franco
Sure no problem. I'm just gonna stop this then. But thank you again.

Lauren
No problem.

Post-Interview Transcript – Lauren

Franco
Thanks for coming again. I do really appreciate the time you're putting into this. So I'll ask a lot of similar questions to last time just to follow up, but with a couple of extra things special to the end. So how would you say, if at all, that your ideas about physics are different now than at the beginning of the course?

Lauren
I think I understand a bit more now, how things are more just not necessarily theoretical but also hands-on, and how we can prove everything with experiments rather than just reading in the book and then knowing that's what we have to do and that's it. Rather, when we do the experiments, we also see it and real life. The experiments take more than just the theory.

Franco
So a different perspective on the physics I guess, nice. What about the course helped you shape that opinion or idea?

Lauren
Honestly, I liked the course, I liked the lab. I think it was a fun part of the week where I get here, read the lab, and then do some experiment, write it down, and then I know that everything I write down will be used in my exam. So it also makes me think that I have to write it very clear, not just to get it done with. And yeah, I honestly liked that.

Franco
Ok, I'm glad to hear that. Though how about lab reports? How do you feel about that requirement now that the lab course is done?

Lauren
I honestly think… The lab reports are important, especially if I get to keep them later. But I don't think I do. I think I have to give in my notebook and not be able to keep it… So I guess it's important in some aspects, but the fact that we don't get to keep the lab reports is kind of detrimental. We don't get to see our work eventually if I wanna look back at it.

Franco
Yeah it's kind of weird actually, now that you mention it.

Lauren
[laughs] Yeah cause in other classes we get to keep our lab reports. And for example, in another biology class, we can look back at the old biology labs and be like, "Oh look, that's what I did before and that's what I remember."

Franco
That would make sense, definitely. So you think it could be a useful, nice thing to have, but as it currently is, it's a bit pointless, perhaps.

Lauren
I mean since I have an exam, that's important of course. But… No honestly, I think writing things down also makes it stick, and the organization. Especially the way we have to write the lab reports with a specific structure makes it stick more when you want to remember it later.

Franco
And for the writing, you don't mind doing it too much?

Lauren
No, it wasn't a lot of writing since it's very structured. I don't need to do a lot of writing here, a lot of writing there. It was just titles, and then I have to put under the titles, which makes it more simplistic and also effective.

Franco
Yeah, efficient too, I imagine.

Lauren
For sure.

Franco
Did you find that the way you prepared for labs changed at all throughout the semester? [3:02]

Lauren
I can say that the pre-tests, like I read the labs at the beginning, and I understood it and everything, and then I saw the way the pre-tests were structured again and realized how we get negative marks and… I guess that made me change the way I look at it. Like I don't just understand it now. I also have to focus more on specific things just for the pre-tests. Honestly, I thought the pre-tests were… They didn't show if I learned it or not. It just took off a lot of grades [laughs].

Franco
That's true, they're 10% total right? Yeah it's a pretty big chunk.

Lauren
Yeah especially because there were negative marks on it. That hurt [laughs].

Franco
I think it's more like a… I didn't put those in there, they were already there. But I think it's meant to be a motivator to actually prepare for the lab, not a meaningful assessment. Which is unfortunate since it could be both, but anyways. I get what you mean, with negative marks… The final's not like that though, so you can guess all you want [laughs]. Did you find that reading the manual and all that before was helpful for you to understand the material and understand what was going on in the lab?

Lauren
Yeah for sure. I think the fact that the lab manual was organized. There was organization… The more I read more labs, the more I realized how each one of them has a specific structure. That made me realize, "Ok, this is what we were doing here. This is the theory. This is the experiment," and I saw how clear and structured it is, which made me understand it even more.

Franco
You mean the material itself or?

Lauren
Yeah the material. Cause for me, when things are structured, I understand things better. So the fact that there's structure in the lab manual helped me understand the material more.

Franco
Sure, it's easier to follow I guess, right?

Lauren
And to retain stuff, yeah.

Franco
Absolutely. Also, this may be a half-repeat, but what did you expect from the lab course at the beginning, and did the labs actually end up meeting those expectations that you had? [5:04]

Lauren
I think they did exceed my expectations at some point. I thought it would be like I just have to sit down, write the report, and leave. But I feel like I also learned stuff, which had to do with the TA also. He was very helpful with things, and he explained things several times. So I think that was helpful. I think I enjoyed it more than I thought I would. And also the fact that the stuff I learned, since I'm doing it parallel to the course, they complete each other. Although they're not together, they complete each other a lot, and they made me realize the things that come together.

Franco
Yeah. The fact that some of the labs are a bit out of sync is unfortunate, but the content definitely does mirror itself to a degree.

Lauren
For sure.

Franco
Well I'm glad to hear it was better than you thought. That's always a nice surprise. So more specifically I guess, do you have any things about the labs specifically or just in general that you really really liked or really really didn't like? Like what were your least and most favourite things basically?

Lauren
I honestly, I liked the reports. I liked writing the reports. I liked the structure, like when just doing something, it's all over the place. But writing the reports myself, I think that was good. And if I compare it to other labs, other ones were just like, I had to fill in the blanks in some places, and that didn't make me retain things. Writing it down I think was helpful. So I think that was my favourite part. My least favourite part were the pre-tests. I'm still holding that [laughs].

Franco
That's totally fair.

Lauren
Yeah, yeah… That's it.

Franco
Anything else that stood out to you about the course?

Lauren
I think at some point, the lab manual wasn't very clear, and like I would read it before and would be like, "I don't really understand the procedure, but I'm sure the TA will explain it properly." So there

were these parts that just weren't very clear, but eventually they cleared up. I guess that had to do with the phrasing in the manual or something. Especially in the procedure part, that's the part where it seemed the most unclear.

Franco
So I guess it could use a bit of rewording or rewriting, perhaps.

Lauren
Yup.

Franco
This is always a weird question to ask since you only had 2 labs where you were actually in teams, but let's say on either an individual or team level, could you describe any ways in which your process for working through the lab changed over the course of the semester? [7:41]

Lauren
I think when we were in teams, there was a little bit more, when we talked a bit more, there was a little bit of distraction maybe that when we were in a group, we tried to help each other, but somehow someone missed something and no one really got it, and then there was something lost in the air. Whereas when I do it individually, I can ask the TA or someone next to me, but I can do my own work and my results don't rely on someone else. But doing it in a group can also be helpful since they might know something that I don't, and they could also be beneficial to me.

Franco
For sure. So this semester, did both of those things happen? The good and the bad?

Lauren
Yeah.

Franco
So there were some helpful peer-learning/teaching moments, but also maybe it wasn't super efficient sometimes.

Lauren
Yeah exactly.

Franco
Gotcha.

Lauren
Like today's lab could have been done in like an hour an a half, but there were small mistakes that we did because of lack of concentration in the group, which can maybe have caused that we stayed there a bit longer. But it's ok, it was solved at the end. It was just that effect [laughs].

Franco
Even though you were only two people?

Lauren
Mhm.

Franco
Ah I see. Well it happens sometimes, so I wouldn't worry about it too much. How about with the TA? How did you find the interactions were throughout the semester?

Lauren
I think the TA was very helpful and very ready to help at all times. And whenever he explained anything to us, it was very clear. And whenever I had a question, he really understood what I meant and helped me with it. So I think the TA was really really good this semester.

Franco
Nice. And how did that compare to labs you've had in the past? Even if it's not physics.

Lauren
I think generally, TAs are very helpful. But in this lab, I don't know, there was more of a friendly environment rather than authority. It was more open. "Can you help me with this? Can you help me with that?" So it was friendly. In other labs, it was more like an authority kind of thing. But yeah, it was good.

Franco
I'm glad to hear that. I mean I'm not sure if it's a physics thing or not, since I've heard some bad stories about chem or bio TAs times like, "Oh you should just know this." It kind of defeats the purpose, I think.

Lauren
Yeah for sure.

Franco
I think you already mentioned this, but as far as… Would you prefer working in teams or alone? Cause I know in teams there can be distractions sometimes, but there's also benefits.

Lauren
I think it depends on the experiment itself. Some experiments are meant to be done in groups, and some are better individual. So I think it just really depends on it, on the experiment.

Franco
That makes sense. This is a slight tangent, but kind of also maybe related, could you try and compare your feelings about expressing your own ideas about physics at the beginning vs. at the end of the course?

Lauren
Like you mean the material itself?

Franco
Yeah sure or…

Lauren
Like how I feel about it?

Franco
Yeah or voicing your opinions or your thoughts on a particular problem or procedure or something.

Lauren
Oh, I mean now I think I'm definitely more confident some of the stuff we did. I can talk about it more confidently. Cause not only did I do it in the class as theory and lab, but I also did it as an experiment, which kind of makes you back to reality and see how it is, remembering that connection.

Franco
Yeah makes sense. And would you say the same, would you say you felt comfortable between… Like you were alone most of the time, but for labs 1 and 6… Well you were with Eden for the last one so it's not a fair comparison. But let's say you were working with other people. Would you still feel comfortable expressing those ideas with others as well even if you're not sure about yourself perhaps?

Lauren
Yeah for sure. I also talked with several other people about stuff we did in the lab, and I was definitely comfortable expressing these ideas with other people.

Franco
Ok good. So you said that improved over the semester? Or was that more because of the experiments themselves you think?

Lauren
I think it had to do with both, the fact that the longer we were throughout the semester, there were no surprises. At the beginning I was like, "Oh no, what is this lab gonna look like?" But when you go through each lab, you realize that there's a standard form they're gonna look like, so you become more comfortable with it. And also the fact that I learned how to read the labs more detailed and understand things more thorough. So that also made me more comfortable in that aspect.

Franco
Nice. That makes sense. How about for, again on confidence, but let's say for problem solving, or generally thinking independently about, yeah problem solving? Did you feel any more or less confident in thinking about that now than at the beginning?

Lauren
I'd say about the same since I don't think… Since the labs are not really based on each other, I think it had to do more with my understanding of each individual lab. So the individual, independent thinking, I think that had to do in the lab really, but it's not like it deteriorated than before [laughs].

Franco
Ok yeah, cause they were pretty isolated topics I suppose. Well they're all mechanics, but not connected with each other across the labs. So it's hard to say if you saw in the problems if you'd feel so much more confident, it's hard to judge.

Lauren
Yeah exactly. Like I know how to approach them maybe a bit more now, but it's not like I can say, "Now I'm really comfortable about that."

Franco
That's totally reasonable. So now taking a different turn, we're gonna enter the last section, where all the questions pertain to conceptual understanding and learning in general since that's what I'm

looking at for my own project. Like last time, I'm just gonna briefly recap what the definition of pre-understanding is since it's an important topic. It's just the collection of ideas you have about physics upon entering the course, which could include ideas about things like force, acceleration, whatever. And you may have learned those in your previous classes, or you might just know them from your everyday experiences and intuition in the world. So how do you think this pre-understanding helped you learn in the class? [14:37]

Lauren
I think it helped me for sure, like stuff I've learned before, helped me. But at the same time, it got more like set in stone in my brain, if that makes sense. Like I understand a bit more now that we did that. So it definitely helped me through with the lab. But it wasn't really the basis I based everything on. Like I also tried… There was a lot of new learning, being open-minded to everything that's still to come, and not completely relying on what I learned before.

Franco
Ok, so it was a base I guess, but you weren't totally stuck on only thinking in that one way.

Lauren
Yeah, it's not like, "Oh I know all of this, it's ok." [laughs]

Franco
For sure. That's a good approach, a good outlook I think. So do you think there are any ways in which the labs helped you or might allow you to use your pre-understanding? Not rely on it, but just use it in some way.

Lauren
I think, yeah for sure. Some things that were common knowledge that we think, when we drop the ball what's gonna happen, things like that. That was a lot of pre-understanding realizing that when I drop a ball it's gonna go down and not up and things like that [laughs]. Just simple things where… Yeah, it definitely helped me… Yeah.

Franco
It helped you in what way? Could you be a bit more specific maybe?

Lauren
It helped me, like my, not necessarily my pre-understanding, but my common knowledge helped me understand basic concepts that I was like, if I look at and answer be like, and someone would see this and be like, "It's wrong." Like, "How much force is used to push a little ball? It's not gonna be too much." These little things put perspective into the answers and perspectives into the things I do.

Franco
Because of expectations I guess.

Lauren
Exactly.

Franco
You know what probably should happen. And if it doesn't you'd be like, "Wait what? What's going on here?"

Lauren
Yeah for sure.

Franco
And speaking of that scenario, let's say if that happens, it's probably because you have some kind of misconceptions or misunderstanding about something. How do you think a lab can help you use that perhaps initially false pre-understanding to deal with the misconception itself? [17:23]

Lauren
I don't think I actually faced that situation where I was like, where my previous knowledge was incorrect and then the lab fixed it. But yeah, I don't think I can have a proper answer to that.

Franco
That's ok, let's just do a thought experiment. A classic example is like for the pendulum lab, with the period of the pendulum and all that, I think you were just verifying the formula. But a lot of people might come into that thinking intuitively that the period should depend on the mass, which is not unreasonable. Cause maybe it's heaver so it's slower or something like that. But there's no mass dependence. So how do you think the lab can help you overcome that inner barrier?

Lauren
Yeah I think the fact that we saw that not only would we see the formula, but we also see it in real life. That not only proves it even more, but like kind of makes you remember things more just cause you saw it in an experiment, and you saw how it happens. So it makes you not only fix your knowledge from before, but also make it really stick.

Franco
Yeah. So if you already know it, it sticks more. And if not, then I guess it makes you realize that there's some kind of inconsistency.

Lauren
Exactly.

Franco
Seeing is believing to a degree, I suppose.

Lauren
Yeah for sure.

Franco
Could you also, on a side note, just share some thoughts again about what you thought about the protocol format of the labs? You know, the very recipe-like approach to labs.

Lauren
I think at the beginning I wasn't really supportive of it. But I think now that I did it, the fact that it's really structured that way, it makes it more and more clear to see how… Not only clear to understand, but also at the same time, clear to remember things for longer. Like now when I remember a lab, I'm gonna remember the instructions. It's gonna make me remember what we did there. Yeah.

Franco
If I may ask, what made you not so crazy about it at the beginning?

Lauren
I think because I don't necessarily like to stick to something like that. I have to make a lab report with a specific structure. So I don't really think me sticking to it was gonna help. But I think now that I did all the labs with the same format, this format is helpful, and how it helped me just generally.

Franco
Well if it helps you, then that's what matters in the end. But I agree that it could be, maybe feel a little bit restrictive perhaps in terms of just the lab, making it one way of doing it and there's no… You don't think so much sometimes, you just do it. But it has benefits sometimes as well sometimes, like you're saying. Now looking after a lab, instead, since that's pretty much the place where we say these things, the conceptual questions, how would you say you felt about the conceptual questions that you would see on the post-tests, for example? [20:23]

Lauren
I think that they're definitely good to challenge myself again to see if I understand the material. So it was… Most of them were definitely a real-life example, which helps you not only apply what you learned in the lab, but think about it outside of the bubble and just apply that knowledge. So I definitely think the post-test questions were a good challenge, like a good challenge to apply your knowledge and see how you feel about that.

Franco
It forces you to think I suppose, which is why they're always harder, definitely. What if, hypothetically speaking, the lab experiment itself had similar, not necessarily questions like that, but some kind of small conceptual questions spread throughout the procedural steps?

Lauren
I don't really… I can't imagine where it would fit in the lab. But it definitely is a good idea to have questions like this throughout the lab. It's just that since we were talking about the structure, I don't really know where it would fit in the structure. But generally, I think questions like this throughout the lab would be a good idea.

Franco
What could they help you with if they were in there and somehow fit in a nice way? What kind of benefit do you think they would have?

Lauren
I think they would have the same benefit as the post-test right now, which is just that little extra thinking, making sure that you really can apply the knowledge you have, which means you understand it fully.

Franco
Ok that makes sense. Stopping to check, "Do I know what's going on right now?" And then you would keep going.

Lauren
Exactly.

Franco
Ok cool, I think that would be a nice idea too. How would you say, now that the course is done, that your current understanding compares with your pre-understanding before the course?

Lauren
I think it definitely developed. There're more understanding of things so it definitely makes my pre-understanding richer. So now for another course, I'm definitely more comfortable, and I definitely understand more than I did before, which I think is good since now all the labs I feel about, and I think a lot of stuff will stick. Not that I just did it in the lab and then I'll forget it, but I think a lot will stuck due to the lab report, and the post-quizzes and all that.

Franco
Do you think that was more on a lab-to-lab basis, or just overall for the whole course?

Lauren
I think that lab-by-lab, which adds up to the whole course in total. So lab-by-lab I learned a little bit more, which in total has like a good basis of knowledge.

Franco
Ok, that's fair. To be honest, it was kind of a dumb question since the labs are all very separate topic-wise anyways, so I was thinking, "What if there was overlap?" But anyways…

Lauren
Well there was some overlap at some point, like some things I needed to understand… I see how there was a bit of overlap, but yeah.

Franco
That makes sense then. If you had the ability to improve or change something about the lab courses, or the labs themselves, what would you do to further improve students' conceptual understanding of the topics?

Lauren
Honestly, I can't really think of something since there's always an explanation for each group that happens, which makes sure everyone knows what they're doing. And the fact that the TA was always very involved and very helpful… So I can't really think of anything that would help me understand things further because the help was always there, and everything that could have been done to help the students was offered.

Franco
Ok, so even in terms of the style, the structure of the labs, you wouldn't change anything then?

Lauren
I can't really think of something… I know we can get our post-tests back, I didn't know that before… I know that now.

Franco
Well you can go see them at least…

Lauren
Yeah, so that's good, but now I know. So the fact that you can see your answers and where you lost points is good. But I can't really think of anything that can be improved. I think that everything one needs to perform well on this lab is offered.

Franco
Ok, that's good to hear. I guess you get some feedback from the TA, you said you can also check your post-test, and I left feedback on those so you can also look at that… I'm more or less kind of fishing for ideas of how, in an ideal lab course if I could design one, what would I wanna put in it you know? Cause honestly I don't like everything about this class, but that's just kind of my perspective on things, so I was wondering what you thought. I suppose if you had to pick one thing, what would you say your biggest take-away from this class is? Whether it's specific to the content, or something general about physics? [25:06]

Lauren
That's a hard question…

Franco
Take your time, it's all good.

Lauren
I think I learned a lot. The biggest thing I took out of this lab is the structure I guess. There's a specific structure to the labs that kind of flowed, which is I think… Whenever I have to write a report again or something, I think this is the first things that's gonna come to mind, the specific structure of writing the title, experiment, name, date, and all that, and then going with what's the objective. Like coming back to that is always really good since it's really structured, not just like, "Here are the results. But results from what?" That structure is definitely something I'll keep.

Franco
Even beyond labs, I guess it's a way to structure and organize your own thoughts, right? So communicating your ideas or whatever in the future, you can like… It helps you organize it, as you said, present them in a logical way I suppose.

Lauren
Exactly.

Franco
Cool. Is there anything else, by any chance? I know I asked for one, but is there anything else you took away from the class or?

Lauren
I mean I even… Like a lot of the content of the class… I don't think there was anything else [laughs].

Franco
Ok so structure-wise, and you learned a bit about each of the topics. So that would be a few little take-aways.

Lauren
Yeah exactly. Like I'll keep a lot of everything I learned. It's just the main part was definitely not the physics, but the structure part. I don't know why that stuck with me so much.

Franco
That's ok. If it did, then it's a great answer to the question [laughs]. It's whatever sticks with you the most. And last little thing. If you had to take another lab course, which I think you do, the other two for physics, what kind of lab course would you want it to be? Would you want it to be the exact same structure… Well ok, when I say that, I mean… Let's just say same *style* overall? Or is there a different kind of course you would want or something different about them?

Lauren
I think because the lab was so simple, the structure fit perfectly. But if it was more complex topics that were not just like basic, I think there would be… There needs to be more details in the lab manual to understand it more. But I honestly don't know what one could do to make it more understandable if it's a more complex topic, but… Yeah, I think for a basic course, like introductory courses, I think the structure is good. But if it's more complex, I don't know if it would suit it since they would take longer probably, which means they would need more thinking and… So I don't know what one could do. But I think this structure suits more simple, basic physics courses.

Franco
Yeah, that makes sense. So I guess since 225 and 226 are different topics, but on the same level of courses, you'd be ok with the same kind of lab?

Lauren
Yeah probably.

Franco
Ok, well I guess there's not much of a choice. That's what you're gonna get unfortunately, oh, or fortunately, whichever…

Lauren
[laughs] That's ok.

Franco
I say unfortunately since I'm doing education research, so that's my perspective. But if your experience was good, then that's good for you. I'm happy for that as well. Is there anything else you wanted to mention or share before we close off?

Lauren
No, I think that's all I've got.

Franco
Ok, well that's all I got too.

Lauren
Perfect, well thank you for having me.

Franco
No no, thank you so much.

Lauren
Oh no worries.

Appendix K

Qualitatively Analyzed Post-Test and Final Exam Questions

The following is a compilation of the post-test and final exam questions that were selected for qualitative analysis. The questions were selected on the basis of several statistical tests.

Post Test 1 – Question 2

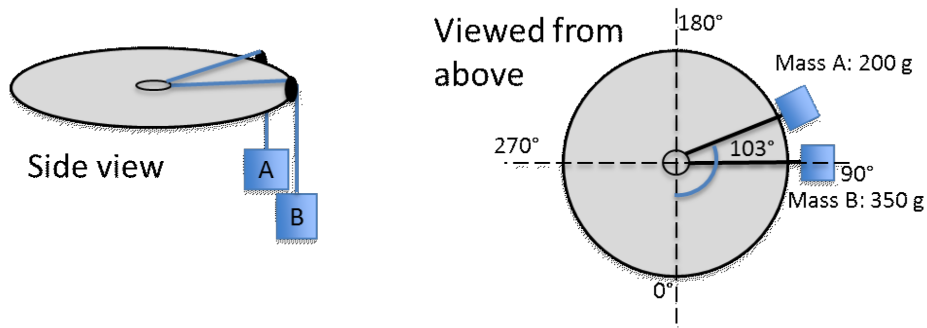
One of the reasons we were able to use the pycnometer method to measure the density of granular glass was that it was insoluble in the liquid used. It also happened to be non-absorbent. Could we use this method to measure the density of sand, which is absorbent? Explain your reasoning.

Final Exam – Question 5

When investigating the relationship between centripetal force and tangential speed for a rotating system, one often plots a graph of the centripetal force as a function of v^2. Explain why one would choose these axes for the graph; refer to the equation of centripetal force.

Final Exam – Question 8

Two masses are connected with strings to the central ring of a force table, as shown in the following diagram. If the central ring were free to move, the masses would fall to the floor. If we want the setup to be in equilibrium (not to move), calculate the 3rd mass that should be installed and at what angle it should be connected to the central ring?



Final Exam – Question 9

An object collides horizontally with a wall and bounces back having lost 70% of its energy in the collision. Calculate the coefficient of restitution of this collision.

Final Exam – Question 10

Consider the orbits of Earth and Saturn around the Sun to be approximately circular. Despite Saturn being further away from the Sun, both planets actually experience approximately the same force of gravity due to the Sun.

a. Sketch the two orbits (assuming that both planets move counter clockwise) and draw on this diagram the force experienced by each planet due to the Sun.
b. On the same diagram, draw the acceleration vector of each planet.

Final Exam – Question 14

Two balls of equal size are dropped from equal heights. However, it takes one ball more time to stop bouncing and come to equilibrium than the other. Assume that air resistance is negligible.

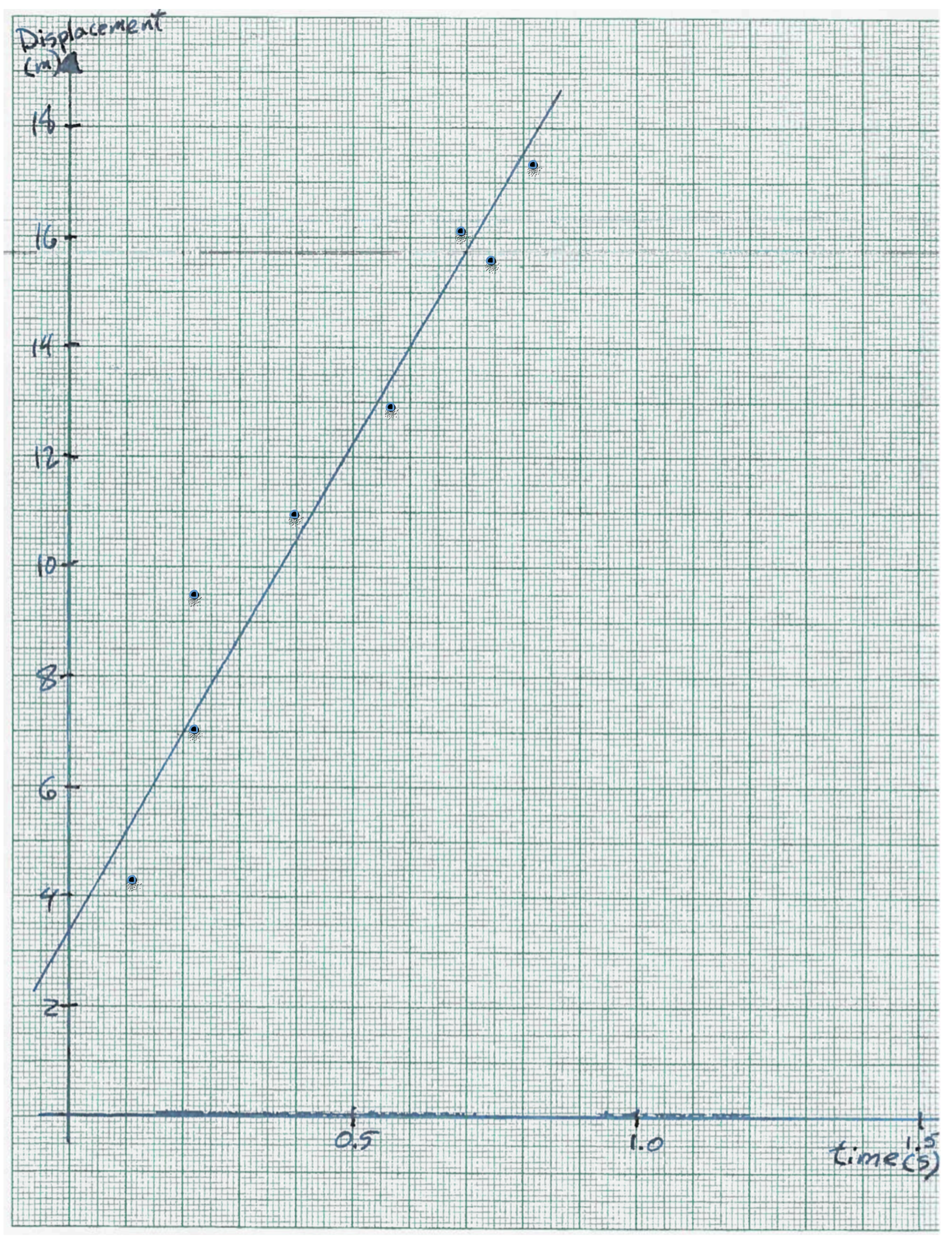
How do you know which one has the larger coefficient of restitution?

Final Exam – Question 15

A student finds the fractional mass (f) of the spring to be 1/3. Assuming that the mass of spring is 200 g, what would you expect the value of M (T^2=0) to be, in kg, on a plot of T^2 vs. M?

Final Exam – Question 17

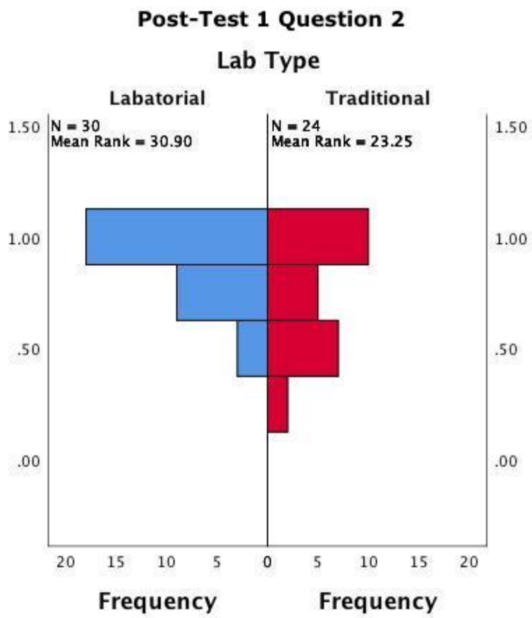
In a certain experiment, a student found the relationship between the displacement of an object and the time to be described by the following graph. The student wants to find the average speed of his object, which should be the slope of the best-fit line that was drawn through his data points. Using the graph, **calculate the average speed of the object**. Show the steps of your calculation and your units.

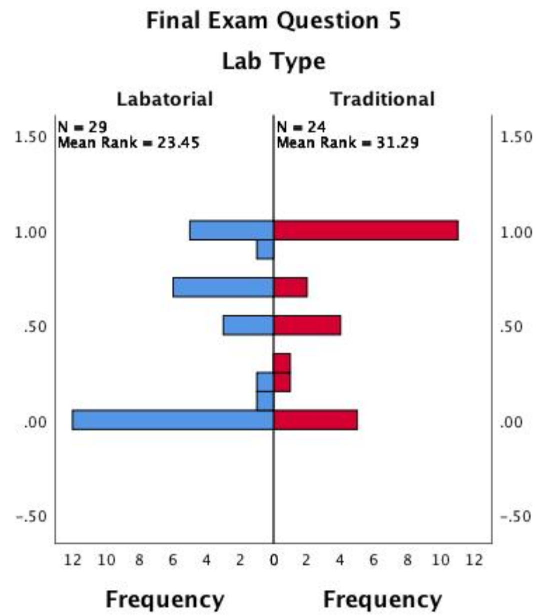


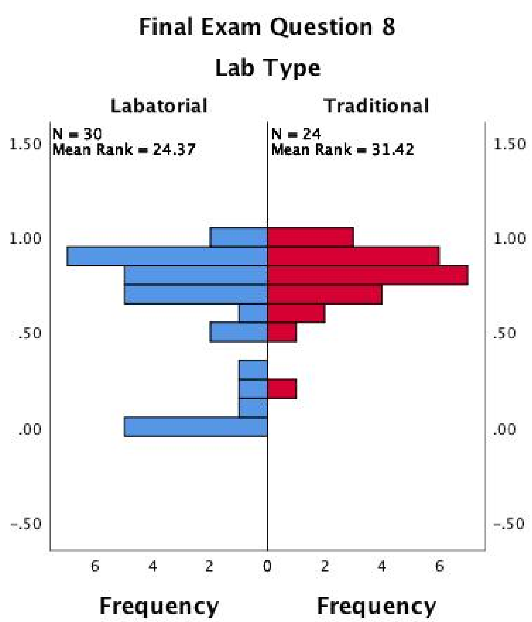
Appendix L

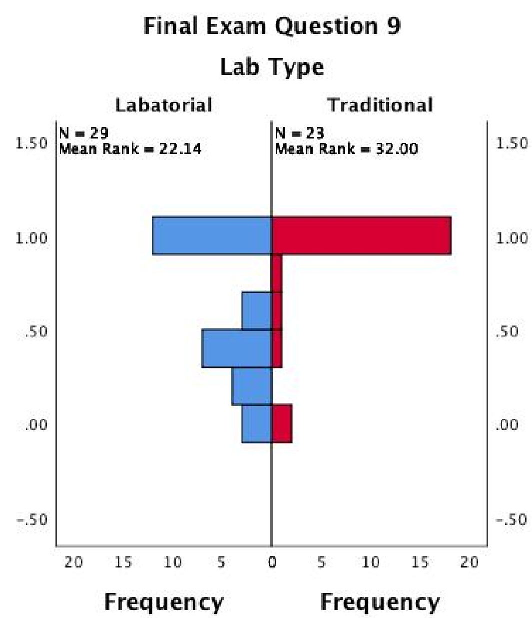
Score Distributions for Selected Post-Test and Final Exam Questions

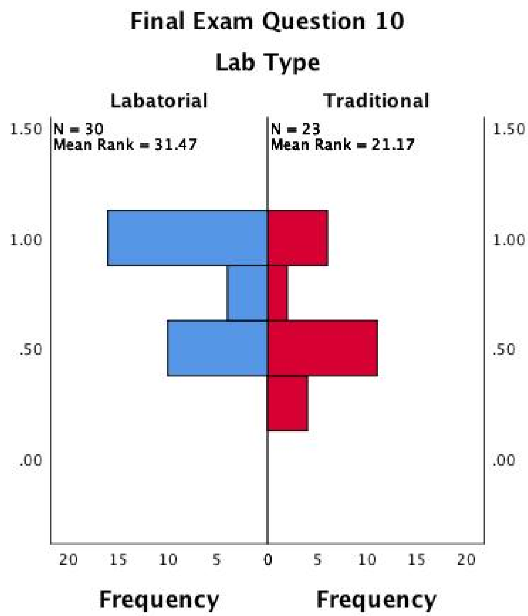
This is a compilation of the score distributions for the post-test and final exam questions that are qualitatively analyzed in detail. Not all the scores are normally distributed, and so different statistical tests are required to quantitatively analyze them.


Post-Test 1 Question 2
Lab Type
Labatorial
Traditional
N = 30
Mean Rank = 30.90
N = 24
Mean Rank = 23.25
Frequency
Frequency

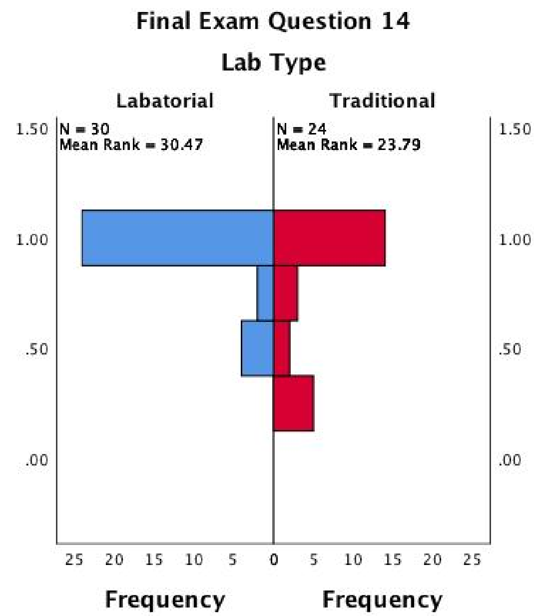

Final Exam Question 5
Lab Type
Labatorial
Traditional
N = 29
Mean Rank = 23.45
N = 24
Mean Rank = 31.29
Frequency
Frequency


Final Exam Question 8
Lab Type
Labatorial
Traditional
N = 30
Mean Rank = 24.37
N = 24
Mean Rank = 31.42
Frequency
Frequency

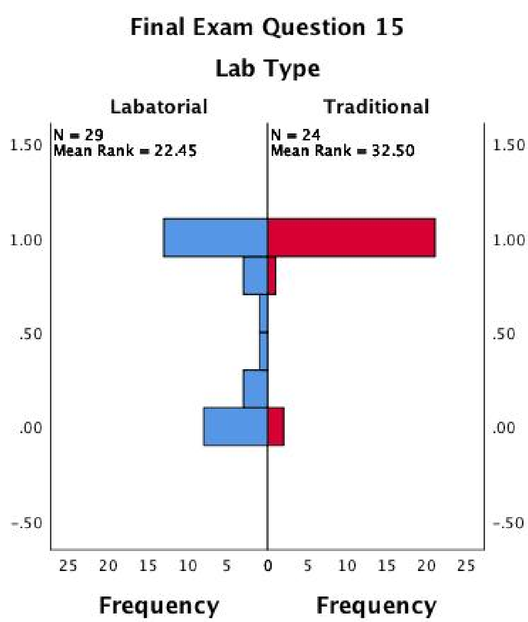

Final Exam Question 9
Lab Type
Labatorial
Traditional
N = 29
Mean Rank = 22.14
N = 23
Mean Rank = 32.00
Frequency
Frequency



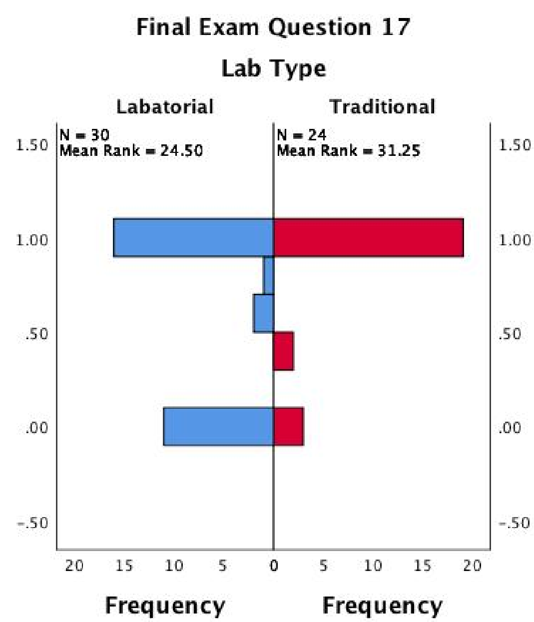
Final Exam Question 10
Lab Type
Labatorial
Traditional
N = 30
Mean Rank = 31.47
N = 23
Mean Rank = 21.17
1.50
1.00
.50
.00
20 15 10 5 0 5 10 15 20
Frequency
Frequency



Final Exam Question 14
Lab Type
Labatorial
Traditional
N = 30
Mean Rank = 30.47
N = 24
Mean Rank = 23.79
1.50
1.00
.50
.00
25 20 15 10 5 0 5 10 15 20 25
Frequency
Frequency



Final Exam Question 15
Lab Type
Labatorial
Traditional
N = 29
Mean Rank = 22.45
N = 24
Mean Rank = 32.50
1.50
1.00
.50
.00
-.50
25 20 15 10 5 0 5 10 15 20 25
Frequency
Frequency



Final Exam Question 17
Lab Type
Labatorial
Traditional
N = 30
Mean Rank = 24.50
N = 24
Mean Rank = 31.25
1.50
1.00
.50
.00
-.50
20 15 10 5 0 5 10 15 20
Frequency
Frequency

Appendix M

In-Depth Qualitative Exam Response Analyses

M.1 An Example Analysis of Students' Responses

To illustrate the approach to qualitatively analyzing students' responses to post-test and final exam questions, we consider the responses for Question 10 of the final exam, a conceptual question pertaining to centripetal force and acceleration. In designing this question, we purposely chose a problem context (i.e. the solar system) that neither group dealt with explicitly in the lab since this was the one lab where the two groups performed a different experiment. See Figure M.1 for the problem statement and a sample correct student solution.

For a labatorial student whose solution is shown in the figure, I commented that the student drew the velocity, centripetal acceleration, and centripetal force vectors in the correct direction, albeit without the correct relative magnitudes for the acceleration vectors. However, this was not the purpose of the question, in part due to the partially unrealistic simplifying assumption of the question. On the other hand, for one labatorial student who did not answer the question correctly, I commented that they drew the acceleration including a tangential component and the force as pointing "downward" in the reference frame of

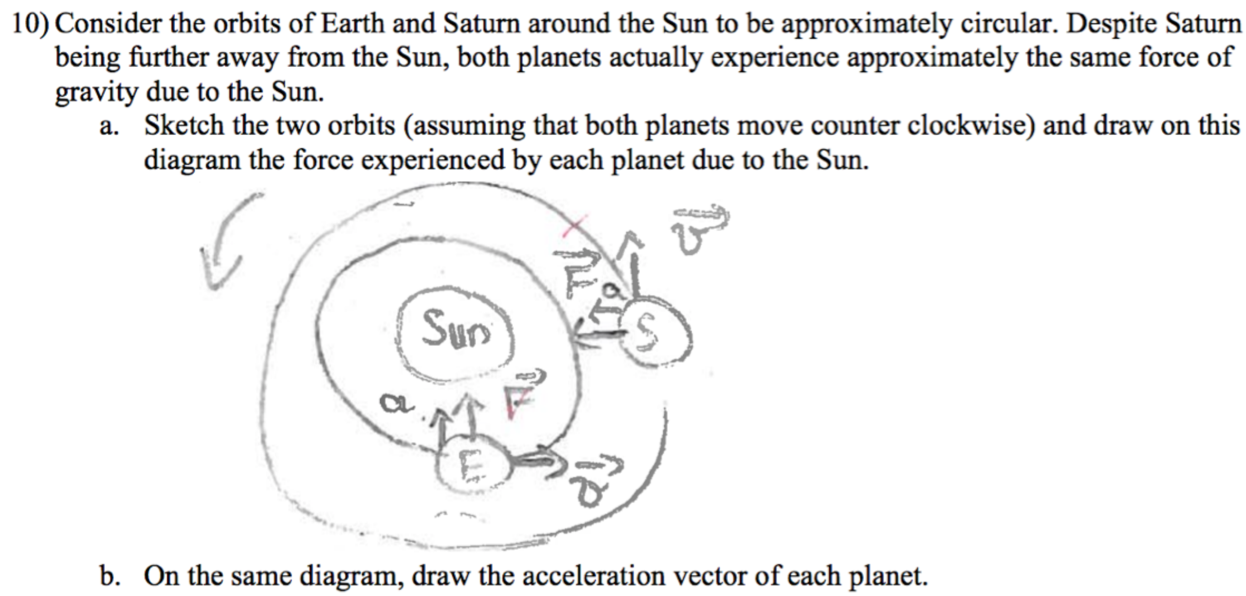


Figure M.1: Problem statement for Question 10 of the final exam and a sample student solution

the solar system. However, they simultaneously (and correctly) drew a separate vector for the centripetal acceleration, indicating that they at least knew as a fact that the centripetal acceleration always points toward the centre in uniform circular motion.

Overall, the labatorial students seem to understand the direction of the centripetal force and acceleration, with 8/12 students understanding centripetal force and 9/12 students understanding centripetal acceleration. However, the misconception of a tangential acceleration and absolute downward gravity remained among some students. The former error may have been a confusion associated to the tangential velocity of the planets, and the latter may have been influenced by the frequently heard naive notion that "gravity always points down."

Among the traditional lab students, similar conceptual errors were made overall, with 6/12 students understanding centripetal force and 4/6 understanding centripetal acceleration. There was also the additional error of drawing the centripetal acceleration vector inward toward each planet rather than toward the Sun in one case, which may have been due to mixing up the circular motion of the planets around the Sun and the rotation of the Earth around its own axis. In addition to explicit conceptual errors, two students appeared to not understand at all; one did not write anything for the question, and the other left a comment stating that they "never saw this."

In comparing the results for the labatorial and traditional lab students, we see that there are some common lingering misconceptions in both groups. However, errors occurred more frequently in the traditional group, with the issue of drawing a tangential component in particular appearing to be more prominent among traditional lab students. The labatorial in question did not target the issue of tangential accelerations explicitly, though students went through many of exercises addressing the centripetal acceleration direction. I believed this would be sufficient to help them understand in designing the worksheet. However, since the absence of a tangential acceleration was never explicitly addressed in the worksheet, it is conceivable that some students might still think it exists. For traditional labs, on the other hand, it makes sense that they would have more conceptual errors since their lab did not place any emphasis on the direction aspect of the concepts (especially not for acceleration), instead only focusing on verifying the centripetal force equation. Therefore, we see that a labatorial worksheet likely has the ability to improve students' understanding of the centripetal force and acceleration concepts in general compared to traditional lab students, albeit there is still room for improvement. This is consistent with the statistical test results of Table 5.4.

It is also interesting to note the possibility based on the "never saw this" comment that some traditional lab students may be reluctant to reason through a given problem (in particular those appearing unfamiliar to them) while labatorial students may be more accustomed to such thinking due to that being a regular part of the lab experience. However, the data collected for this study is not suited to examining such general features of students' thinking, and so this hypothesis will need to be addressed in a future study.

M.2 Summary of Selected Question Analyses

An in-depth analysis similar to that just demonstrated was conducted for each of the eight selected post-test and final exam questions. We summarize those results in the same order they are presented in Table 5.4.

Question 9 is a short calculation question involving the percentage of kinetic energy lost in an inelastic condition. The statistical analysis strongly indicated that the traditional lab students performed better. This is apparent in students' responses as well, with 5/12 labatorial students and 11/12 traditional lab students answering correctly. However, this may not correspond to a stronger conceptual understanding. The traditional lab students nearly always directly used the formula in their notebook (which they had access to as a resource during the final exam) without any justification, while labatorial students tended to try and explain much of their reasoning first, often attempting to derive the necessary equation. This is regardless of the fact that the labatorial group also had the final formula already written in their workbooks (also allowed at the exam), which shows that they tried to think about the concept more deeply as they had done in the lab. As such, conceptual errors also became more apparent with labatorial students. Since traditional students did not show the steps of their reasoning, their conceptual understanding would not have come to light even if they possessed misconceptions.

Question 15 is a short calculation question involving the effect of the typically ignored mass of a spring on its motion. In agreement with the statistical analysis (both before and after considering the outliers discussed in Section 5.5.1), 8/12 labatorial students and 10/12 traditional lab students answered correctly, although the difference is small. The same trend for student responses as in Question 9 appeared; labatorial students tended to rely on their intuition of the method applied in the lab to develop their answers, while traditional lab students tended to copy the formula and calculation from their lab notebook. Therefore, while traditional lab students performed better overall, many labatorial students appear to have a better understanding of the underlying concept.

Question 17 is a short calculation question involving calculating the slope of a line of best fit provided for some data. 7/12 labatorial students and 9/12 traditional lab students answered correctly, which is consistent with the statistical results, although the difference is not large. The most common error among both groups was using the data points instead of points on the line to calculate the slope, and it was more prominent among labatorial students. Akin to the graph linearization procedure, calculating a line of best fit is something that traditional lab students do regularly in their lab reports, which the TA can carefully grade and easily indicate any errors in. While labatorial students also perform similar tasks, it may be more difficult for the TA to verify the precision of each student's graphs, which may allow certain difficulties to propagate. Additionally, the worksheets often placed the graphing activities near the end, and so if students were low on time, they may not have had time to properly compare with their peers. Therefore, traditional students may be stronger at answering questions involving repetitive, template-based tasks from the lab.

Question 5 was a qualitative question regarding linearizing data for graphing, a procedure done in most of the labs. While the raw statistical results indicated that traditional students performed better—consistent with 4/12 of the labatorial responses and 8/12 of the traditional lab responses being correct—there may not be any significant difference in understanding once the possible outliers discussed in Section 5.5.1 are taken into account. A closer examination of students' responses indicate that many students in both groups have a general understanding of proportionality and linearization, but also that both (particularly the labatorial students) appear to have trouble expressing that properly. The result that the traditional lab students are more proficient is unexpected since the labatorial worksheets were designed to scaffold students' intuition on linearization. This may be because traditional students needed to do this as part of their reports in a more formulaic way, whereas labatorial students often just talked about the idea or sketched the graph, which may have affected how they absorbed the concept. Refinements to the worksheets may also be necessary.

Question 14 is a conceptual question involving the elasticity of collisions and the coefficient of restitution. Examining the responses revealed that 12/12 labatorial students and 8/12 understood the concept, which supports the statistical analysis. In addition to there being more conceptual errors in the traditional group, some traditional lab students try to answer the question using a formula from their notebook without reasoning conceptually, which is consistent with the previously noted tendency of traditional lab students to rely on formulas. This suggests that labatorial students may have a better intuitive understanding of the meaning of the coefficient of restitution.

Question 2 of the first post-test is a conceptual question that asks students to think about their intuition of density of granular solids in a new context (i.e. measuring the density of sand instead of glass beads). 8/12 labatorial student understood the core idea, while 5/12 traditional students understood. Due to the nature of the question, students in both groups attempted to explain their reasoning thoroughly. However, the labatorial students were generally closer to understanding the concept behind the question, more frequently making explicit connections between the changes in mass and thus density that occur due to the absorptivity of sand and how that would affect a measurement. As such, their intuition of the fluids concept of volume displacement appears to be stronger.

Question 8 is a long calculation question involving the composition of force vectors using a force table, an experimental apparatus used in Lab 2. 6/12 labatorial students and 5/12 traditional students answered correctly. Although the original statistical analysis indicated that traditional lab students performed better, the qualitative analysis is much more consistent with the statistical results that took the outliers into account; both groups made similar mistakes just as frequently (e.g. a calculator error, incorrectly calculating the angle of the resultant force, etc.), and their approaches to the problem were largely the same. Therefore, we cannot conclude that there is any significant difference between students' understanding of this topic.

Appendix N

Colour-Coding and Hierarchical Summarization of TA Surveys

The following is an illustration of the developed colour-coding and hierarchical summarization schemes used to analyze certain qualitative data sources. They are applied to the results of the post-lab TA surveys for each lab. Different colours are used to indicate different elements of the data that are useful for triangulation, and the paraphrased comments of each TA are progressively summarized so as to identify underlying themes.

TA Survey Summaries

Colour Code:

- Red: key conceptual difficulty
- Orange: hard to read
- Yellow: key code or theme from the interviews
- Green: key conceptual gain
- Blue: contradiction to a key code or theme

Lab 1: Density of Granular Solids

Labatorials

Israel: He mentioned students had trouble doing the uncertainty calculations at first, but got used to applying it to other problems after seeing an example. He also said they really have a problem with Q6e that deals with the volume of the displaced fluid being equal to that of the solid.

Jun Hyung: He points out the difference in starting abilities of students, but that for most students peer instruction was helpful since they teach and learn from each other. Most important to him is that that students do the pre-readings and come to the lab with a basic understanding.

Linxiang: He's not sure how much they developed conceptually in the lab, but he thinks some students try to think about the concepts like significant figures. He also said they became more likely to discuss together to solve problems, which he thinks should help them understand concepts.

SUMMARY: They also say very different things, but nothing contradictory. Only Israel pointed out one of the key concepts of the lab, and that they had difficulty with it. But the other two pointed out that indeed some of the key learning techniques that are being used in the lab, which is consistent with the interviews.

Traditional labs

Israel: He points out how it's hard to assess conceptual understanding from their reports because is some labs the focus is all on the measurements, graphs, and plugging into equations. But he still mentions that students lack understanding about where the equations come from since they never really use that for the experiment. He also mentions, however, that there was an improvement in their understanding about proportions/assumptions in d = m/V and its relation to temperature.

Linxiang: He had 3 key points. (1) He seems to have originally thought that students discuss more in labatorials, but that he was mistaken. Namely, he thinks it depends mainly on the individuals. (2) He said doing the experiments like measuring the mass of the solid, the mass of the unknown liquid will, in his words, just help them understand concepts about density. (3) (Can't read, come back later.)

SUMMARY: They both seem to think that there was some improvement in students' understanding of the density equation, though I need to verify Israel's first, and Linxiang is vague about it.

Conclusion: I'll need to finalize this, but it seems that since the goals of the labs are somewhat different, I'll be hard to compare the understanding of the two groups properly.

Post-Test and Final Exam Questions (only the ones for which the t-test indicated a significant difference in the means): For Post-Test 1, the only statistically significant difference occurred in Q2, which was the hypothetically question about measuring the density of an absorbent granular solid. Nothing mentioned above particular relates to this question, except perhaps how students were thinking about things more throughout the labatorials, and so perhaps they were more prepared for this kind of open question. As for final exam questions, there were no questions with a significant statistical difference.

Lab 2: Composition of Concurrent Forces

Labatorials

Israel: He says they all have good intuition for vector addition, the equilibrant and resultant vectors, etc. Though he said students had trouble with the graphical methods because of scale issues (and some people also didn't have good notes on the graphical methods). Overall, he says students improve on most parts except the component method.

Jun Hyung: He says students seem to understand the concepts better through the experiment, but that many of them had procedural issues, likely how the directions were not always clear for students. For example, many students used a graphical method instead of rough sketching for Q5, where we've had them draw 3 vectors individually and then ask students to sketch the equilibrant and resultant vectors.

Linxiang: His only comment was that things were smoother this time since most students came prepared (i.e. did the pre-readings and had summaries).

SUMMARY: Here, two of the TAs indicate improvement, though Jun Hyung is less clear. Israel is a bit vague too, but we know that the hard part was the component method, and so this should likely be the focus in the first place. On a different note, Linxiang's comment about preparation nicely responds to Jun Hyung's comment from Lab 1.

Traditional labs

Israel: He points out that students don't know how to distinguish the experimental and theoretical quantity except for in the component method. He says the hardest part for them was figuring out how to use the graphical methods and how to get the wanted path from it

(_____ or ruler and scale). On his second sheet, he reaffirmed the difficulty of the graphical method in that they needed to be shown many examples in order for them to be able to do it on their own, while for the other methods just the manual was enough.

Linxiang: He didn't notice any particular difficulties, saying that the experiment was easy to the students. Almost every student was able to do well in drawing the graphs and calculating the resultant and equilibrant forces.

SUMMARY: The two have pretty different pictures of students' understanding, but when you also look at the quantitative part of the survey, they both gave similar positive scores.

Conclusion: Here there are some interesting things to compare. Namely, it seems that there was some sort of difficulty in the component method for both groups, but the cause seems to have been different. The same goes for the graphical methods. However, only for the labatorial groups do we seem comments about students' understanding improving, despite similarly positive scores.

Post-Test and Final Exam Questions: It seems none of the other post-test questions showed a significant difference, so I won't mention them anymore from here on out. For the final, Q8 had a negative confidence interval, showing a better performance for the traditional group. This question was a pure component method vector sum calculation. At least based on Israel's comments, there seems to have been slightly more trouble in accomplishing the component method in labatorials than in traditional labs. If you consider this, then the result makes sense. However, the underlying reason is not clear.

Lab 3: Springs

Labatorials

Israel: He said students intuitively understand the vertical spring-block problem, but have difficulty setting up the equation from the free body diagram.

Jun Hyung: He said it seemed very effective that the students actually discussed with each other and him to understand the core concepts in this labatorial.

Linxiang: He found this experiment hard to understand for students, in particular the part about the fractional mass. They don't know where it coms from, and their attempt at designing an experiment to measure the fraction, in his words, is not even close. He thinks it can be challenging unless the book can give some hints.

SUMMARY: Israel's answer shows a deficiency in basics that they should already have. Linxiang's answer, on the other hand, addresses the hardest part of the lab, and the two have comparably negative quantitative scores. Although Jun Hyung's response seems too positive in comparison, it actually makes sense since given the difficulty of this topic, it is important that students help each other and ask the TA for guidance when needed.

Traditional labs

Israel: He noted that the dynamical method was challenging for all students. He had explain the physical reason behind the equations for the dynamical method, from which point students were able to figure it out. In his second sheet, he confirms that the static method wasn't an issue. For the dynamic method, he adds on that they were only able to understand why they needed to take into account the fractional mass of the spring through physical demonstration, presumably by him.

Linxiang: He says that fractional mass was hard for the students to understand since it isn't clear in the manual where this fraction comes from.

SUMMARY: Both TAs mention how the dynamical method was difficulty because of the spring mass fraction. Though it seems that according to Israel, the students were only able to understand after the TA got directly involved. As for explaining the physical reason behind things, this makes sense from a learning perspective, and Israel just had to do it since the manual didn't, as Linxiang said. Though for the physical demonstration part, it looks like the TA needed to explain directly.

Conclusion: Once again, the main difficulty for both groups was the same. It's a little bit hard to compare in this case, but although the comments by the TAs in each group are qualitatively similar, the quantitative ratings for labatorials are slightly worse. This is likely because we ask them to do and think about much more in labatorials, so naturally there are more things for them to have trouble with. [**Edit**: I forgot to take into account the updated scores Israel had indicated for the labatorials. After doing so, the scores for the two groups, on average at least, now also seem comparable.] But as indicated by Jun Hyung, at least they do seem to be collaborating. **For now I will focus on the comments, but then I will go through the quantitative part again and try to match the matching questions from each group to so what parts exactly were better/worse for traditional/labatorial students, and then see if that lines up with the final exam scores**.

Post-Test and Final Exam Questions: Here, we see a negative confidence interval for Q15 of the final, which asked to calculate M(T^2=0) from the mass fraction. Above, I wrote how students in both groups basically had trouble understanding the mass fraction f, and Linxiang went as far as to say that they had no idea what they were doing for the experiment for that. So it sounds like that was a big detriment to the score. But also, Q15 is really not conceptual in anyway: it's an exercise in how well you can follow instructions, do your calculations and record them in your book. That seems like the kind of task that you're asked to do all the time in traditional labs, so it's not too surprising they did better on this question, especially given that you don't really have to understand do know what's going on here. In labatorials they had to do things more from the ground up, so there may have been a higher potential for error there.

Lab 4: Centripetal Force

Labatorials

Israel: He said that people understand things intuitively, but have a tough time explaining inertia and the relationship between Fc vs. v and r (at first). He also said that about half of people got the tension force as the sum F_T = F_C + F_g. Interestingly, he lastly said that as students used the centripetal force equation a couple of times, they were able to intuitively attach physical meaning to each of the parameters.

Jun Hyung: He said the lab went well for everyone in general. Although some students struggled with the conceptual understanding of the theory at first, they seemed to figure it out at the end through discussion with colleagues.

Linxiang: N/A

SUMMARY: Overall a pretty positive lab, with both TAs indicating a progression from not understanding to understanding. For Israel, this was due to students playing with the equations a few times, and for Jun Hyung this was more due to discussion with peers. Unfortunately, Linxiang left no comments on this one.

Traditional labs

Israel: He said students were prepared and understood conceptually the important things about F_c = mv^2/r. But he also said that although students had more time to do this lab (since it was normally designed to be 2 hours), no one was able to understand that the best fit line represents all the data and that that's where the error coms from.

Linxiang: He said students did well overall since this lab was easy. They were just maybe confused about the Port A changing voltage to keep the rotational velocity the same.

SUMMARY: Linxiang didn't have any comments regarding the concepts we are looking at, though Israel's were interesting. Apparently, they understood the centripetal force equation. Based on what I recall of the post-test for that lab, this likely means they know how F_c will change if either v or r changes. Though it's interesting that even though this was their last lab and they've been doing graphs extensively throughout the course, they still don't seem to understand the nature of best fit lines and their relation to error.

Conclusion: There seems to have been some growth in both groups, but because the content and goals were so different for this one in particular, it's hard to compare which was more successful from the qualitative alone. But each one stands reasonably well alone. I'll need to look at more specific questions for this too.

Post-Test and Final Exam Questions: Here, the confidence interval for Q10 is positive, indicating a better performance by the labatorial students. This was the question where they had to sketch the force and acceleration vectors of two planets. There was nothing in particular mentioned about the direction of the force above, only the relationship between F and v and r, so it's hard to draw any connections between the results and the comments above beyond what I already wrote about in the grade summary document.

Lab 5: Coefficient of Restitution

Labatorials

Israel: He noted that only when students compute e for the extreme cases they understand the values it can take. He also said that there wasn't enough time to finish the derivation part of this lab due to algebra problems again. Because of the math, this is the hardest experiment, to the point that only 2 out of 4 teams were able to do the algebra by themselves.

Jun Hyung: He said that students struggled with the theoretical computation parts at first, but they seemed to follow and understand explanations pretty quickly in the end. He also thought that the experimental part could use some improvement, ideally if it can be performed for more varied heights from which the steel ball can be dropped.

Linxiang: He said that although students had difficulty deriving the expression for the total time, they understand where the energy goes during a collision.

SUMMARY: The message here is clear: the math was hard for the students, a theme common throughout the course. However, it seems according to Jun Hyung that students did seem to be able to more or less follow the explanations given near the end, so they may still have made some improvement. Plus, Linxiang also noted that they were able to understand the kinetic energy loss concept, which is one of the more core ideas of the lab anyway.

Traditional labs

Israel: He noted that students had a good intuition on air friction, potential, and kinetic energy. They were also able to relate the concepts to experiment. He said that overall there were no major problems in conceptual understanding, and that it was more about taking good measurements. His second sheet said similar things, saying there were no major obstacles for students understanding e or l. However, they seem to forget that all objects fall at the same rate in vacuum regardless of their mass.

Linxiang: He said that they know how to calculate the coefficient of restitution, but don't understand what it means.

SUMMARY: Their two answers are a bit contradictory in a way, but it reveals that there can still be some important conceptual issues after this particular lab. It's interesting that Israel had no major problems in conceptual understanding in his group. Given that he's saying that the focus was on taking good measurements, this lack of problems could be due to the lack of a need to address concepts in the first place, which would be consistent with my theme about focusing on correctness over understanding.

Conclusion: The TAs talked about different things for each group, but it seems that all the labatorial ones mentioned the math difficulty above all else, and the traditional ones mentioned conceptual difficulties (though there were some intuitive successes as well, according to Israel).

Post-Test and Final Exam Questions: Here we need to look at Q9 and Q14 of the final. For Q9, which was about calculating percentage kinetic energy lost after a collision, the confidence interval is negative, indicating better performance by the traditional group. There was nothing about this mentioned at all in the comments above, so I'll have to go with my hunches from the exam scores thoughts file for now. For Q14, which was about qualitatively determining which ball had the higher coefficient of restitution given only their bounce times, the confidence interval is positive, indicating better performance by the labatorial students. Again, nothing was mentioned about this here.

Lab 6: Pendulum Motion

Labatorials

Israel: He noted that students had some idea about matching both sides of the equation in terms of their units, but needed confirmation to do it. They also had a hard time interpolating their graph to get meaningful parameters. Unfortunately, in his group they could not finish the slope analysis part in full. Nevertheless, he said that this labatorial helped students go through the process a physicist uses. Those who did not know the actual period equation learned much more than those who already knew T = 2pi*sqrt(L/g).

Jun Hyung: N/A

Linxiang: He said students had difficulty converting units when calculating the slope, but that they know how to design the experiment and their data is good. Also, they may not really understand the uncertainty of the unknown quantity part.

SUMMARY: Although it sounds like there were some difficulties that were as usual fundamentally mathematical in nature, students seem to have learned from this lab. In the case of Israel, it's interesting how he pointed out what kind of students learned more, which I believe is due to them being scaffolded correctly. (Since indeed if you know the answer already then it's a useless exercise.) And surprisingly, for the first time a TA indicates that they did well designing the experiment and collecting data. Although this may have perhaps been a simpler experiment, this is quite a significant growth given that for the third lab, Linxiang said that their experiment design wasn't good at all. So they may have also become more proficient in this regard.

Traditional labs

Israel: He noted that here it was all about taking good measurements (calibration of pendulum with photo detector) and relating air friction to loss of kinetic energy. He also said that there were no massive issues in their conceptual understanding, and that students have a strong grasp of kinetic energy in relation to potential energy. Though in his second sheet, he said that the only issue is about understanding T proportional to sqrt(L). Only those who remember their trigonometry well understood that relationship.

Linxiang: He said that students do not really understanding how different forms of energy are involved in pendulum motion. It is not all their fault, since this experiment is so inaccurate that you can't even conclude that the mechanical energy is conserved during this motion.

SUMMARY: Once again, there seems to be a conflict between Israel and Linxiang in terms of the conceptual understanding of their students. While Israel said students' understanding of energy was strong, Linxiang said the opposite. Again, we see a strong focus on the measurement side of things mentioned by Israel, which could potentially have contributed to the issues Linxiang's students were having.

Conclusion: For this final lab, again although there are often certain many difficulties mentioned for the labatorials, many improvements are also mentioned. From these comments alone, it is impossible to truly compare the two groups, just like it is impossible to do so from the grades alone. So from here, I should look more closely at the success of students on those questions that are related to the key concepts pointed out in the TA surveys.

Post-Test and Final Exam Questions: There are no questions with a statistically significant difference here either.

Appendix O

Learning Outcome Triangulation for Each Lab Topic

The following tables are the products of a heuristic scheme for triangulating labatorial and traditional lab students' conceptual learning outcomes for the course on a topic-by-topic basis. They allow us to gain insight as to which course topics were the best and worst understood by each group. One table is presented for each lab.

Student Understanding Triangulation

Lab 1: Density of Granular Solids

		Labatorial					Traditional				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*Proportions in d = m/V*							*			
	Density					F12(74)		*	*		F12(76)
	Sources of error			**					***		
	Volume displacement	*		***	****	P1(72) P2(88) F2(78)				**	P1(74) F2(75)
Conceptual Difficulty	*Volume displacement*	**	*	**	**		*			***	P2(74)
	Sources of error			**					***		
	No concept discussion (true in many labs!)						*		**		

Lab 2: Composition of Concurrent Forces

		Labatorial					Traditional				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*Graphical methods*		*	*****		P1(87)					P1(86)
	General		*								
	Vector addition			*							
	Equilibrium, equilibrant force			*****					***		F16(79)
	Component method			*****	***	P1(87)			*	**	F8(78) P1(86)
	Theoretical vs. experimental								*		
Conceptual Difficulty	*Component method*	*	*		***	F8(60)		*		***	
	Force ~ velocity			*							
	Theoretical vs. experimental								**		
	Explaining sources of error								****		
	Equilibrium, equilibrant force					F16(68)					

Lab 3: The Simple Harmonic Motion of a Spring

		Labatorial					**Traditional**				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Score*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Score*
Conceptual Gain	*Modifying period equation*			**							
	Getting f from intercept			***	****					*****	F15(89)
	Spring mass fraction intuition			***		F6a(45*2)					F6a(44*2)
	Hooke's law			*		F1(80)			**		F1(92)
	Random error								*		
	Explaining sources of error								**		
	Equation from FBD	*									
Conceptual Difficulty	*Modifying period equation*			***		F6b(22*2)		*			F6b(24*2)
	Getting f from intercept	*	*	**	**	F15(58)		*		*	
	Spring mass fraction intuition			*			*	*	*		
	Explaining sources of error								***		
	Blindly following instructions								*		
	Brief report								*		
	Expressing ideas clearly								*		
	Equation from FBD	**	*								

Lab 4: Centripetal Force

		Labatorial					Traditional				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*Relationship between Fc and v, r*		*			P2(94)		*			P2(90)
	Fc direction			*	****	P1(83) F10(80)					P1(72)
	a direction			******	****	F10(80)					
	v direction			****							
	T = Fc + Fg			****							
	Inertia			*							
	Linearization				**				**	****	F5(62)
	Line of best fit				***					****	F17(82)
	Sources of error								**		
Conceptual Difficulty	*Inertia*		*	**							
	T = Fc + Fg	*	*	**							
	F direction	*		*	*					*	F10(61)
	a direction			*	*					**	F10(61)
	Line of best fit				**	F17(59)	*	*		**	
	Sources of error								***		
	Focused on formula verification										
	Linearization				****	F5(41)	*		*	**	

Lab 5: The Coefficient of Restitution and g, the Acceleration Due to Gravity:

		Labatorial					Traditional				
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*KE loss*		*	*	*				***		
	Interpretation of e + elastic vs. inelastic		*	*******	******	P5(77) F14(92)			*****	****	P5(76)
	Energy conservation			*****							
	KE loss math			*	**					*****	F9(85)
	Free-fall math			****		F3(85)					F3(73)
	Linearization to find e			****							
	Experiment + linearization to find g			*					*		
	g independent of mass								*		

		Obs.	TA Survey	Work-sheet	Final/ Post	Scores	Obs.	TA Survey	Report	Final/ Post	Scores
Conceptual Difficulty	*g independent of mass*							*	*		
	Interpretation of e + elastic vs. inelastic			*				*		**	F14(78)
	Experiment + linearization to find g			***							
	Free-fall math	**		*					*		
	KE loss math (incl. KE~v)	*		**	***	F9(57)				*	
	KE loss	**							***		

Lab 6: The Period of a Pendulum

		Labatorial						**Traditional**			
		Obs.	*TA Survey*	*Work-sheet*	*Final/ Post*	*Scores*	*Obs.*	*TA Survey*	*Report*	*Final/ Post*	*Scores*
Conceptual Gain	*Energy conservation in pendula*							*	***		
	Designing experiment	*	*	******							
	Period equation		*	****		P6(77) F7(85)			****		P6(80) F7(88)
	Linearization								*		
Conceptual Difficulty	*Period equation*			*				*	*****		
	Energy conservation in pendula					F13(50)		*	**		F13(50)
	Dimensional analysis	*		**							
	Linearization (+ slope parameter extraction)	*		*							
	Designing experiment	*									
	Graphing	**									