Expectations and experiences in a modern physics laboratory course

Helen Mae Cothrel

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Expectations and Experiences in a Modern Physics Laboratory Course

by

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Thesis
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Dedication

This work is dedicated to my parents, who inspired my lifelong love of learning, and my older sister, from whom I’ve learned very much, whether she likes it or not.

As is everything I do, it is also dedicated to Nick Byers, whose memory I carry with me always.
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Abstract

This study examines students’ expectations for and experiences within a modern physics laboratory course. The course instructor and several students were interviewed using a semi-structured protocol at the beginning (pre) and end (post) of the semester. Interviews were video-recorded, then transcribed to text. This thesis presents the results of three students’ interviews as case studies; their interview transcripts were adapted to a more narrative style for inclusion in this report. An interpretation of each student’s responses from pre- to post-interview is given, followed by conclusions which incorporate all three students’ interviews. Particular attention is paid to students’ ideas about experimenting and experiences in the laboratory course which they found valuable or meaningful.

*Keywords:* physics education, laboratories, modern physics, interviews, qualitative research, case studies
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Chapter 1: Introduction and Background

Introduction

Modern physics is a required course for many undergraduate physics majors and minors. Modern is often seen as a bridge between introductory physics and challenging upper-level courses such as electrodynamics and quantum mechanics, particularly because modern begins introducing foundational ideas which students see again in quantum.

Modern physics offers a stark contrast with introductory physics. Students in modern have probably taken physics beyond high school classes already; students in intro classes have only had some physics in high school, or have never taken a physics class. Modern is typically the first physics course students take that includes concepts established no earlier than the twentieth century, such as relativity and quantum mechanics (Fowler, n.d.; Zollman, 2016). Introductory courses rarely discuss ideas from later than the nineteenth century. Concepts in modern physics are more abstract than the ideas in introductory physics, and reveal themselves less readily through casual observation (Zollman, 2016).

Laboratory courses in modern physics are often the first opportunities students have to experiment with specialized measurement instrumentation, conduct independent investigations in a community environment, and exercise skills they are likely to use in contemporary physics research.

These characteristics make modern physics an interesting course for students. They may begin to experience the excitement which motivates researchers in physics through engagement with novel ideas and experiments (Zollman, 2016). Modern physics is potentially a turning point in the careers of budding physicists; they may decide they would like to do more experiments or
fewer experiments, and whether they continue to see physics as a good fit for them as they study higher-level material.

This thesis comprises six chapters. In Chapter 1, context and justification is given for the study. In Chapter 2, relevant literature is discussed. Chapter 3 presents the logistics of the research study, including study design and sampling. Chapter 4 includes the results of selected interviews, with a priority of presenting complete thoughts in participants’ own words. Chapter 5 gives interpretation of the interviews, and Chapter 6 offers closing thoughts and raises further questions for similar research.

Statement of the Problem

Physics educators are interested in modern physics courses for their context as an introduction to foundational ideas in quantum physics. In quantum mechanics (another term for quantum physics), students encounter ideas which are essential to understanding and participating in current research in physics. Quantum mechanics is also notoriously difficult for students academically and conceptually; research indicates that students’ conceptual mastery in quantum mechanics is low, and continues to be even after completing an undergraduate degree in physics (Passante, Emigh, & Shaffer, 2015; Singh, 2001). This lack of content mastery has led educators to question the usefulness and effectiveness of modern physics courses as preparation for tackling quantum mechanics.

Additionally, research involving lower-division physics courses has shown that laboratories do not contribute to content mastery. This raises the question of whether including a laboratory for modern physics is worth the resources required to run it (Holmes, Olsen, Thomas, & Wieman, 2017). As such, investigating students’ experiences in the modern physics laboratory, and whether students perceive these experiences as meaningful to them in ways
Beyond content mastery, will contribute to educators’ holistic understanding of the role of these courses.

**Purpose of the Study**

The purpose of this study is to examine what students expect from the modern physics lab, what they experience, and what (if any) meaning and value they attribute to these experiences. This study aims to contextualize these questions by discussing students’ backgrounds and career goals along with their responses.

**Justification and Significance**

Qualitative research is critical to generating a robust body of knowledge in physics education research (PER), as it informs critical gaps in quantitative results. For example, consider the Colorado Learning Attitudes about Science Survey (CLASS), a quantitative instrument frequently used to evaluate students’ beliefs about learning physics. Since its development in the early 2000s and subsequent adaptation to experimental contexts (the E-CLASS), the survey has been a reliable instrument for comparing students’ beliefs by major and level of study (Gire, Jones, & Price, 2009; Perkins, Adams, Pollock, Finkelstein, & Wieman, 2005; Wilcox & Lewandowski, 2016; Zwickl, Hirokawa, Finkelstein, & Lewandowski, 2014). However, results from the CLASS and E-CLASS raise further questions for research.

Several studies have found that students in higher-level physics courses consistently give more expert-like responses to the CLASS and E-CLASS than students in lower levels (Gire et al., 2009; Perkins et al., 2005; Zwickl et al., 2014). This is curious when considered in tandem with other findings using the same instruments, which showed that student perceptions are relatively stable during laboratory courses and over the first three years of physics majors’
studies (Gire et al., 2009; Wilcox & Lewandowski, 2016). This indicates that quantitative research does not tell the whole story of students’ epistemologies.

Luckily, lingering questions from quantitative research are informed by qualitative research. Stanley, Dounas-Frazer, Kiepura, and Lewandowski (2016) combined the Project Ownership Survey (POS) and interviews of students in mixed-methods research. They found that students’ experiences in an upper-division optics laboratory course were more complex than are captured by a survey by studying survey results and interview data in tandem (Stanley et al., 2016). This demonstrates the need for interview research to inform quantitative results and pedagogical strategies beyond the introductory level. Continuing research in upper-division courses will contribute toward answering the question of if, how, and when students’ epistemologies change over the course of their undergraduate study.

Using midterm and final exam scores, quantitative research has shown that introductory-level students who take lab courses in addition to lectures do not demonstrate higher content mastery than students who do not take labs (Holmes et al., 2017). Further research using the CLASS adapted for experimental contexts (E-CLASS) suggests that students who take labs at the introductory level and beyond do not develop more expert-like beliefs about the nature of experimental physics (Wilcox & Lewandowski, 2017a; Wilcox & Lewandowski, 2017b). Students in upper-level courses did have more expert-like beliefs, but data from an eight-semester longitudinal study indicate that this was due to a selection effect; students with more expert-like beliefs persisted into the upper-level, rather than becoming more expert-like over time (Wilcox & Lewandowski, 2017b). This raises questions about student mindset and persistence, which are best examined through qualitative studies.
The American Association of Physics Teachers (AAPT, 2014) published a set of guidelines for undergraduate laboratory courses which included some broad recommendations for learning outcomes. Most of the learning outcomes do not incorporate conceptual mastery; for example, students should engage with data through analysis, visualization, and presentation. The AAPT (2014) also suggests that students should gain laboratory skills and experience in designing experiments. These outcomes would be difficult to assess with quantitative instruments.

The growing data around laboratory courses points to two possible lines of inquiry for further research: Can labs be changed to meaningfully contribute to content knowledge? Or, do labs contribute something other than conceptual mastery, which is already valuable, such as skills or experiences that are not measured by quantitative instruments—and can they be measured through other approaches? This research follows the spirit of the second question, and forgoes the study of students’ performance or knowledge to examine their experiences in their own words.
Chapter 2: Review of Literature

Modern Physics in PER

“Modern physics” courses and interest in their teaching date back as far as 1937; however, as one might expect, courses in the 1930s bore little resemblance to those which are taught today (Hull, 1937). An early documented case of modern physics as a sophomore-level course for physics majors with similar experiments to those in today’s courses wasn’t published until 1960 (Brody, 1960). Brody’s laboratory course in 1960 included similar or identical experiments to many of today’s modern physics labs, such as the Millikan oil drop experiment.

Researchers have recently published a surge of literature on upper-division undergraduate physics courses in the form of a focused collection in Physical Review Special Topics: Physics Education Research (Loverude & Ambrose, 2015). Upper-division courses are those like modern physics which are beyond introductory physics (or “beyond first year”) and are intended for physics majors. The editors of the focused collection noted that researchers have traditionally focused on research involving introductory courses, which have larger class sizes, run more frequently, and are easier to access than many upper-division courses (Loverude & Ambrose, 2015).

Interviews in PER

Interview studies exclusively including students in modern physics are an extremely narrow research focus. In the spirit of establishing a more complete context for this study, interview research is discussed here for a variety of course levels.

Mixed-methods PER. Interviews are common in mixed-methods PER to support quantitative data, inform the results of performance assessments, or validate students’
interpretations of quantitative instruments (Sadaghiana & Pollock, 2015; Zhu & Singh, 2009; Zwickl et al., 2014; Stanley et al., 2016).

**Qualitative PER.** Researchers have used interviews in qualitative PER from the introductory level to the graduate level. Blue and Jacob (2009) interviewed students in an introductory lab who were STEM majors but not physics majors; they found that most students believed the purpose of the lab was to support the material they had already learned in lecture. They also noted that students who contrasted the laboratory with the lecture indicated they had alternative learning styles or other obstacles to learning from the lecture (Blue & Jacob, 2009).

Other interview research at the introductory level has demonstrated the complex nature of STEM students’ mindsets in different contexts; mindset (growth versus fixed, for example) has implications for student success in college (Little, Sawtelle, & Humphrey, 2016). The work by Blue and Jacob (2009) and Little et al. (2016) are examples of how interviews provide valuable insight for educators. Understanding the variety of learning styles and mindsets that STEM students exhibit in lower-level courses provides a foundation for what to expect from students at higher levels.

Irving and Sayre (2015) interviewed a variety of students in upper-division courses, including students from modern physics, with a goal of identifying how students perceived physicists and whether their perceptions changed over the course of three to six semesters. Through comparing pre- and post-interviews, they found that students’ perceptions of physics can develop over time, most students believed that conducting research is important, and many students did not have clear ideas of what research actually involves. They also determined that undergraduate research experience can play a significant role in students’ development as
physicists, particularly in the context of becoming members of the physics community (Irving & Sayre, 2015).

Irving and Sayre (2014) also conducted semester-long observations and individual interviews to study community of practice in an upper-level laboratory course. They found that the quality and quantity of student interactions in the laboratory increased over time, and they associated these trends with the development of a community of practice within the course. Both studies by Irving and Sayre establish that upper-level physics students develop within complex contexts, and the community in a laboratory course or research can be a valuable context for development.

Beyond studying development, interviews of upper-level physics students have also illustrated the complexity of students’ physical interpretations of quantum mechanics. Baily and Finkelstein (2010) found that students in a modern physics course sometimes maintain multiple perspectives on quantum mechanics (for example, they may maintain a perspective which “makes sense” to them and contrast it with a perspective which they think is probably correct). Maintaining these contrasting perspectives often leads to cognitive tension, which may be one reason why students struggle with quantum physics (Baily & Finkelstein, 2010).

The sum of interview research basically points toward one certain conclusion so far: that undergraduate students are complex people having complex experiences within their physics courses.

Current State of PER Regarding Modern Physics

Modern physics in research without a laboratory focus. In addition to Irving and Sayre’s (2014) interview research in the context of communities of practice at the upper level, researchers have made qualitative explorations into students’ conceptions of specific ideas in
modern physics. A phenomenographic study in Ethiopia used semi-structured interviews to establish descriptions of students’ understanding of wave-particle duality and the uncertainty principle (Ayene, Kriek, & Damtie, 2011). The interviews included students who had taken a semester of modern and a semester of quantum mechanics.

The researchers found that 80% of students’ descriptions of wave-particle duality were influenced by classical determinism, and that although all participants could state the mathematical formalism of the uncertainty principle, only 12% could give a description of its meaning appropriate to quantum mechanics (Ayene et al., 2011). This agrees with more research from Baily and Finkelstein (2009), who used the Colorado Learning Attitudes about Science Survey (CLASS) to show that students in modern physics did not have a consistent perspective of uncertainty and measurement between contexts.

In Turkey, Didiş, Eryılmaz, and Erkoç (2014) applied the theory of mental models to investigate students’ understanding of quantization of physical observables in a modern physics course. They used pre- and post-interviews, tests, and exams to establish six different mental models which students used to describe quantization (Didiş et al., 2014). They also found that students’ mental models were context-dependent, models were often characterized by a mixture of scientific and unscientific reasoning, and students may rely on multiple models during reasoning (Didiş et al., 2014).

McKagan, Perkins, and Wieman (2010) used observations, interviews, and other established instruments to develop the Quantum Mechanics Conceptual Survey (QMCS), a short multiple-choice survey appropriate as a post-test for students who have taken modern physics. At the University of British Columbia, Deslauriers and Wieman (2011) used the QMCS to show that students demonstrate good retention of concepts from modern physics (i.e., students’ scores
were consistent over time after taking the course) and that students’ conceptual mastery was improved in courses which included more student engagement and interaction. This indicates that weak instruction in modern physics is more significant than student memory in the mastery of quantum mechanics after a modern course.

The results of this research by Deslauriers and Wieman (2011) are also interesting to consider in the context of the studies by Ayene et al. (2011) and Didiş et al. (2014). Using the QMCS, even students in the “traditional” lecture course scored 67% on average at the end of modern physics and 65% after 18 months (Deslauriers & Wieman, 2011). This is a sharp contrast to the qualitative studies which found that very few students (as low as 12 to 20%) cannot accurately describe key concepts after a modern physics course. This indicates that there may be a significant gap between students’ learning to succeed on exam-type assessments versus retaining meaningful conceptualizations in modern physics.

**Modern physics in research with a laboratory focus.** Research regarding modern physics labs commonly falls into the theme of developing specific experiments or activities to incorporate into the course. An example of an early article regarding laboratory design in modern physics was written by Wilson (1980), who developed simulations of experiments for students to use as pre-lab exercises. The simulations explored concepts, like particle and wave behavior, instrumentation, and spectrometers and interferometers (Wilson, 1980). Wilson (1980) reported higher student satisfaction in an open-laboratory format and improved quality of lab reports after implementing the simulated pre-labs, though did not provide data to support these conclusions.

Very little research investigates students’ experiences in lab courses and perceptions of the role of experiments using qualitative approaches. This includes the studies by Irving and Sayre (2014, 2015) which had participants in upper-level labs but were not focused exclusively
on modern physics. Some students from a modern physics laboratory (as well as intro labs and graduate students) were included in qualitative research by Hu and Zwickl (2018). Students responded to open-ended surveys about the role of experiments in physics as a field. Hu and Zwickl (2018) found that the upper-level (modern physics) lab students valued comparing results with others (a results-based criterion) and uncertainty evaluation (a process-based criterion) in establishing experimental validity.

Another study including upper-level (such as, but not exclusively, modern physics) lab students along with intro-level lab students added open-ended prompts to the E-CLASS (Hu, Zwickl, Wilcox, & Lewandowski, 2017). The researchers found that some students believed that classroom experiments based on confirming known results were valuable for learning (Hu et al., 2017). This is interesting to consider when reflecting back on quantitative results which show that laboratories do not meaningfully contribute to content knowledge (Holmes et al., 2017).

This contrast between students’ perceived value of laboratory courses and the actual (lack of) benefits to conceptual mastery raises many questions. For example, is it enough if students are motivated by conceptual mastery? That is, can students who are motivated by conceptual mastery still make gains in intended learning outcomes that are skills-, process-, or communication-based? Additionally, this suggests that students’ internal assessments of their own conceptual progress differ significantly from educators’ assessments and that there is still much progress to be made in bridging the gap between educators’ goals and students’ experiences.
Chapter 3: Methodology

Research Design and Sample Selection

This study included a semi-structured interview protocol that was an adaptation of the three-interview structure described by Seidman (2013). Seidman’s three recommended interviews are focused life history, the details of experience, and reflection on the meaning of experience; the combination of these three interviews creates the most complete story of an interviewee.

This study modified the content of Seidman’s three interviews into a pre- and post-interview structure. The pre-interview comprised the background information suggested for focused life history as well as the details of students’ expected experiences. In the post-interview, students described the details of their actual experience and reflected on these experiences and the course. A schematic of these interview structures is shown in Figure 1. The pre- and post-interview protocols are included in Appendix A.

Several questions were added to the post-interviews based on each student’s pre-interview. For example, one student, Francis, said in the first interview that he expected that one experiment just wouldn’t go well. The protocol for his post-interview was updated to include the
question, “You mentioned last time that you expected that for at least one of the labs you’d just end up with bad data and that would be it. Did that end up happening?”

This study used a convenience sample ($n = 7$) at a tier 2, mid-size, public university in the midwestern United States. The interviews were conducted over one semester (one instance of the modern physics course). A segment of the course syllabus is included in Appendix B.

The primary researcher recruited students by visiting the modern physics lecture in person on the first day of class and circulating an email sign-up sheet. The instructor for the course left the room while the primary researcher read the recruitment script, which is included in Appendix C. All seven students participated in both the pre- and post-interviews. The sample reflected the demographics of enrollment in the class, which was mostly white men.

This study does not invoke research questions explicitly related to certain identities, so detailed demographics were not included in data collection and are not presented here. Instead of asking about gender, participants were only asked what pronouns they use, so they could be correctly referred to in the research.

The course instructor was also interviewed to establish his intent for the modern physics course, and to discuss changes to the laboratory manuals and coursework. The protocol used for the instructor interview is included in Appendix D. Highlights from the instructor interview are presented in Appendix E.

**Data Processing and Analysis**

The data collected for this study were completely in the form of recorded verbal interviews. As such, the data presented in this text have been twice-processed: once, in the original transcription to text, and twice, in the editing of quotes and segments to include in this report. Many modern speech patterns are intrusive and distracting when read from the written
word, so were edited out. Great effort has been spent to preserve as much of the original meaning as possible; however, like with any data, observation and analysis have inevitably rendered some information—and possible interpretations—lost. For an example of an original passage from a transcript and an edited version used in this text, see Appendix F.

Data analysis was conducted with the text transcripts and resulting narratives presented in Chapter 4 (Results). Three of the seven participants were selected as cases to be presented; the included cases were chosen based on the clarity and completeness of the students’ interviews. Two of the students included here, Skylar and Jamie, were lab partners. As lab partners, they conducted eight experiments individually over an eight-week period. They would each conduct a new experiment during the odd-numbered weeks and then swap places for the even-numbered weeks. The only exception was the Millikan oil-drop experiment, where they worked together over a two-week period.

All names included in this research are pseudonyms. Additionally, students’ majors have been generalized to reduce the possibility of identification. For example, “engineering physics,” “physics research,” and “physics,” are all possible majors at their university; these majors are collapsed into one, “physics.” Although this does obscure some detail, students’ career intentions and ideas about physics are included to provide context for their statements.
Chapter 4: Results

Skylar’s Pre-Interview

**Skylar’s background.** Skylar is a senior physics major. He described himself as someone who is good at—and enjoys—math. This interest in math is part of what motivated Skylar to choose physics as a major; he mentioned that he loves “applying math to real-world problems” in physics classes.

Skylar wants to go to graduate school and earn a PhD, but is undecided about his career path. When asked about his plans, he said,

I love physics, so it’s hard to choose which part of physics I like the most, but I’m really interested in renewable energies. So, I was thinking about going for renewable energy to get my PhD, work in the field for a bit, and then maybe go back and teach.

He elaborated on this by noting his desire to use physics to help people:

Part of the reason why I want to be a physicist is to help people. I’m sure you’ve heard people say a physics degree is a problem-solving degree. So, I want to be able to take this degree and solve a problem that will help people, and I feel like if I work in the industry, I’ll be able to help more people. But, I also enjoy teaching people and sharing knowledge.

Skylar has research experience in computational physics, which he said he enjoyed doing. He described computational modeling as “super powerful,” and likes that it is a practical skill used in industry. He also said he’s interested in trying experimental work to expand his skillset.

Before modern physics, Skylar had taken the introductory physics labs, an upper-level mechanics lab, and chemistry labs. The mechanics lab had much more independence than the intro labs—to the extent that the instructor typically was not in the room during experiments.
Skylar noted that this independence led to a different experience from the introductory labs, in which a graduate assistant (GA) was constantly present:

- I think you learn different skills, because in intro lab, if you come upon a problem, normally you just raise your hand, get the GA to come over, and they’ll just tell you what to do. But, I think it allows you to try different things and test things out yourself. And you have more of an opportunity to fail, which you can learn from. So, I think you can learn a different set of skills versus just following instructions.

When asked about previous experiences during which he had felt like a physicist, Skylar first brought up seeing “cool results” in labs, such as a beating pendulum they set up in the mechanics lab. He then went on to discuss a “rewarding” experience he had attending a national meeting through the Society of Physics Students: “Moments like that where I’m able to interact with and listen to these amazing physicists who are forerunners in their field—to talk and connect with them is really cool, and makes me feel like I’m in the field.”

He has a friend who is a physicist working in industry, and Skylar said they often talk about physics together. He described their friendship, saying, “He’s 10 years older than me, and he’s already working in the field so he’s able to help guide me through my physics career and tell me if this is a good idea.” Skylar’s friend has also helped him with physics before: “He knows a lot of physics, so I’ll just go to him and ask him a question, and he’ll guide me in the right direction.”

**Skylar’s thoughts on the modern physics lab.** Skylar expected he would spend time preparing for the lab,
so that way once I go into lab, what I’ll be able to do is just run the experiment and collect data. And then, if I have extra time, use that time to think about what the data means and any questions I have about the data.

He also said that he would do data analysis outside of lab if he didn’t finish it in time.

He speculated that he would be mostly working on his own during the lab, saying, “I think compared to the introductory labs, there’ll be more independence.” Skylar expected that the instructor would spend time checking in with students, “but other than that, we’re going to be by ourselves.”

Skylar said he didn’t expect to encounter many challenges during the modern lab. He had heard from friends who had taken the class that the Millikan oil drop experiment can be tricky, but he didn’t think it would be a big obstacle for him and his lab partner.

When asked what skills he thought would be important for the modern lab, Skylar said, “Being able to read through a lab and get knowledge from that beforehand. That’s going to be a big skill that will help once we go to take our data.” He added, “knowing what equipment is there, and knowing what each thing does would also help facilitate your process of doing the lab. Versus just sitting down and saying, ‘what is this?’”

He expected that he would learn more from the lecture, “because I’m really a numbers-based person.” Skylar said, “learning concepts is going to be the main chunk of it, and then the lab’s just going to reinforce those concepts.” He continued, “So, we’ll learn these concepts and then we’ll just go to the lab and experimentally verify these concepts. It’ll strengthen the concepts because we’re actually visually seeing it and doing the experiment, versus just doing numbers on paper.”

He still expected to get something out of the lab:
In the lecture we’ll learn problem-solving techniques and stuff like that, but in the lab, we’ll learn different techniques for doing experimentation. So, sort of different knowledge that we’re learning, like problem-solving and then hands-on problem-solving…for example, if a laser’s not working or it’s not right, we have to adjust it with our hands. But in class, if our equation’s not working, we’re not just going to adjust it like we would a laser. We’d have to figure it out in a different way. So, there’s two different types of thinking.

Skylar also brought up that this class would be the first time he would use a lab notebook. He said,

In this class we’re doing a lab notebook, versus in all of the other ones we’ve just had a pre-made notebook. This is just a blank notebook, and that will teach us how to use a lab journal and record our data versus just having these pre-made things. I think that’ll be a good thing to learn…and I don’t think any other classes up to this point have done that. I think that’s a valuable skill for if you plan your own research or if you go to work in the field for a company.

Skylar’s thoughts on the purpose of the modern lab experiments focused on measuring constants.

With modern, it seems like we’re going to measure a lot of constants that we use throughout physics. That will give us a background knowledge of why we use those constants. Now, we can actually take these constants for real because we know that we measured them ourselves. It will help strengthen our confidence when using those constants.
Skylar brought up concepts and independence again when talking about how the modern lab fit into his long-term goals, saying, “I plan on doing physics for a while, so strengthening those concepts and the ideas we learn in lecture that I’ll probably use throughout my career is definitely going to help me out.” He continued, 

Being able to have that independence in the lab where we have to basically do everything ourselves, but there’s somebody there helping, I think that sets me and everyone else up well for if we want to go do our own experiments or if we work for a company and they just give us a task. We’re able to set up the experiment ourselves and plan stuff out ourselves versus just getting an instruction manual. It definitely makes us more marketable to people in the field. Also, if you do stay in academia, if you plan on doing research, then you have a base of what you need to do for that research.

When asked about the purpose of the modern physics experiments, Skylar focused on concepts again. He said, 

The concepts we’re learning in this class are used today a lot. Being able to perform these experiments that they did in the past, you get more of a feel why you’re doing things, and more of a background versus just being like, here’s a constant that you’ve been using. You’re able to figure out why you’re using that constant and where it came from, which gives more background knowledge on physics.

Skylar also shared his ideas for the role experiments play in physics as a field. He said, 

People will do theoretical physics on paper and stuff like that, but you can’t actually verify that until you do these experiments. Outside of just the math and stuff like that, to see actual results that will verify and prove this theoretical stuff that you’ve done on paper.
Skylar’s Post-Interview

**Skylar’s description of the lab.** Skylar described the breakdown of his time during the lab period as follows:

I spent probably the first fifteen minutes or so just looking through the lab again and making sure I knew what the procedures were, and then probably fifteen to thirty minutes actually setting up the experiment and figuring out what everything does. I’d spend about twenty to thirty minutes taking data. Then, if I saw my data was good, I would just be done, clean up everything, and go home. If it didn’t seem like it was good, I’d take another set of data, which would take another fifteen or twenty minutes.

He said that he did most of the work for the modern lab at home, when he had more time: “I think the time outside of the lab is when I did most of the work for it. I thought at the beginning of the semester it was going to be the opposite.” Skylar also mentioned that a heavy schedule meant he would be exhausted by the time he was taking data in the lab:

I would just be so tired, I’d want to take the data and get out of there. So, most of the time I’d just get the data that I would need, and then at home I would do all the calculations, answer all the questions, and figure out what my data actually means.

He added, “I would learn enough in the lab to know what I was doing and take the data, but then actually understand my results and why I got these results at home.”

Skylar thought that lab manual revisions (which were ongoing during the semester) were helpful. He described the differences between the old and new manuals, saying,

For my first few experiments I had the old lab manual, which was just the equipment booklet. It was a little bit more difficult because it was hard to figure out the steps exactly. With the new lab manual, it was pretty easy because [the professor] had the steps...
clearly written out with what we needed to do. The original one wasn’t as clear, and there was a lot of other information that was unnecessary for our lab.

Skylar said the new manual was easier because “[the professor] sorted through it, instead of us having to sort through it ourselves.”

He also described what it was like to work independently in the lab, which was unlike other lab courses he had taken. He said it went well:

I think what ended up happening most of the time was I would learn basically what I needed to do for one experiment. Then, I would talk with my partner and say, “here’s a few tips,” and then [Jamie] would also give me a few tips on how to do mine. If we had a question during the process, we would ask each other, so we sort of helped each other out with them. It was nice because you had somebody that already did the experiment the week before, and they knew the ins and outs of it.

**Skylar’s takeaways.** Skylar said one of his big takeaways from the lab was “keeping a detailed lab notebook, so that way it’s easier if you want to reference back to something.” Using a lab notebook was something he’d never done before, and he said, “it was cool, because you get that experience of keeping a lab notebook like you would in a professional lab.”

He brought up the lab notebook again when asked about what skills he thought were important for the lab:

I think organization was really big. Organizing your data and your lab notebook. That way it was easier to look back on what you did that day and figure out what you were doing. Also, keeping a detailed record of what you did in the lab notebook. So, I would write down each step that I did so that way once I looked back at my lab notebook—because I normally waited until close to when it was time to turn it in to do it instead of
doing it right afterwards—I was able to easily go back in there and refresh my memory on what I did.

Skylar said he knew early on that he would need a good lab notebook to finish his work for the lab. He said, “I knew I was going to push it off, because I know how I do my lab reports.” He also mentioned the lab notebook when asked about research, saying, “some things from the lab will definitely help for doing actual research, like keeping a lab notebook and writing the lab reports as a professional journal article.”

He also thought the lab notebooks were one way the modern lab had more freedom than other labs he had taken:

Keeping the lab notebooks was actually more of a freedom than having a given lab notebook that we have to fill out, so that was nice. We had a little bit more freedom for how we want to take the data, how we want to format it, and stuff like that.

Skylar had more thoughts about lab reports, which he shared when asked about things he found challenging for the lab course. He said,

For our lab reports—I haven’t done the second one yet, but the first one—it was a completely different format. It was really difficult to learn that formatting at first, because he wanted us to have written it like a scientific journal article. Learning that formatting and making sure everything was right was a long process. I think it took me six or seven hours to write the lab report that was two and a half pages long, with pictures. But once I was done with it, it looked very professional and seemed like it could be published, it was that good of quality.

Skylar also described writing the first lab report a time during the modern lab when he felt like he was a physicist:
When I was writing my first lab report, I just went to a coffee shop and sat down for like six hours and wrote stuff. I felt like that was a more realistic view of physics. I’m not just going to be in a lab all the time doing experiments and doing cool things. In order to do those cool things, you still have to write these reports and publish stuff, too.

Overall, he found the modern course “pretty easy”: “I haven’t really needed help in modern,” he said, “all the concepts I seem to get pretty easily, so I haven’t really struggled through it.”

Skylar had thoughts on how the lab contributed to his long-term goals: “Well, it’ll help me graduate because it’s required.” He also brought up the reports and notebook again as two big takeaways from the lab. He added, “Getting background knowledge in things, and then touching on some skills I already knew like using an oscilloscope. So, it just helps solidify some of the knowledge that I have that I’ll continue with in physics.”

**Thoughts on the experiments.** Of the nine experiments he did in modern, Skylar said the Millikan oil drop stood out because “it’s a two-week lab, and everybody’s really intimidated by it.” However, he added, he wasn’t intimidated by it, “and doing it actually wasn’t as bad as everybody said.” Skylar and his lab partner, Jamie, would have been able to finish the experiment in one lab period, but they forgot to record the voltage for several drops on the first day.

Despite having to take extra data, Skylar said,

It was fine. I think me and my lab partner are pretty confident in our abilities to take data and stuff like that. Us both going into it with the attitude of “we want to finish this in one day” and our confidence helped us get it done pretty fast.
He also thought “what most people worry about is not being able to get enough data, but we didn’t really have that issue.”

Skylar brought up Millikan again when he was talking about things he thought were cool in the lab:

Millikan was pretty cool because you’re doing things on such small scale, but then you can measure these fundamental constants that we use in all of physics, which was pretty cool. Also, there were a lot of experiments where we were just measuring constants, and it never would’ve gone through my mind that this is how we were going to do it. And then I get my data and it’s like, “oh, that actually worked, I got a pretty close value to what it should be.”

Regarding constants, he added, “it seemed like a lot of our labs were measuring different constants, like the speed of light” and others. When asked what he thought he got out of making these measurements, Skylar said, “I wouldn’t say it strengthened my trust in those, but it was just cool to measure them and see how scientists did it in the past. But, it wasn’t anything super special.”

One of the other constants he measured was the charge-to-mass ratio of the electron, which did not stand out. He said,

That was one of the labs that I spent a minimal amount of time on, because I was really sick that week. So, I literally walked into lab, took my data and stuff in thirty minutes or less, and got out of there. I don’t think that one made an impact on me at all, in any way possible.
Skylar’s ideas about lab and lecture. Overall, Skylar said, “I don’t think I really got much out of the lab, to be honest.” He said he learned the theory from the lecture. When asked about doing the experiments out of order with the lecture, he said,

Because not everybody can do the same experiment at once, we just started in different orders. I think some of them I learned before lecture, but then some of them I did after lecture, so it was a split. I don’t know if that really solidified my knowledge either way. I don’t think it really changed anything.

He explained that he thought this was because he didn’t need know any theory to finish the lab: “None of it was really difficult to do…I could probably take the lab before I even took the lecture and still do fine in it.” He added, “I didn’t need any knowledge prior to doing the lab,” so he thought, “having lecture wasn’t beneficial to what I did in the lab.”

Skylar did say that he thought the lab was supposed to contribute to the lecture. “I think they’re supposed to solidify the stuff that you’re learning in lecture,” he said, “but it didn’t seem like that’s what I got out of it, but that could just be me. There could be a lot of people that it actually does solidify what they learned in the lecture.”

However, Skylar commented that there were some things that he remembered seeing in lab before lecture:

I would say there was some stuff that carried over, where I did it in the lab before we learned it. Once we were going through and learning it, I thought, “oh, I’ve already seen these equations before, and sort of know how they work and what we’re doing with them.” I could also see the hands-on—if we shoot these electrons through here we can see the big D versus the little d spacing of the lattice for the electron diffraction
experiment. It was cool to be able to do the experiment in lab and then learn about it in class.

He also thought that the modern lab did not give a good impression of experimental research. Skylar said,

I don’t know if it gave a good look at what lab research actually is, because we were doing one experiment that has the stuff already outlined step-by-step. It was sort of just collect data, and you know what you should get and then leave, versus with research, sometimes you still know what you’re going to expect, but it’s a lot different. And I feel you have more freedom for what you’re doing for research.

**Plans to do lab work in an independent study.** Skylar said he thought he would be using the lab notebook again soon, in an independent study in a lab next semester. He described his motivation for seeking the experience, saying,

I think it’s good to have hands-on lab experience because all of my research in the past has been computational, which I would say is more theory than actual lab work. So, I think it’s good to get experience in a lab, especially because I want to go on to grad school.

He spoke with a professor who does experimental research and set up the independent study. One of the things Skylar was interested in was seeing a lab notebook in a context outside of class:

I’m hoping that I’ll learn a lot about how to use the lab notebook more for—it seems like it’s going to be used a lot differently, because we’re going to be using it for each instrument versus how we used it to take data for a bunch of instruments.
He said he was excited for the independent study because he’d never worked in a lab before, and he expected to learn from the experience:

I think that I’ll learn some skills in the lab that I’ve never learned before or thought about. It’s a new environment, and I’m sure there’s unknowns that I don’t know anything about, and working with him in that aspect will help me learn skills that I can use in future labs. Despite looking forward to learning new skills, Skylar expressed that he still sees computation as the research he wants to do the most. He said, “I still think if I end up doing research—well, I will end up doing research if I go to grad school—I will want to do it with computational tools.”

**The purpose of experiments.** Skylar thought that the role of the experiments in the modern lab was to “teach us in-lab skills.” He said,

They want to give us as much lab experience as possible….I know we don’t have the best labs among schools just because of money and stuff like that, but doing it so that we have a ton of lab experience will equip us for if we want to go work in a laboratory or once we go to grad school.

When asked about the role of experiments in physics, Skylar said, “I think that probably most of the experiments being done now, in today’s society, are used to verify results that have already been theoretically found but not experimentally found.” However, he continued by describing an experience he had visiting another university for a conference during the semester: “I got to see some of their labs and some of the work that they’re doing, and they’re doing experiments that haven’t been theoretically done, and optimizing things to make things more efficient.”
He gave an example, saying,

One of the PhD students, he just graduated this past summer, he was doing something with the thermoelectric effect and optimizing it to get the most energy output from it. So, doing different things like that in the lab to optimize these experiments to try and maximize things. I think that’s something I haven’t thought about before, because I was just thinking that the majority was just verifying things, but this is more like taking things we already know and making them the most optimal they can be.

**Jamie’s Pre-Interview**

**Jamie’s background.** Jamie is a junior physics major. He started college as an undecided major, but then he decided to major in physics after taking his first physics class. He said he liked the challenge of physics, saying, “if it’s too easy, I get bored.” He also has a math major and said he added it because he would need very few additional classes to earn it.

Jamie doesn’t have a clear career path planned but said he could see himself working on research and development. He thought he might like to do a mix of lab work and computational work; he said, “I like doing a lot of different things. I think it’s more interesting that way.” Jamie has not had research experience, but he plans to do research with a professor before he graduates.

Jamie had taken the introductory physics labs, a chemistry lab, and an upper-level mechanics lab before modern. He said that he thought the modern lab would have a different emphasis on reports than the introductory labs:

Mechanics had a little less emphasis, so I’m thinking modern’s going to be even less emphasis on the lab reports, but more on the process of how you got there—the data analysis stuff—rather than just collecting data and just putting it on a piece of paper.
Jamie described doing homework for an electricity and magnetism course as a previous time he had felt like a physicist, saying, “That stuff is pretty difficult, and then actually getting it right was—I was like, ‘oh shoot, this is actual physics, this isn’t something some math guy can do, this is an actual physics thing.’” When asked to elaborate, Jamie said that the difference between a math problem and a physics problem is “the conceptual stuff, because a lot of people can just do straight calculus, but when you need more than calculus to solve the problem…that’s when it becomes a physics problem.” Jamie also said, “nothing can ever be as challenging as electricity and magnetism,” except maybe quantum, which he hadn’t taken yet.

Jamie took engineering classes in high school, which he said introduced him to using lab notebooks. However, he said, “we didn’t really use the lab notebooks how I feel they were supposed to be used,” because “basically we just used it as notes. There was the concept of you write in pen, you cross something out, but it wasn’t really organized very well.”

**Jamie’s thoughts on the modern physics lab.** Jamie said that the lecture is theoretical and conceptual, and he thought the purpose of taking the lab in addition to the lecture was “the lab gives a tangible thing of what those concepts are to help understand what the class is talking about.” He continued, “there’s definitely something about seeing this concept being demonstrated in front of you opposed to hearing, ‘hey, this happens.’”

When asked about learning from lab and lecture, Jamie said, “I feel like the lecture’s going to contribute most to my learning, but the lab’s going to reinforce that learning.” He elaborated,

I feel like the lecture helps you apply—or, lays out the concepts so you can apply it to multiple things. So, you learn it in lecture so you understand the concept, and then lab shows an example of that concept to reinforce what that concept is.
Jamie expected that his time in the lab would be mostly spent “doing the actual experiment itself.” He said, “I’m sure there’s going to be some confusion with some of the labs, so I’m going to spend a good amount of time trying to figure out where I went wrong.” He also thought he’d spend time working on the lab notebook because he hadn’t used one since the engineering classes he had taken in high school. Jamie expected the structure of the lab notebook for modern to be different than the notebooks he had used before:

After previous labs and stuff, I understand more of the structure of how you should structure your data so it makes sense when you’re doing data analysis. You don’t always just write a list of all the numbers you get.

Jamie brought up the lab notebooks again when asked about how the lab fit into his long-term goals. He said,

Since I plan to do more problem-solving and experimentation, I think any lab funnels into that direction. I think the lab notebook’s going to be the biggest thing. There’s always going to be more experiments and more things to do, but I think the lab notebook’s going to be the big takeaway from this class. You know, learning or polishing how to keep a good clean lab notebook that can be understood by other people, and documents what you did in your lab.

Jamie continued to say the point of a good lab notebook is that research “is not going to have any impact unless other people can know what you did.”

Jamie said he expected to spend time preparing for the modern lab, so that he would be ready to do the experiments on his own:

I know we’re all doing individual labs, which is new because usually it’s a partner lab and you have someone to bounce ideas off of. So, I think a lot of it is going to be prep
work beforehand so when I go in I know exactly what equipment I need and what
experiment I’m doing.
He also mentioned preparing data tables before the lab: “So all I have to do in lab is just take the
data.”

When asked about skills he thought would be important for the lab, Jamie brought up
“preparation” again. He also said, “being able to stay focused on something, being able to
problem-solve….and patience” would all be important.

Jamie said the lab wouldn’t be “terribly bad,” and he expected he would not “be stressing
out about time.” He said the Millikan oil drop experiment might be a challenge, because he had
heard it is difficult from other people who had taken the class. He didn’t expect many other
challenges; he added, “other than that, I feel like I’ve gotten pretty good at labs and taking data
so I should be alright.”

Jamie said his confidence in the lab came from other labs he had taken. When asked how
he got good at taking data, he said,

A lot of that was my intro lab. The instructor was super detail-oriented in the first few
weeks, saying you have to do this, this, this, and this to get good data and have a good
lab. Then in the mechanics lab, it was a partner lab but you did it on your own, in your
own room. So, the experiment was set up and you did it. So that was like, you can’t just
go to the front of the room and ask, “How do you do this?” You had to really figure it out
yourself. I guess between those two things it was stepping stones to doing a completely
individual lab.
When asked about how the lab and lecture would compare, Jamie brought up that he would be doing the labs out of order from how the material would be presented in the lecture. He said,

So, knowing that, it seems like they won’t be as tied to the lecture. It won’t be like, “oh this week in lecture we’re learning this and we’re going to go do this in lab.” I feel like we’re going to do all these things and then we’re going to learn about how they actually work in lecture. And we might be lucky and be working on something in lecture that we’re doing in lab that week.

Jamie said that the random order of experiments would change things; he said,

You have to do more background work on the labs, because you didn’t learn it in class yet. I’m sure there’s definitely enough background information to do it, because it would be silly to do a lab that you don’t know how to do.

When asked about the role of experiments in physics as a field, Jamie said their purpose is “proving that the concepts actually work, so what you do on paper actually can translate to real life.” He added, “It’s like, I guess, the proof of physics.” Jamie elaborated on how experimenting differs from other forms of research, saying,

It’s more tangible. The math work and computer work you can do, but it doesn’t really have an impact in the rest of the world. It’s like, we know that this can happen, but if you’re doing actual experiments, then it can affect people and the world and stuff. You know this is something that exists and is going on and you can prove it. That’s a lot different than, hey I can prove that math exists.

When asked the same question, but about the experiments specific to the modern lab, Jamie said,
I feel like they’re not breaking any new thing because they’re all experiments that were done before and proven over time to work. So, it’s not some cutting-edge experiment that we’re doing in there. But, I think it’s to show what you can do with physics, because I feel like these are going to be more interesting than making a circuit with a resistor. It’s like, cool, you can make a circuit with a resistor, but then when you look at a computer there’s a huge gap. But I think going from the modern experiments to maybe some more cutting-edge experiments, there’s not that much of a gap.

**Jamie’s Post-Interview**

**Jamie’s thoughts on the lab.** Jamie said most of his time in the lab was spent “just doing the experiment and collecting data.” He said he analyzed his data outside of lab. He described the lab periods, saying, “I think about half the time was spent trying to understand what I was supposed to collect data on, and then the other half was actually collecting data.”

When asked about the process of figuring out an experiment, Jamie said he would look in the lab manual for “what we’re trying to find, and then how you find that.” He elaborated, saying,

I always look at the end goal first, because there’s no point of trying to go through it without knowing what you’re trying to find. So, I look at the end goal, and how you get there. Then, I go back to the setup and set up the experiment, because I feel like if you try to set up the experiment without understanding what you’re trying to do, it’s a lot more difficult.

Jamie said he didn’t need to use outside resources to support his lab work: “It was more about analyzing the data and checking with the expected results,” most of which he said were in the lab manual.
Jamie compared the rewritten lab manuals to the original equipment manuals, saying, “I think the lab manual was a lot easier, but the equipment manual I think I learned more from, because you actually had to look deeper into it as opposed to just following a step-by-step thing.”

He added,

I’m not really sure which one I prefer. The lab manual is definitely easier, but I think if it was a mix, that would be kind of neat. An experimental procedure, but all the setup you had to look in the manual, or something like that.

Jamie described his time doing data analysis outside of the lab using spreadsheets. He said,

I’d make spreadsheets, and then print them off and put them in the lab notebook. Most of the actual, or the theory stuff was taken care of, either in lab or before lab. So, it was just inputting the data and analyzing the data, which were almost all spreadsheets.

He continued by sharing his thoughts about the lab notebook. Jamie said it was structured differently than other notebooks he had used, but “it was kind of an easy transition, because the first few labs [the professor] was really lenient on it and he gave a lot of feedback.”

Jamie had more ideas about the lab notebook; when asked about takeaways from the lab, he said, “I like the lab notebook. I think it’s a better way of structuring data than just making an excel spreadsheet, because you have to remember what you did.” He also recognized that the notebook for modern wasn’t what he had expected:

I might’ve expected a little more out of it….I don’t know that I’d use that as like a final copy for anything, but it was definitely neat being able to lay out your data to look back on for writing a report later on. Formatting the data made writing the lab report easier.

But, I don’t know if I’d ever submit that lab notebook as a piece of work.
He added, “I guess it was exactly as it should be, but I guess I expected more out of it.” When asked to explain, Jamie said, “It turned out to be a way of recording all your lab data in one organized place, which I guess I expected, but for some reason I expected it to be more organized and professional….which, looking back that doesn’t really seem practical.”

When asked about important skills for the modern lab, Jamie said “focus” was important “because there were quite a few distractions in the lab,” such as people talking. He also said that “problem solving or critical thinking” were important, “especially for the ones without manuals, because those you actually had to figure out what you were doing.” He added, “so, I don’t think a lot of physics skills played a part, but things that go along with the physics like problem-solving were really important.” Jamie elaborated by saying that the physics skills he didn’t use in lab were “book knowledge.”

Jamie thought that overall the lab was “straightforward.” He said, “I know some other people struggled, but I feel like I’ve had some experience in lab so I know what’s kind of expected.” He described what he found easy about the lab:

Everything’s pretty well-outlined. We know when we’re doing what experiment, what we’re doing for that experiment, and then we also know what we’re supposed to do with the data and stuff. There wasn’t really anything up in the air that we had to try to figure out.

When asked about how this contrasts with his description of having to figure out each experiment, Jamie said he had expected having to do so. He also noted that the mechanics lab he had taken had more independence than the modern lab; he said mechanics was “more like, ‘on your own, figure this out’ than modern was.”
Jamie’s thoughts on the modern lab experiments. When asked about experiments that stood out to him from the semester, Jamie said,

I thought the Millikan one was cool. It was kind of frustrating, but it was neat. You’re suspending an oil drop with, you know, the electromagnetic force. It’s kind of a neat thing to think about, and not something that you usually do day-to-day. I think that one because it was more challenging than the rest, so it made me think a bit more. It was still really straightforward, it was just frustrating.

Jamie described his frustration with forgetting to record some of the data for the Millikan oil drop experiment, which he did with his lab partner, Skylar:

We got six drops in the first day, we probably could’ve been done in the first day, except we didn’t take the suspending voltages down. We didn’t record it. We couldn’t use any of those six data points. We thought we were going to be done with a two-day lab in one day, but we just wasted an entire day taking data points.

Jamie said they did end up getting enough data in the next lab period, but it was frustrating to spend “two and a half hours, or whatever, taking data and all this stuff and then realizing at the end of it that we missed one important part of all of it, which takes maybe thirty seconds a point to do.”

Other than their mistake, Jamie said he thought Millikan was “okay.” He said, “I don’t think we were as frustrated as some other groups, because we understood how to clear the screen or get the right amount of oil drops in there,” which he said were common problems other groups had.

Despite this frustration, Jamie did say that he liked being able to work with a partner to do the Millikan oil drop experiment:
I like the partner labs more, because you had someone to bounce ideas off of, and someone to talk to while you’re doing it. Some of the experiments are kind of boring, so having someone there to talk to makes a boring experiment not so boring.

Jamie described what he thought was tedious about the “boring” experiments, saying,

You hit a button, take data. Hit a button, take data. And it’s not like any cutting-edge data that you’re taking, it’s all stuff that we already know like the speed of the light….so it’s just kind of tedious.

He added, “it’s cool to be able to measure some of these things, but then again, we already know that this is.”

When asked about the purpose of the modern lab experiments, Jamie said, “It’s the progression of physics.” He added,

A lot of them were new things in physics at the time….so this is kind of like, you have to look back in order to move forward kind of thing. You have to understand how you got to this place, before we can go from this place forward.

He continued, “if we can have all of these experiments in one lab, and there’s only one lock on the door to hide them, you know they’re not that cutting-edge anymore.” Jamie also said that’s how he thinks about school in general: “We’re learning what’s already been done, because you can’t work on your own new thing until you know what’s been done already.”

Jamie said he thought about half the experiments were measuring constants. He shared his thoughts on those experiments; he said,

I learned from the process of doing it. I don’t know if I necessarily learned measuring constants, because I already knew the constants that I was measuring. So, we got a thing
and then we compared it. I guess it was more of trying to figure out what the difference is, like what could be done better to get closer to the constant.

He added, “it all comes back to lab practices.”

**Jamie’s thoughts on lab and lecture.** Jamie said he would have preferred doing the experiments in the same order as the lecture material:

I think it would’ve been better if I could’ve done the experiments as we went through lecture, because some of the experiments I started with we didn’t see until later in the semester. It was kind of cool to look back and see, “oh this works because of that,” but I think it would’ve been a lot better if it was, “oh we just learned about this last week in lecture.”

He added that he knew it wasn’t practical due to a limited amount of equipment, but he thought it “could’ve been better.”

When asked what was different about doing a lab before seeing it in the lecture, Jamie said,

When I did the lab before we saw it in lecture, I was learning how it works. Then, when we saw it in lecture I was like, “oh yeah, I had to teach myself this three weeks ago.” It made that part of lecture kind of boring. I mean, it was still important because we got all the equations and stuff that we needed, but the conceptual part of it wasn’t new.

He continued, “I think it’s cooler to learn about something then put it into practice.”

Jamie thought that overall, he got more out of lecture than lab. He said there were some experiments for which he’d “take the data and just get out of there because it’s not really interesting.” He added, “I probably enjoyed lab more, but I think I learned more in lecture,” and
“it’s good to have them concurrently, but if I had to pick one to take instead of the other I would’ve taken lecture.”

When asked why he thought lab was required in addition to lecture, Jamie said,

I think it supports the material that you learn in lecture. That’s usually the point of lab. Or, to test something, to test an idea you came up with or you know just in general. I think in this case, it was really to reinforce that these things actually do work like this. Or, this is the case for these concepts, they may seem weird, but this is proof that they work like this.

**The purpose of experimenting.** Jamie said he thought the purpose of doing experiments in physics is “proving that what you can put on paper actually applies to the real world.” He added,

A lot of what we do is theory and ideal conditions and stuff like that, which if you can show that that actually is true, then it’s a lot more convincing and cool. I think the experiments are the practical side of physics. I think all the analytical or pen-to-paper stuff should be moving towards an experiment, because that’s what you’re trying to find...I think they’re kind of the end goal of whatever you’re doing.”

**Jamie’s takeaways.** Jamie said that as he expected, modern was not as hard as the electricity and magnetism (E&M) class he had taken. He shared a few ideas about why modern felt easier than E&M; he said E&M had harder problems that used higher-level math. He added, “it might also be the environment, too, because E&M was a lot more structured, and modern was a bit more loose.” He also noted that he had been one of the younger physics students in E&M when he took it, but by the time he got to modern he was “more of the upper-level physics kid.”
Jamie said that the focus of the modern lab was on “making sure you did your data correctly, your analysis correctly, you hit the right points.” He said it was important that “you’re actually comparing what the experiment was designed to compare.”

When asked whether he’d like to take more labs like the modern lab, Jamie said,

Yes and no. I like the structure of it, but I’d want some different experiments. I guess the one-lab-period experiments are not as exciting as taking multiple days to do something, because they just seem really straightforward and they’ve already been done before. I guess a multiple-day experiment probably would have been done before, too, but it’d be more setup and yourself coming to conclusions, opposed to already knowing what’s going to happen.

He clarified that he had not done a multiple-day experiment in a lab before, saying “it’s just something I think would be cool.” Jamie added that after having taken a few lab classes, “I kind of want a new style, or more complex experiments…I’d rather have it be more process-focused than results-focused.” He also mused, “maybe I just want to do independent research.”

Jamie said his thoughts about doing research didn’t change during modern lab. When asked about it, he responded with, “Got to figure that out….I’m still very much unsure.” He said he would still like to try doing a mix of lab work and computational work, especially after taking a computational physics class.

Jamie was noncommittal when asked how excited he was about modern physics; he said he liked the first half of the semester more than the second half:

The first half is more of what I expected from modern physics, you know the time shifts and that kind of thing. The second half is a bit more confusing but it’s kind of more
quantum stuff. I don’t know, I think it’s a neat class, but… I really liked it at first, and now it’s kind of just like another physics class.

When asked what he meant by “just another physics class”, Jamie said,

[A typical physics class is] stuff that’s neat, but nothing that I’d go home and be like, “oh, I just learned this in physics.” So, it’s cool to know but it’s not something that I could talk about with anyone else outside of physics. I can kind of explain the relativistic speeds or whatever to non-physics people, in an easier way. Whereas, it’s kind of hard to explain stuff like wave functions. So, it’s harder to get excited about things that you can’t share with other people.

He added, “no one’s excited about wave equations.”

Jamie described a few things in the lab that made him feel like a physicist during the semester. He said,

Probably about half the experiments, it was like, this is cool, this is something that a physicist might do. Then the other half was like the one where you’re measuring the spectrum lines…I remember looking through one of those when I was in middle school. Jamie added, “But some of the other ones were definitely neat. Like the e-over-m experiment.”

He said it was “really neat to see how the interactions between everything—you could actually see while you adjust everything.” Jamie explained that the experiments he enjoyed were “the experiments that you actually needed to understand physics to see that they work.”

**Cameron’s Pre-Interview**

**Cameron’s background.** Cameron is a graduate student studying science education. He described how he ended up focusing on teaching:
In undergrad I did earth science and geoscience, and I did some field work for a while and tested the waters of academia and really didn't like it. The whole grant-writing process is horrifying to me, and just the idea of the whole funding aspect really turned me off because of the extremely competitive, cutthroat nature. What I realized is that I wanted to go into academia so I could teach geology to students—I was like “wait, oh I could just go be a teacher, that makes way more sense.” He said the field work he did in undergrad comprised taking samples for biology research in various ecosystems.

Cameron plans to teach science at the middle-school or high-school level, and hopes that he will be able to teach physics: “I can pretty much guarantee I'm going to end up teaching it, because there are not many physics teachers, and I'm excited to teach it.”

Cameron had taken a wide variety of lab classes prior to modern physics, including chemistry, geology, biology, and earth science. He also took the introductory physics labs as a graduate student.

Cameron is very excited about physics. He likes physics because it helps him make meaning of math. “Something that I’ve really learned in physics is the practical application of math,” he said,

and as someone that considers myself somewhat of a scientist, sort of, or at least someone that’s going to be a science educator, math is really important. That’s always been something I struggle a lot with, but in physics, the math is easy.

He was taking a calculus class at the same time as modern physics; he said, “it’s so hard, but if I can contextualize the calculus into a physics problem, it’s so easy.” He added that he found math
such as bio-statistics “nebulous,” but that “position, velocity, and acceleration graphs, and derivatives and integrating between—that was a lights-on moment.”

When asked about previous times when Cameron had felt like a physicist, he said, “Sometimes during the labs, when you get your expected result and your error is really low. It’s, ‘okay, I made this work.’ That would be the point I would say that I feel like a, yeah.” Cameron also said he wishes he would’ve taken physics classes earlier—he said, “it would be cool to be able to take something beyond modern physics,” and “I’d be interested in trying the experimentation side of things.”

Cameron’s thoughts on the modern physics lab. When asked how he thought he’d spend his time for the modern lab, Cameron said,

I definitely want to stay on the pattern of staying the full time every time, getting as much done as you can when you have the resource and whatnot right there. I say that now—I think I’ll probably do a good job of that because I do enjoy it.

He continued, “Overall, I am interested enough independently, that if work goes outside of [the lab] it’d still be fun.” He said he looks forward to modern, unlike some other classes: “Some of my other classes I dread, but modern is one of my, sort of, relief classes, and I kind of expect the lab to be even more so.”

Cameron described what he thought a modern lab experiment would be like:

I probably would have done a prelab, I would think, beforehand. So, I would be pretty well-aware of procedure and hopefully the theory as well. Then, obviously if I have any questions on either of those two things, try to clear that up first. Then I know we’re going to have to do a bunch of stuff in our lab notebook, so I’d try to make sure I have that all
set up….then just starting on the procedure and working the way through, and trying to efficiently get good results.

He said he planned to use Excel spreadsheets to collect data; he continued, “if you have an Excel spreadsheet you’re going to see right away what your error is, and then hopefully have plenty of time to do some analysis.”

Cameron said that he was excited that there would be a mix of individual work and collaboration in modern because “at this point in [his] academic career, group work is just exhausting.” He added that he had a “bad partner” in one of the introductory labs, which “made the experience so much worse.”

Cameron had been into the modern physics lab for the first lab period, during which the professor gave an overview of the class. He commented on being in that environment, saying, “That was the first time I’ve ever even been in an actual physics lab setup for upper-level physics research projects.” He said it was “cool” and felt different from all the chemistry labs he had spent time in.

**Cameron’s ideas about experimenting in modern.** Cameron was excited about the experiments he would be doing in modern physics. He said,

The experiments seem really cool, the setup seems cool that everyone’s kind of doing their own thing and you get to do a lot of different stuff. The implication is that the quality of each experiment will be much better since you have one individual station of each one.

He added that in the introductory physics labs, the equipment felt “mass-produced.” For modern, he said, “There is something appealing about getting my own sweet piece of equipment and doing my own projects. I’m excited.”
Cameron said he expected some challenges in the lab: “If you’re doing nine experiments, they’re not all going to go smoothly. Already, it sounds like that oil drop one’s going to be interesting.” He had heard the oil-drop experiment was tricky from people who had taken the class before, and from the professor mentioning it during the introduction to the lab.

When asked about skills he thought would be important for the lab, Cameron said, “definitely time management, and organization for sure, because you are on your own.” He added, “preparation, because if you’re not prepared, you don’t have a partner” who can keep you up-to-speed. Finally, he said, “hard work.”

Cameron explained the purpose of the modern lab’s experiments, saying, “It’s important, and even broader than just physics, I think anyone that’s interested in science and interested in being science literate, you have to have some exposure to the process through which we make scientific explanation.” He continued by describing this process:

It’s not true scientific explanation unless there’s reasoning behind it. And the reasoning comes from, you know, this group of evidence that you’ve collected. To me, those are three really key parts—so, scientific explanation, you have claim, supported by evidence, backed up by reasoning.

Finally, Cameron added that in the lab, “you’re forced to work your way through those things, and even though it’s not the discovery that you find in upper-level research science, it’s still working those muscles of how science works.” He also said, “we’ve been talking about this for like two weeks now in my bio education course.”

When asked why he thought he was required to take lab in addition to lecture, Cameron said, “I think it’s really important, as a future teacher, to be forced, or to just take as many labs as
you can.” He added that in high schools and middle schools, laboratories are “really lacking in general.”

Cameron also shared his thoughts on the schedule for lab and lecture: “They’re separately-listed courses, so you can’t expect them to line up, but that is the one unfortunate thing.” He continued, “In an ideal world you could go to lecture, learn, get lectured on what you’re going to do in lab the next day.”

Cameron compared what he’d learn from lab and lecture, saying that lab would “stick with you” in a more long-term way because “it’s active learning.” However, he thought he might not use that lab knowledge much because he “won’t be in a physics lab regularly, unfortunately.” He said, “In terms of breadth of knowledge….I can see myself using more of the lecture-type material in the future,” and added that what he’d learned in lecture had already contributed to his “ability to read other science articles, or even read news articles.”

Cameron continued, returning to the idea of active learning: “Any time somebody would ask me is learning going to be more meaningful in a passive or active sense, you always have to say active. So, I do think the lab really will give lessons that stick with you.” He said what made lab active was the “practical lab-work skills….it’s skills and knowledge, it’s not just information.”

**Cameron’s thoughts about experimenting.** When asked about the role of experimenting in physics as a field, Cameron said, “they’re the foundation. As any science, experiments are vital.” He compared experimenting in physics to research in geology or biology, saying, “Physics, it’s much more active in a testing sense because you can—it’s as simple as friction—you can test these things and you can do it in a lab, you can get repeatable results.” He continued,
You can’t go back and set up the things that made this pattern of minerals in the cretaceous period. You can’t do that. But you can do—pretty much any physics problem can be set up in the right situation.

Physics “seems much more testable,” he added.

Cameron’s Post-Interview

Cameron’s description of the lab. Cameron said he spent his time in the lab “going through the lab procedure, and then trying to do the initial calculations to make sure the data was going to be good enough to do the lab report and everything.” Normally the experiment would be set up already, but he would “run through that part, make sure everything’s setup properly.” He said, “most of the time I would have some data tables set up already so I would have an idea of where I was going.” He said, “I don’t think I was actually ever there for the whole time,” and that collecting data usually took an hour or two.

Cameron said the lab was “pretty collaborative…everyone was helping each other a lot,” but that most of the work felt independent. He liked working without a lab partner; he brought up the bad lab partner he had for an introductory lab, saying that they would copy from his Excel spreadsheets and data without contributing anything: “that was frustrating.”

Cameron had more to say about the independence in the lab, adding,

You feel special doing your own thing, and you’re on your own speed. I think part of it, too, is that doing it alone made it feel more authentic, in a way, because if in a class where everyone is doing it, everyone is like, “oh, what are you getting,” or, “is this the range” of whatever you’re measuring. So, you have this sort of safety blanket of checking with everyone else. When you’re doing it [alone], I think it’s much more rewarding when
you finally do the percent error calculation in Excel, and then drag it down your column and it’s, boom, all under five percent.

He contrasted it with the introductory labs:

No one does science in a room with twenty people all doing the exact same simple thing. Obviously, collaboration’s great, but it felt more like a real lab sort of scenario, where people know what’s going on with each other’s stuff, but they’re working on their own and they’re collaborating.

Cameron did one experiment for which the lab manual had not been revised. “For that one, it was definitely a little more vague,” he said, “it appeared to be the manual for the equipment, at least partially.” He described that manual as “like there was a page or two missing, and added, “I wasn’t sure what I was supposed to really report.”

When asked about the lab notebook, Cameron said, “It was awesome.” He said he’d done lab notebooks for chemistry classes before, but they were “very strict, like ‘put this here in this font, and this there, and that.’” With modern, however, “it felt more personal because you had to have all the components, but what the professor wanted to see was you taking down your data and actually going through it.” Cameron added that it made the experience feel more “authentic,” and he enjoyed the “freedom” of having control over the lab notebook.

Cameron said the modern lab was his “first, and probably only, experience really getting an idea of what an actual physics lab could look like on a higher level.” He said part of it was the setting of the lab, which shared space with the professor’s research lab. “I can see real physics happening here,” he said about the setting, “we’re doing stuff that feels like real physics.” He added, “it almost gave it context, in a way. You felt like, ‘oh, there’s actual physics going on here.’”
Thoughts on the modern lab experiments. Cameron elaborated on what made the experiments feel more like “real” physics: “Part of it was definitely the setup where we were all doing our own projects, and it felt like you were really doing your thing. It felt personal.” He added that the level of the experiments they were doing also made it feel more like a “real science environment.” Cameron said it felt almost like doing research; he said, “I can definitely trick myself when all the lights are off, you’ve got your own little lamp, you’re taking your own data.”

Two experiments stood out to Cameron: the speed of light, because “it just worked perfectly” and his percent error was less than a percent, and Millikan, because of “the ridiculousness of that experimental design.” He said, “[Millikan was] fun in the opposite direction, where it was like, ‘this data is horrible, I may or may not have followed the same drop this whole time.’” He added it was cool because “it was a really good example of dirty, grungy research science.”

Cameron’s ideas about experimenting. When asked about the role of experimenting in physics as a field, Cameron said, “They’re the basis.” He added, “It all goes back to the concepts. Everything is based on being able to see it, it being real, that comes from experimentation. Or at least, the proof of it being real comes from experimentation.”

He continued by presenting two ideas about the “foundation” of physics: “Is the foundation of physics asking why does this ball drop when I let go, or is the foundation of physics proving the fact that it drops every time, with this acceleration?” When pressed further, Cameron said, “I think the foundation is the data, is the experimentation….the question is the first person saying, ‘we should build there.’ And then you build your foundation” off of the question by experimenting.
Thoughts on lab and lecture. Cameron said, “the lecture felt paced and laid out like a traditional course.” He thought the lab “felt more contextualized, just because we were replicating all these real experiments,” and he mentioned that the lab manual would often have a paragraph about the significance of each experiment. So, “the context is sort of inherent in the lab,” he said, and, “the lecture definitely felt more theoretical and more conceptual.”

He clarified how the lecture and lab contrasted, saying,

When somebody does a problem on the board, you’re showing a concept. When you’re doing an experiment, taking data, going through calculations, you’re walking the footsteps of these scientists that came before us. You’re getting to experience not the big “aha” moment that they did, but you’re getting to experience the actual process that led us to what we have today, what led to where we’re at with physics. So, basically the lab is almost like the justification for the lecture. It’s the tangible aspect of the concepts that you learn in lecture.

When asked to elaborate on what he meant by “justification for the lecture,” Cameron continued, “Any concept that you’re going to teach has to be proven somewhere, somehow.” He said,

A lot of these concepts, we’re proving, and we go through the same process that led to the thoughts and the hypotheses that gave us the concepts that we’re building off of….the concepts are all very important, but it was the actual experiments that gave us those—because science, you need data. You have to be able to prove it.

Responding to a question about whether he thought he got more out of lab or lecture, Cameron said,

for me, personally, I would say probably the lab, just because I can talk about the experiences of doing physics, those types of experiments. It was also broad, so I got to
touch on a lot of different things, got to really see it. But, if I were a physics major, it would probably be lecture.

He continued,

Obviously, the lab didn’t teach me how to sit down and do a relativity problem, and depending on what you’re doing, that could be very important and it doesn’t teach you that. But, in terms of being able to converse about physics with someone who’s not a physicist—or even someone that is but, more conversational or points of interest—definitely lab is much more helpful for that.

Cameron shared why he thought lab was required in addition to lecture. “I think laboratory practices are generally universally applicable,” he said, and for physics majors it’s “maybe even more important than progressing through the more difficult lecture series. You have to build better laboratory skills, because you’re going to need to go out there and do the research on your own at some point.”

Cameron was asked to revisit his ideas about active learning from the pre-interview. He affirmed, “I stand by what I said,” and added that “educational theories” support the importance of active learning. He also said that beyond theory, “I get more out of learning when I participate.” However, Cameron added, “at this level, in college, if you’re a physics major, you better be able to sit there in the lecture and learn….I don’t know how you would get around it. That’s just the reality of this level.”

**Cameron’s takeaways.** Cameron said modern was his favorite lab class he’d taken; he said it was the most difficult conceptually, but also the most interesting. When asked about his takeaways, he said, “How you behave and how you operate in a lab was definitely a big takeaway, because of it feeling like the first true physics lab. I’d never even stepped inside of a
true physics research lab before that.” He added that he also did some programming for the first time in the modern lab; it was “not a lot, but [he’d] never done anything. Now [he] can do some stuff on Python, Anaconda.”

He also brought up the lab reports for modern. “The formal reports were really cool,” he said,

That was the first time I’ve ever really been required to write in more of a journal style. It seemed different. It seemed more, I don’t know, more usable or more applicable in general than the first two physics labs’ report style.

Cameron recognized that taking the class with an education major changed his experience. “I think I just probably approach this class differently than almost everyone in there just because of my major and doing what I’m doing. I do enjoy the material and enjoy physics in general,” he said, “I never felt pressure to get a certain grade, or to be perfect or absolutely understand every concept, because for me it’s all bonus information.” He added that modern was “fun physics….it felt pretty exploratory, so that was cool.”

Cameron also described what his takeaways from the modern lab were from an educator’s point-of-view. He said,

I think the best part of this from an educator standpoint was getting to experience how a student might feel if they’re not so good on concepts, or not feeling super confident about what’s going on in a lab, then also knowing they need to work through it somehow. I mean, I sat in the lab a couple times like, “this is over my head,” kind of feeling like I’m treading water getting through this, trying to pull out data, and then make connections.
He continued, “From an education standpoint, I think it’s really important. Science is my thing, I enjoy it, I love it, that’s why I’m going to go teach science, but a majority of my students probably aren’t going to feel that way.”

Cameron also said he thought the professor for modern was a “really good educator.” He said that what stood out to him was “approachability and personability…you don’t feel bad asking a question,” as well as providing “contextualization.”

When asked about feeling like a physicist in modern, Cameron brought up the speed of light experiment again, saying, “it just worked out great.” He continued,

There were other times with other experiments where I’d be sitting there sort of confused about, “why are we doing this,” or, “what does this mean, how does this relate.” Then, sometimes the calculations kind of lead to that “aha” moment, or the professor comes over and explains what’s going on.
Chapter 5: Discussion

Interpretation of Skylar’s Interviews

**Skylar as a physicist.** Skylar seems to be a budding theorist. He likes physics as “applied math.” Skylar often brings up concepts and background knowledge (learning concepts and gaining background knowledge). He enjoys computation and hopes to continue to do computational research in the future. His motivation to get laboratory experience is driven by his perception that it will be productive towards his plans to attend graduate school, not because he expects to change his mind about his research intentions.

Skylar is idealistic; his priority in his career is to help people by solving problems. He sees industry as a better opportunity to do so than academia, even though he also said he enjoys teaching. His conception of helping people is dominated by his ideas about problem-solving, and his fixation on industry suggests that he has some misconceptions about research in academia. Skylar’s interactions with his friend, a physicist who has been working in industry for some time, may be why he prioritizes industry over academia.

**Skylar’s thoughts on experimenting.** Skylar doesn’t see experimenting as a way of generating new knowledge. He said he sees an experiment as “working” when the result is close to an expected value; this suggests that he has overlooked the possibility for new explanations which may come from unexpected results. In both interviews, he said that the purpose of experimenting in general is to verify theory.

In the first interview, Skylar said he expected the lab to reinforce conceptual learning from the lecture. In the post-interview, he admitted that he thought he could pass the modern lab without taking the lecture. He does not see much connection between the lab and lecture, and he did not attribute value to taking them concurrently.
An experience outside of the modern lab impacted Skylar’s ideas about experimenting; his visit to another university’s research labs made him aware of optimization in experimenting. He briefly mentioned experiments that were not “theoretically done,” but optimizing stood out to him. Skylar’s ideas were still dominated by experimenting with physics we already know, whether it be verifying theory or improving an existing process.

The desire to gain laboratory skills for his future career motivated Skylar to pursue experimental research experience. He said it is valuable to him because he wants to go to graduate school, even though he plans to continue doing computational research. This suggests that Skylar has some misconceptions about research in graduate school—he does not realize how narrow in scope the typical research experience is.

**Skylar’s ideas about measuring constants.** At the beginning of the semester, Skylar brought up measuring constants as one of the main themes of the modern lab. He expected that doing so would increase his trust in the quantities and give him more confidence when using them later. He also thought it would provide more background knowledge in physics because you would be able to see how the results were obtained in the past.

Skylar’s expectations for the value of measuring constants did not play out. At the end of the semester, he said measuring constants did not strengthen his trust in them, after all. He was also noncommittal about how exciting it was to do such experiments. Skylar said it was “cool” to see how scientists measured them in the past and to make measurements on a small scale, but he also said the experience wasn’t “super special.”

Skylar’s comment about conducting experiments from the past contrasts with his experience visiting the active research lab during the semester. He sees measuring constants as having historical relevance, but as they ultimately did not have a strong impact on him, he does
not see them as being relevant to him as a physicist today. However, just seeing the research lab led him to reconsider the role which experiments play in physics. This effect confounds the traditional idea that doing is better than seeing; he found doing the modern experiments underwhelming, but seeing current research exciting.

Although Skylar brought up measuring constants in both interviews, he brought them up in different contexts. In the first interview, he thought the purpose of the modern experiments was to measure constants to gain background knowledge. In the second interview, he thought the purpose of the modern experiments was to gain laboratory skills.

**Takeaways.** Skylar made it clear that he didn’t think he got much out of the modern lab. He didn’t think it was an authentic experience in experimenting, and he found the modern lab to be easy overall. Skylar admitted that he didn’t spend time during the lab course making sense of the data; this probably contributed to the experience having a low impact overall.

In both interviews, he brought up the “historical” aspects of the modern experiments. It is interesting that even though he recognizes the historical context of the experiments, he doesn’t seem to recognize the impact that experimenting had on discovery in the past. Or, perhaps, Skylar thinks of experimenting to discover as something that happened in the past, but not anymore.

Skylar values freedom and independence in laboratory courses because he sees it as being better preparation for his career. This reflects his general mindset; he is career-focused, and he is motivated to pursue experience, which he believes will prepare him for graduate school or industry.

Skylar has a mix of sophisticated ideas about being a physicist and ideas that are still developing. He was struck by the feeling of belonging in a greater community of physicists; this
kind of socializing is an important aspect of a scientist’s identity (Hunter, Laursen, & Seymour, 2007). Skylar also recognized the unglamorous aspects of research, such as the reality of preparing “publications” under deadlines and the perils of procrastination when doing so. He felt a sense of pride regarding his finished lab report, which shows he feels a sense of ownership over his work.

Skylar does not have a good grasp on the purpose of experimenting in research, although his ideas are developing. He also has some misconceptions about careers in academia, including graduate school and research.

**Interpretation of Jamie’s Interviews**

**Jamie as a physicist.** Jamie is still figuring out his place in physics. He has not had research experience, and he admitted that although he hoped the modern lab would help him find a sense of direction, it did not. He is excited by research, however; he often brought up “cutting-edge” research and sees school as a means of becoming a researcher.

Jamie’s feelings about being a physicist are centered around understanding concepts. In the pre-interview, he said he felt like a physicist while doing challenging homework; he said that physics goes beyond math to incorporate concepts in problem-solving. In the post-interview, he shared that the modern experiments he enjoyed were the ones that connected with understanding physics. Jamie seems to be motivated by the study of physics for its own sake.

Jamie values sharing knowledge. In the pre-interview, he pointed out that a good lab notebook can be a tool for sharing research. In the post-interview, he said he finds physics less exciting if he can’t discuss it with his friends. In both interviews, Jamie said he prefers having a lab partner over doing a lab alone, so he can have someone to “bounce ideas off of.” He sees physics as collaborative—and enjoys it when it is.
Jamie’s ideas about lab and lecture. Jamie’s most significant complaint was that he would have preferred that the lab and lecture follow the material in the same order. It is worth noting Jamie’s description of labs before lecture; he said he taught the ideas to himself in order to do the experiment, not that doing the experiments taught him the concepts.

In both interviews, Jamie said that the purpose of a lab course is to support or reinforce lecture, by giving examples or proof of concepts from lecture. He also thought he would learn more from the lecture, and at the end of the semester, he felt this expectation held up.

Jamie’s thoughts on experimenting. Like Skylar, Jamie brings up the historical context of the modern lab experiments, but he gives more reasoning for why it is valuable. He sees the experiments as closing a gap between work at the introductory level and doing research. He said they are a way of learning where experimenting has led physics; as such, they are a jumping-off point toward continuing beyond established work.

Jamie’s thoughts on the role of experimenting in physics echo Skylar’s; he said that experimental results “prove” theory. He sees theory as having little impact on the real world—an idea that was consistent between his two interviews. This also matches his ideas about the purpose of a lab course to “prove” concepts from lecture.

Jamie is process oriented. He likes to be challenged and said he learned more from the equipment manuals, which took time to figure out. He also saw measuring constants valuable from a process perspective, not a concepts perspective; he recognized that you can learn about best practices (“what could be done better”) from replicating such experiments.

In the post-interview, Jamie brings up setting up experiments twice. In the context of the lab manuals, he would like to preserve the guidance in the form of step-by-step procedures but thought he would like more time figuring out the setup. He also would like to try experimenting
beyond one lab period (“multiple-day experiments”) where he could spend more time on setup. There is a clear limit to what Jamie sees as valuable to figure out; he does not care to spend time deciding what to measure or what procedure to try, decisions which align with inquiry in a laboratory. Jamie has a persistent idea that you should know what you are doing—such as the steps to take and what the end goal is—before beginning an experiment.

Takeaways. Jamie expected the lab notebook to be a big takeaway in the pre-interview and felt that it was at the end of the semester. He thought the value of the lab notebook was that it can be used to record your process (“what you did”) and not just results. However, he was also somewhat underwhelmed by the lab notebook. Jamie admitted he expected more from the lab notebook, but he had trouble articulating how it fell short of his expectations. It is possible that since the lab notebook was graded for the course, he expected it to be more like a finished product.

Interpretation of Cameron’s Interviews

Cameron as a scientist (and student, and educator). Cameron has a complicated identity, and he seems to be at the crossroads of feeling like a scientist, a student, and an educator. In the pre-interview, he called himself a “scientist, sort of,” and he added that he’s “going to be” an educator (not that he already is one); this is despite his extensive background in the sciences, and his mention of engaging with scientific literature in the pre-interview. At one point he even says, “science is my thing,” showing that science is part of his identity. Cameron also shied away from referring to himself as a physicist in response to a question about ever feeling like one, although he also said that he wished he could take more physics classes and would even be interested in doing experimenting.
In both interviews, Cameron is obviously excited about modern physics. He expected it to be one of his favorite classes, and it was. In the post-interview, when talking about the environment of the modern lab, Cameron even mentions that he could “trick himself” into feeling like he was doing research. One of his takeaways from the lab is also being able to talk about his “experience of doing physics.” Cameron may not be a physicist and will not become one like some of the other students who were interviewed, but he still connected deeply with the experience of the modern lab.

Some of Cameron’s ideas clearly come from an educator mindset. However, many of them seem rote, like he is repeating them from a class. For example, in the pre-interview, he said you “have to” say active learning is always better than passive learning. Although he stood by it and gave some more reasoning in the post-interview, his initial response showed that he leans heavily on what other educators have told him about teaching. This shows up again in the pre-interview; he gave a sophisticated response about the purpose of the modern lab experiments, and he added that he had been talking about it in one of his education courses.

**Cameron on the modern lab.** Cameron brought up the setting of the lab multiple times and in both the pre- and post-interviews. He fixated on the feeling of it being a “real” or “actual” physics lab (one in which research was being conducted, and not just a classroom lab). He also brought up “authenticity” in the post-interview, especially in the context of independence. This contrasts with Skylar’s feelings that the modern lab was not a very authentic lab experience.

In the pre- and post-interviews, Cameron focuses on percent error as a metric for success in an experiment. As will be discussed in Chapter 6, this is likely a remnant from the introductory-level labs.
Cameron on experimenting. Cameron gives a mix of responses about experimenting that reflect different aspects of his identity as a scientist, student, and educator. As a scientist, he placed high value on the process of experimenting and on practicing lab skills. As a student, he was report-focused; the reports were his motivation to get data that was “good enough,” and he found the old lab manual frustrating because it was difficult to figure out what to report. As an educator, he sees the value of students gaining laboratory experience and appreciation for the foundations of science.

Cameron is the only student among these cases who ever brought up “discovery” in the context of experimenting; he brought it up in passing when discussing the modern lab experiments in the pre-interview. The closest he got to bringing up discovery again was in the post-interview, when he mentioned that experimenting can lead to an “aha moment.” However, his explanations for the role of experimenting in physics did not incorporate discovery. He recognized that experimenting is the foundation of physics, but he focused on either testing existing ideas, such as friction, or proving concepts. One of his statements echoed other students’ ideas about experimenting: that experimenting proves theory is “real.”

Takeaways. Cameron brought up “aha moments” twice in the post-interview. Look closely at the context of these statements: the experiments in modern originally led to “aha moments” for scientists, and he felt like a physicist when he would experience an “aha moment” when doing calculations or understanding an explanation. These suggest that Cameron’s conception of physicists involve working to reach these moments of understanding. These statements also show an interesting contrast with his comment that the speed of light experiment made him feel like a physicist because “it just worked.”
Cameron has a lot of ideas about “contextualization.” He seems to value context, for anything from learning mathematics, to gaining greater appreciation for the modern lab experiments.

Cameron spent some time talking about physics majors and how he sees them. In the post-interview, he said he thought physics majors would probably get more out of lecture. This contrasts with another statement in which he says he thinks it’s maybe more important for physics majors to gain lab skills than to master upper-level lecture topics, so they are prepared for research. This contrast echoes Skylar’s mindset—Skylar values theory because he hopes to do computational research and sees himself as a math person, but he thinks that it is important to gain lab skills to prepare himself for research, possibly in graduate school.
Chapter 6: Conclusions and Future Work

Conclusions

For continued reflection on the conclusions presented here, see Appendix G for quotes from three other students who participated in this study.

Students on experimenting. Generally, these students thought that experimenting backs up theory, and they did not change their minds over the course of the semester. They also shared a curious idea about experimenting being more “real” than theory. Despite recognizing the historical significance of the modern lab experiments (and as such, recognizing the role they played in the discovery of foundational ideas), experimenting for discovery was only mentioned briefly. This perception of physics in general mirrors the idea that “learning” happens in lecture and the lab reinforces it; this was also common in students’ responses.

Two of the students—Jamie and Cameron—both said they thought that an ideal lab would follow the same order as lecture, but their reasoning was not clear. Jamie also recognized that he could teach himself what he needed to know to do a lab before seeing the material in lecture. Skylar was noncommittal about the order of the experiments and mentioned that some things stood out to him that he saw in lab before lecture. These comments from Jamie and Skylar are curious to consider with their perspective that lab should back up lecture—both experienced lecture reinforcing lab.

Cameron and Jamie were both process focused, or at least they thought learning the process of experimenting was important. Skylar was more content focused regarding experimenting, and often brought up learning concepts; however, he appreciated experience with processes outside of the lab, such as figuring out how to write a formal report. Having a variety of projects associated with lab helped the course feel at least somewhat relevant to Skylar.
The “lab skills” referenced by students throughout their interviews are not specific to the modern lab, or even laboratories. Very few actual laboratory skills—such as using an oscilloscope and keeping lab notebooks—were mentioned. However, preparation, time management, organization, and problem-solving were all discussed; these are all useful skills for succeeding in college in general (and even in life beyond college). The focus on general skills suggests that students see the modern lab as another class and do not focus on modern as a laboratory experience.

**Practices that students found valuable.** Overall, students valued gaining authentic lab experience. However, different students had different perceptions of what was and wasn’t authentic in the modern physics lab. Cameron was the most excited overall and thought the lab felt very authentic, but he also recognized that his approach to the lab was very different from a physics major’s. Jamie seemed to enjoy getting some lab experience, but he still felt restricted within the structure of the course. Skylar was mostly underwhelmed by modern, did not think it was an authentic experience, and appreciated only a few practical skills he was able to use.

The lab notebook is the clearest takeaway for students, and one thing they all agreed felt relevant to real research. They appreciated the practicality of the notebook because they saw it as a skill they may use again in their careers. They also enjoyed the freedom of starting from a blank notebook; for example, they liked being able to make their own decisions about formatting data and what information to record. Beyond being a takeaway for students, the lab notebooks are also a rare example of a practice which students and educators value equally, and for similar reasons.

Skylar and Cameron also liked writing lab reports in a professional style. As with the lab notebook, they saw it as practical and relevant to real experience as a research scientist. Finally,
the students generally liked working independently but still in a collaborative environment. Cameron appreciated being unfettered after his previous experience with a bad lab partner, and Skylar saw working independently as good career preparation. Jamie didn’t enjoy working alone, although it was mostly because of boredom.

**A few comments on ideas which likely came from the introductory labs.** The introductory labs at this university have been focused heavily on using percent error and percent difference to test equations, laws, and constants. (They are currently being changed to rely on uncertainty analysis instead.) Additionally, students are required to use Microsoft Excel in the introductory labs for data collection and analysis. All the students included here took these introductory labs; as such, it is plausible that the frequency of these ideas was a result of experiences in the intro labs.

**Further Questions**

Most of the students brought up or alluded to obtaining “good data” when taking measurements. It is not clear how they decide on-the-spot if data are good enough to move on. Additionally, students whose ideas about experimenting included verifying theory were not asked how experimenting verifies theory. It would be worth asking students in future studies about data in more detail (for example, asking how they know when data are good enough to support a theory).

These students did not effectively identify and describe specific laboratory skills—it would be useful to probe their ideas about skills further. For example, are there laboratory courses after which students can identify lab skills? Alternatively, do students preferentially attribute gaining skills to research experience outside of courses (and subsequently identify more skills which they learned during research)?
Students’ ideas about discovery in physics should be investigated further. The students here thought that physics usually progresses from an “equations first” perspective; that is, theory generates equations, which are then tested through experimenting. Contrast this perspective with that of the instructor: that many equations and relationships have been established through experimenting. It would be worth engaging with students regarding this idea, and examining whether it is new to them or whether they do not internalize this idea because they hold on to the other perspective.

**Limitations of the Study**

All data processing and the bulk of data analysis in this study was conducted by a single researcher. That is, the results were generated primarily through the lens of one person. As such, this research should be considered subjective.

There was very little diversity in the sample, which limits how relevant the results of this study are to educators at different universities. Additionally, upper-division courses are highly variable from year-to-year due to the small number of students who take these courses. Continuing qualitative studies in future iterations of the laboratory is likely to yield new information and further enrich the conversation around students’ experiences.
References


APPENDICES
Appendix A: Interview Protocol

Clarifying questions to ask at any time:

- Can you explain why you said (idea)?
- Can you clarify (previous statement)?
- Can you tell me a little more about (idea)?

Pre
Thank the participant for meeting with you. Give them a copy of the informed consent letter and give them enough time to read it. Answer any questions they might have about the letter or the interview. Clearly state that you are going to begin recording. Begin recording.

Obtaining recorded documentation of consent:
“Before we get started with questions, I just need to confirm in the recording that you have consented to be part of this study. Have you read the consent form?” [response] “Did you understand the form?” [response] “Do you have any further questions about the form or the interview?” [response] “Alright, I’m going to go ahead with the questions. What I have in front of me here is a little script for myself so I don’t forget anything. If you have questions at any time or if you need a break, please let me know.”

Questions:

“First, I want to get just a little background so I know where you’re coming from.”

- By credits, what’s your year at Eastern?
- What is your major?
  - Okay, so you’re a [year] and you study [major].
  - How did you choose your major?
    - What was your motivation in choosing your major?
    - Have you ever changed majors?
    - Did you know anybody in physics before you decided to study it?
      - How did that play in to your decision?
  - Do you have an idea of what kind of career you might pursue?
    - What influenced your idea to pursue that?/Can you tell me about that?
- Do you have any research experience as a researcher?
  - Y:
    - Can you tell me about it?
    - Did it involve experiments?
    - How did you feel about the research?
    - Do you want continue doing similar research?
      - Can you tell me about what you’d like to try next? (clarify if needed: stop doing research or do different research)

- N:
  - Are you interested in research experience?
  - Do you have an idea of what kind of research you’d like to do?
- What lab courses have you taken already?
  - How do you think this lab will compare to the labs you’ve taken?
  - (Follow-ups if needed: How do you think the difficulty will compare? How do you think the work for this lab will compare? Do you think this lab will involve different skills?)
  - For clarification: Why do you think [comparison]?
- Have there been any moments with physics in or out of school when you’ve really felt like a physicist?
  - What about any times where you’ve noticed something really cool in physics?

“Alright, that’s all the background I need. Now I’m going to ask you about some of your thoughts about physics and more about your expectations for this course.”

- Why do you think you are required to take the modern lab in addition to the lecture?
- How do you think you will spend your time in the lab for modern physics?
  - Can you walk me through what you think a typical lab period will be like?
  - With respect to this course and its work, how do you think you will spend your time outside of the lab?
- Do you expect there will be any challenges in the lab this semester?
  - Can you tell me about that?
- How do you think what you learn in the lab will compare to what you learn in the lecture for this course?
  - Which do you think will contribute the most to your learning?
    - Why?
  - What resources do you think you will use to support your lab work? Are they different resources than what you think you will use in the lecture?
  - Do you expect to get more out of the lecture or the lab?
    - Can you explain?
- What skills do you think will be important to you in this lab?
  - Why do you think [skill] will be important?
- What role do you think experiments play in physics as a field?
  - What role do you think experiments in a lab course like this play in physics?
- How do you think this lab will fit into your long-term goals?

“Is there anything else that you wanted to say, or any other ideas you had today?”

Thank the participant for their time. End recording.
Post
Thank the participant for arranging another interview with you. Provide them with the informed consent form again. Ask if they have any questions and answer them. Clearly state that you are going to begin recording. Begin recording.

“Before we get started with questions, I just need to confirm in the recording that you have consented to be part of this study. This is the same thing we did in the first interview. Have you read the consent form?” [response] “Did you understand the form?” [response] “Do you have any further questions about the form or the interview?” [response] “Alright, I’m going to go ahead with the questions. If you have questions at any time or if you need a break, please let me know.”

“So, I’m going to start out with some questions about what you did in the lab this semester.“

- How did you spend your time in the lab?
  - Can you walk me through what a typical lab period was like?
- Just thinking about the modern physics course, how did you spend your time outside of the lab?
  - So, when you were doing lab work for modern physics this semester, what resources did you use to support your lab work?
    - Were they different resources than you used in the lecture?
    - What did you use for your lecture homework?
    - Were they helpful?
- What skills were important to you for this lab?
  - Why do you think [skill] was important?
- Were there any experiments or projects that stood out to you? Why?
  - When you were working on it, what was going through your head?
- Were there any challenges you dealt with in the lab this semester?
  - Can you tell me about that?
- How did this lab compare to other lab courses you’ve taken?
  - (Follow-ups if needed: How did the difficulty of this lab compare to other labs you’ve taken? How did the coursework compare? Do you think this lab involved different skills?)
  - For clarification: Why do you think [comparison]?
- Do you want to take more labs like this one?
  - How do you think those would compare?

“Okay, now I’m going to ask some questions about what you really got out of the lab this semester.”

- What are a couple of big takeaways from the lab for you?
  - What I mean is, what are the big ideas you learned this semester?
  - How excited are you about modern physics?
- Were there any moments in this lab when you really felt like a physicist?
What about any times where you noticed something really cool in this lab?

How do you think what you learned in the lab compared to what you learned in the lecture?
  - Do you think you got more out of the lecture or the lab?
    - Can you tell me a little more about that?
  - Why do you think this course includes the lab? (rather than just lecture)

Based on your experience with this lab, are you interested in taking more labs like this one?

Do you think this lab changed how you feel about research at all?
  - Do you think your experience with this lab changed how interested you are in doing research?
  - Are you interested in the same kind of research you were interested in before this lab?

How does this lab fit into your long-term goals?

"Is there anything else that you wanted to say, or any other ideas you had today?"

Thank the participant for their time. End recording.
Appendix B: Segment of Course Syllabus

This Appendix includes part of the course syllabus for the modern physics lab. (Syllabus shared at the courtesy of the instructor.)

COURSE (CATALOG) DESCRIPTION
A laboratory course providing experimental studies in such areas as late classical, relativistic, quantum, and nuclear physics.

COURSE CO-REQUISITES
Introduction to Modern Physics.

REQUIRED MATERIALS
Each student must purchase his or her own laboratory notebook, specifically National Brand’s Computational Notebook (# 43648), which is the only acceptable notebook for this course. It can be purchased at many retailers including the campus bookstore. An electronic version of the laboratory manual will be provided by the instructor.

LAB OUTLINE / CALENDAR

<table>
<thead>
<tr>
<th>Week</th>
<th>Class Dates</th>
<th>Agenda</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9/11 or 9/12</td>
<td>Introduction: Lab Safety, Expectations, and Error Analysis</td>
</tr>
<tr>
<td>3</td>
<td>9/18 or 9/19</td>
<td>(1) Measurement of the Speed of Light</td>
</tr>
<tr>
<td>4</td>
<td>9/25 or 9/26</td>
<td>(2) Thomson’s e/m Experiment</td>
</tr>
<tr>
<td>5</td>
<td>10/2 or 10/3</td>
<td>(3) Blackbody Radiation</td>
</tr>
<tr>
<td>6</td>
<td>10/9 or 10/10</td>
<td>(4) Photoelectric Effect</td>
</tr>
<tr>
<td>7</td>
<td>10/16 or 10/17</td>
<td>(5) Hydrogen Spectrum</td>
</tr>
<tr>
<td>8</td>
<td>10/23 or 10/24</td>
<td>(6) Franck-Hertz Experiment</td>
</tr>
<tr>
<td>9</td>
<td>10/30 or 10/31</td>
<td>No labs this week. Work on 1st formal lab report.</td>
</tr>
<tr>
<td>10</td>
<td>11/6 or 11/7</td>
<td>(7) Electron Diffraction</td>
</tr>
<tr>
<td>11</td>
<td>11/13 or 11/14</td>
<td>(8) Electron Spin Resonance (ESR) Experiment</td>
</tr>
<tr>
<td>12</td>
<td>11/20 or 11/21</td>
<td>(9) Millikan’s Oil-Drop Experiment</td>
</tr>
<tr>
<td>13</td>
<td>11/27 or 11/28</td>
<td>(9) Millikan’s Oil-Drop Experiment</td>
</tr>
<tr>
<td>14</td>
<td>12/4 or 12/5</td>
<td>No labs this week. Work on 2nd formal lab report &amp; group presentation.</td>
</tr>
<tr>
<td>15</td>
<td>12/11 or 12/12</td>
<td>Group presentations</td>
</tr>
</tbody>
</table>

CANVAS
Canvas will be used to post ALL course materials, including, but not limited to the syllabus, laboratory manual, safety info, lab schedule, lab notebook and technical report templates, as well as to communicate with students about all aspects of the course.

LATE SUBMISSION POLICY
Late lab notebooks and formal reports will NOT be accepted, unless there is an excused absence with documentation. Discretion is left to the instructor. Please notify me within 24 hours of the due date.
EVALUATION / ASSESSMENT METHODS
Weightings for the various lab activities are as follows:
63% Lab Notebooks (*Nine experiments @ 7% each*)
30% Formal Lab Reports (*2 reports @ 15% each*)
7% Group presentation

LAB EXPERIMENTS AND NOTEBOOKS
Each individual will have **one lab class** to perform each experiment (except for Millikan’s Oil-Drop experiment where two individuals will work together as a lab group for two classes) to the best of his/her ability according to the schedule located in the lab manual. If an individual misses a week, it must be made-up on either December 4 or 5. Each individual must turn in his/her lab notebook every **Friday by 12 pm** for grading before the next lab class.

FORMAL LAB REPORTS
Each individual will turn in a formal lab report (both a printed hard copy and electronic copy) for Experiment 4 (Photoelectric effect) and Experiment 7 (Electron diffraction). The first report is **due during lab on November 6 or 7** and the second report is **due during lab on December 11 or 12**. A template and grading rubric will be provided.
Appendix C: Study Recruitment Script

Hi everybody, my name is Helen Cothrel. I’m a graduate student here in the physics department, studying physics education. I’m starting a research project this fall which will hopefully include most of you.

I’m interested the experiences and ideas that students have coming into the modern physics lab and how they might change during the semester. So, to learn more about this, I’d like to interview people who are taking the lab. This is where you all come in. I’m going to do two interviews with each person who agrees to participate, one within the next few weeks before you really get into the thick of things, and then one toward the end of the semester to see how it all went. This way, I can compare what you think about the lab now to what you think after you’ve been in it for a semester. And, these interviews are really geared toward your experiences in the lab—I’m not going to ask any questions about concepts or have you solve problems.

I’ve done practice interviews which have lasted about 20 minutes, but we’re going to schedule for 45 minutes, just to be sure we have time to get set up and talk. I’m going to video record the interviews, because that gives us the most complete set of data because we can see non-verbal communication such as body language.

Dr. Skuza is my advisor for this research, but he won’t be analyzing the video, and he won’t have a list of who is or isn’t participating. So, you don’t have to worry about any pressure on you to participate in this class. I’m the only person who will be directly analyzing the videos, so you don’t have to worry about your face showing up on YouTube or anything. We might share some video in research presentations, but, if we do, your face and any identifying features will be blurred out.
For everyone who does decide to participate in the interviews, I’ll send you a $5 Amazon gift card for each interview. So, you can get two gift cards if you do both interviews.

I have a sign-up sheet here which I’m going to pass around. Please put your name and your university email address if you’re interested. For everyone who signs up, I’ll be following up via email to answer any questions you may have and schedule the first interview. If you’re not sure if you want to do the interviews, you can still put your name down, and then decide any time that you don’t want to participate or you want to stop. Does anyone have any questions while this is going around?
Appendix D: Instructor Interview Protocol

12/12/17

- I want to begin by thinking very generally. Can you describe your teaching philosophy a little bit for me?
  - What do you see as being your biggest goals for this course?
    - How do you pursue that goal?
    - Do you feel like you have been successful in pursuing that goal so far?
  - What do you see as being your biggest goals for this lab?
- What do you want students to learn from the modern course?
  - Do you think they did learn ___?
- What about this lab do you think is valuable to students?
- What do you want students to learn from the modern lab?
  - Do you think they did learn ___?
- Can you tell me about what the lab periods were like?
  - How did you spent most of your time while you were teaching the labs?
  - What kind of strategies did you use when students needed help in the lab?
- What did you find challenging about teaching this lab?
- What do you think students found challenging about this lab?
- How does this course compare to other courses you’ve taught?
- Can you walk me through the changes you have been making to this class?
- What was your motivation for requiring lab notebooks?
  - How did you describe the lab notebooks to students?
  - How did it go?
  - Are there any changes you would want to make regarding the lab notebooks in the future?
- Did you notice if students mostly preferred recording data in their notebooks or on laptops?
- Can you tell me about the lab manual revisions that are happening now?
  - Can you describe your motivation for changing the manuals?
  - What have you noticed about the new manuals in action so far?
- What do you see as being your next steps for revamping this course?
- Why do you think students are required to take the lab in addition to the lecture?
- What do you think students get out of the lab that they can’t get out of the lecture?
- Do you think that students learn more in the lab or in the lecture?
Appendix E: Instructor Interview

**Approach to the laboratory course.** The professor said his teaching philosophy focuses on the idea that “you learn by doing.” He added, “I try to get students to do problems….you’re not going to get good at something by watching someone else.” He also said he focuses on applications for concepts in lecture. He wants students in modern physics “to become more appreciative, and become more excited about physics.”

The professor said that he sees experimenting with physical constants as valuable to students. He wants them to see “that’s not some abstract number that someone just pulled out of nowhere, it comes from the physics, the nature of how things work.” He continued,

We’re verifying all these physical constants, so, being able to, as a student, actually do the real experiment and collect real data, and do some real analysis on these data, and obtain a result that agrees closely with our most accurate, most precise values, and being able to work by yourself….you can figure it out. He added that working independently “forces you to test your limits” and “become an active researcher.”

He recognized that different majors bring different needs and backgrounds to the course, so he tries to “bring people together on more of a level playing field of information,” and to “prepare them for some of the upper-level courses, for instance, quantum mechanics.” The professor added that his goals for different majors are to keep them moving in the direction that they’re already moving as majors, or to broaden the knowledge of our secondary education majors, who will never have to teach this material again, but…they can maybe tie something in to one of their classrooms.
The professor discussed how lab and lecture are connected: “Many of the experiments we talk about in class, we cover in lecture. Information that they get in lab, and experiments they do in lab, tie into the class.” He gave an example, saying he based an exam question on ideas used in the electron diffraction lab. He said students are required to take lab in addition to lecture because “physics at its essence is an experimental science. You do an experiment, or you look at something and you make an observation. And you go from there. A lot of our equations are empirical; they’re from observation.”

**Description of changes to the modern lab.** The professor described his motivation for changing the lab manual; “we don’t really need this hardware manual, because you’re not really troubleshooting or doing anything with it.” He said each experiment’s new manual began with an abstract, then had an introduction (which included some historical background). A “results and analysis” section included information about the measurements to be made. He said he framed the measurements as, “You’re measuring between this and this, and I want twelve data points.” He said, “everybody will take at least that amount of data. Some students will take more data.”

The lab notebook was new to the modern lab this semester, and the professor thought it was a good takeaway for students. “They’re picking up research skills on keeping a lab notebook,” he said, and “for the most part, everyone did that quite well.” He said he wanted to include lab notebooks because

when you’re an experimentalist, and doing experiments, you have to record your data, record your procedure, record anything and everything that you think is pertinent, that you think is not pertinent. All of your observations, interpretations, analysis, because you won’t remember what you’re doing.
The professor also described how he graded the lab notebooks. “Mainly I was looking for some sort of organization,” he said, “you had to write in pen, entries had to be dated and titled.” He added,

The main part that I focused on was recording data. Recording a hand-written record of your data as you take it, and then further refining that data, or presenting it in a tabulated format all together, with uncertainties, with some kind of statistical analysis or a fit to an expected model. In our case it was ninety-five percent linear fits. And then an interpretation of that data by asking some specific questions geared toward each experiment.
Appendix F: Editing Transcribed Speech

The following is an example of an un-edited passage from an interview transcript. Notice that interruptions from the interviewer, and common utterances such as “um” and “like,” make the text difficult to read.

Um, I want to, so part of the reason why I want to be a physicist is I wanna help people. (i: okay) And, um, I'm sure you've heard people say like a physics degree is a problem-solving degree (i: right). So, I wanna be able to take this degree and, solve a problem that will help people, (i: mmhm) and I feel like if I work in the industry, I'll be able to help more people (i: okay) um, but I also enjoy teaching people (i: okay) and, like sharing knowledge. So.

For inclusion in the text, this passage was edited to read:

Part of the reason why I want to be a physicist is I want to help people. I’m sure you’ve heard people say a physics degree is a problem-solving degree. So, I want to be able to take this degree and solve a problem that will help people, and I feel like if I work in the industry, I’ll be able to help more people. But, I also enjoy teaching people and sharing knowledge.
Appendix G: Reflecting on Conclusions with Further Quotes

In this Appendix, additional quotes from three other students are presented to reflect on some conclusions from Chapter 6. These students’ academic years and majors are shown below.

Table A1

<table>
<thead>
<tr>
<th>Student</th>
<th>Year</th>
<th>Major</th>
<th>Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan</td>
<td>Senior</td>
<td>Physics</td>
<td>Math</td>
</tr>
<tr>
<td>Francis</td>
<td>Senior</td>
<td>Math</td>
<td>Physics</td>
</tr>
<tr>
<td>Alex</td>
<td>Junior</td>
<td>Math education</td>
<td>Physics education</td>
</tr>
</tbody>
</table>

Table A2 shows selected quotes regarding the role of experimenting in physics.

Table A2

<table>
<thead>
<tr>
<th>Student</th>
<th>Pre/Post</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan</td>
<td>Pre</td>
<td>“The lectures themselves, the stuff that you learn are the backbone, but the experiments sort of, bolster up that.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“It gives us that other way to learn about it, but also the idea of applying your knowledge, rather than just doing a problem. That is applying your knowledge, but applying it real-life scenarios, instead of applying it on a piece of paper.”</td>
</tr>
<tr>
<td>Francis</td>
<td>Pre</td>
<td>“I know like, scientific-method wise what they are. What they are...why they're important to the field. Well I guess I’m not—I haven't really gotten to that point, or I haven't really thought about it.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“Experiments serve as both a better understanding of how the math works with physical characteristics, and getting a better understanding of what might or might not be correct or incorrect.”</td>
</tr>
<tr>
<td></td>
<td>Pre</td>
<td>“It backs up physics, because it seems like most of the physics, or at least what I pay attention to, is theoretical and they're like, ‘okay, there's no way we can mess this up because we're just doing very simple steps.’ Where in the labs, we can then check if that actually worked.”</td>
</tr>
<tr>
<td>Alex</td>
<td>Post</td>
<td>“They sort of confirm or deny certain things. In physics you can combine equations and figure out, ‘oh these things should be related.’ But then you have to do an experiment to see, ‘oh, were they actually’”</td>
</tr>
</tbody>
</table>
Table A3 shows students’ comments on why lab is required in addition to lecture. The abbreviation “n/a” is used to indicate the topic did not come up in that interview.

Table A3

<table>
<thead>
<tr>
<th>Student</th>
<th>Pre/Post</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan</td>
<td>Pre</td>
<td>“It’s always good to practice what is happening, and looking at the labs, they're a lot more, higher-up physics than what the mechanics labs were, so I feel like reason we have to take it is because it'd be better for us to have practice on these higher up physics concepts.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“It applies the knowledge, which is definitely good to have….also, usually, with new information that you’re learning, it’s good to have the lab back it up for different learning types,” and, “It makes you know about these relevant experiences, that most physicists know.”</td>
</tr>
<tr>
<td>Francis</td>
<td>Pre</td>
<td>“The way that I look at it is that the labs make you understand the material really well. It's kind of like they augment the learning from lecture.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>n/a</td>
</tr>
<tr>
<td>Alex</td>
<td>Pre</td>
<td>“In my class list of stuff I have to take, it says I have to take both….but honestly no [reason for it]”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“Money…there’s no real reason, in my opinion. The vast majority of those labs could be done in the intro labs.”</td>
</tr>
</tbody>
</table>
Table A4 shows examples of skills students thought would be (or were) important for the modern lab.

### Table A4

**Additional Quotes Regarding Skills in the Modern Lab**

<table>
<thead>
<tr>
<th>Student</th>
<th>Pre/Post</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan</td>
<td>Pre</td>
<td>“Neatness will be important, time management I'm sure will definitely be important….social skills, you need to talk to someone else in the lab”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“A little bit of time management. I never wanted to get super far close to the end of time, so I want to make sure I’m doing everything efficiently and not just sitting there staring at the equipment being like, ‘what am I supposed to do?’”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Instruction-following skills, patience, as well as observational skills. And then after that, would probably be communications skills, talking with the professor, explaining what's going on…. I mean there's like the obvious like math skills, your understanding of physics”</td>
</tr>
<tr>
<td>Francis</td>
<td>Pre</td>
<td>“Communication with my professor helped out a lot, because a lot of the machines, they don’t really explain what’s going on inside of them,” and, “Reading comprehension and then improvising for a lot of things.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“Time management, that would definitely matter, because you probably can't do the experiment late is my guess. Probably need to be organized, too, because if you mess up your data you have to collect it all again.”</td>
</tr>
<tr>
<td>Alex</td>
<td>Pre</td>
<td>“Patience, definitely was helpful. Patience would definitely be one. Good time management, you definitely don’t want to be there all night. Besides that, being able to interpret the procedures.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td></td>
</tr>
</tbody>
</table>
Table A5 contains quotes on when students felt like physicists, both before taking the modern lab (pre) and during the modern lab (post).

Table A5

<table>
<thead>
<tr>
<th>Student</th>
<th>Pre/Post</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan</td>
<td>Pre</td>
<td>“Whenever learn about something in class, I'm always like, ‘that makes no sense but it also makes sense,’ because in thermodynamics we talked about how there's negative Kelvin, which is hotter than infinite Kelvin, and we haven't fully gone into that yet, but how does that work?”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“While doing the results section and the conclusion, calculating all these things, I was like, ‘Okay, wow, this is like, things that are making sense, I’m using equations that I just learned, I’m using things I know from the past, I’m figuring out things that are very heavy physics-based.’ And even taking the data, sometimes… I created this data.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“When I was in high school I was kind of—it wasn't like an official tutor, but I was helping, or tutoring with the material. I guess that's kind of the thing where I felt like a physicist, because I knew what I was talking about, and I could like even show like, mini-experiments that helped explain what I was trying to say.”</td>
</tr>
<tr>
<td>Francis</td>
<td>Pre</td>
<td>“No…I felt like I was more of an assistant, as in, along the lines of following directions and not collapsing under pressure.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“I was a supplemental instructor. So, I would sit in lectures, I'd help teachers…. on quiz or exam days, I'd have like 40 people in there.”</td>
</tr>
<tr>
<td>Alex</td>
<td>Post</td>
<td>“Maybe during the electron spin one. That one was interesting, because you got to work with things that you can’t even see.”</td>
</tr>
</tbody>
</table>
Ryan, Francis, and Alex all discussed the lab notebooks in their interviews (Table A6).

Table A6

<table>
<thead>
<tr>
<th>Student</th>
<th>Pre/Post</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan</td>
<td>Pre</td>
<td>“That seems like a very interesting thing. It's your notebook and you keep everything research-wise, so if I was doing research later on in life, I'll have my notebook and I'll have everything I need in it.”</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“It was definitely different than I was expecting. I really enjoyed it, because everything was there, all my data was there, the tables I needed to have.”</td>
</tr>
<tr>
<td></td>
<td>Pre</td>
<td>“I forget what it's called, but it's like a grid book that we have to pick up.”</td>
</tr>
<tr>
<td>Francis</td>
<td>Post</td>
<td>“It was definitely interesting having to make my own tables, make my own reports….it was very interesting having very freeform, semi-reports”</td>
</tr>
<tr>
<td>Alex</td>
<td>Pre</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>“I didn’t mind that as much as I thought I would. My big concern was losing it.”</td>
</tr>
</tbody>
</table>
Appendix H: Human Subjects Research Approval Letter

UHSRC Determination: EXEMPT

Date: August 15, 2017

To: Helen Cothrel
Eastern Michigan University

Re: UHSRC: # C20170810-1
Category: Exempt category 2
Approval Date: August 15, 2017

Title: Expectations and Experiences in a Modern Physics Laboratory Course

Your research project, entitled Expectations and Experiences in a Modern Physics Laboratory Course, has been determined Exempt in accordance with federal regulation 45 CFR 46.102. UHSRC policy states that you, as the Principal Investigator, are responsible for protecting the rights and welfare of your research subjects and conducting your research as described in your protocol.

Renewals: Exempt protocols do not need to be renewed. When the project is completed, please submit the Human Subjects Study Completion Form (access through IRBNet on the UHSRC website).

Modifications: You may make minor changes (e.g., study staff changes, sample size changes, contact information changes, etc.) without submitting for review. However, if you plan to make changes that alter study design or any study instruments, you must submit a Human Subjects Approval Request Form and obtain approval prior to implementation. The form is available through IRBNet on the UHSRC website.

Problems: All major deviations from the reviewed protocol, unanticipated problems, adverse events, subject complaints, or other problems that may increase the risk to human subjects or change the category of review must be reported to the UHSRC via an Event Report form, available through IRBNet on the UHSRC website.

Follow-up: If your Exempt project is not completed and closed after three years, the UHSRC office will contact you regarding the status of the project.

Please use the UHSRC number listed above on any forms submitted that relate to this project, or on any correspondence with the UHSRC office.

Good luck in your research. If we can be of further assistance, please contact us at 734-487-3090 or via e-mail at human.subjects@emich.edu. Thank you for your cooperation.
Sincerely,

Sonia Chawla, Ph.D.
Research Compliance Officer