Requiring Students to Create, Revise, and Communicate Scientific Models

Positively Impacts Students' Scientific Modeling in BYU's Physics 108 Course

Carson Chandler

A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

Dr. Adam Bennion, Advisor

Department of Physics and Astronomy

Brigham Young University

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ABSTRACT

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Carson Chandler
Department of Physics and Astronomy, BYU
Bachelor of Science

Traditional lab courses often focus on reinforcing lecture content, yet recent studies indicate that lab courses have little effect on students' content retention. As a result, there has been a shift in the focus of lab courses to emphasize modeling, sense-making, and other scientific practices. In Brigham Young University's Physics 108 lab course, we have implemented new labs emphasizing scientific practices and measured their effects on how well students use scientific modeling. The objective of these new labs is to improve scientific modeling through model creation, revision, and communication, an objective originating from AAPT's recommendations for college-level lab courses. From a cohort of 200 students we analyzed 50 lab submissions from three different labs; two new labs emphasizing model creation, revision, and communication in scientific modeling, and one pre-existing control lab. We used a priori codes developed from sets of national standards to analyze the lab submissions. We observed that the new labs had a positive impact on students' scientific modeling skills, and propose that the new labs elevated students' scientific modeling skills because of the time allotted for the revision and communication of their models.

Keywords: Modeling, Lab, Education, Revision, Physics, PER

ACKNOWLEDGMENTS

Thanks to my wife, Cherileigh, for her support, my dad for wanting me to do amazing things, and my mom for finding time to chat even when things are crazy busy. Thanks to Adam Bennion, Scott Bergeson, Jeanette Lawler, and Nathan Powers for their support and encouragement in doing something the BYU Physics department rarely sees - a senior thesis in education research.

Contents

List of Figures

List of Tables

Chapter 1

Background

Current research suggests that lab courses focus on helping students to "think like scientists". We define "thinking like scientists" as approaching phenomena scientifically by forming hypotheses, developing experiments, and creating scientific models. This definition is based on The University of Colorado Boulder's ECLASS survey [1]. We define scientific models as physical, visual, mathematical, or other representations that describe phenomena. As a result of said research, BYU recently modified the goals for its lab courses to reflect the learning outcomes that current research recommends, and BYU faculty is working to update the lab courses to achieve those outcomes.

1.1 Motivations

In this study, we worked to update Brigham Young University's Physics 108 course, a course where students complete a weekly two-hour physics lab. Focusing BYU's Physics 108 course on helping students to think like scientists is important because it plays to the strengths inherent in a lab course and helps students pursuing a medical career to develop skills they will use in their future. Holmes and Jensen in their 2017 article say that using lab time to reinforce lecture content is largely ineffective, but that labs do offer opportunities for students to develop scientific practices [2].

These scientific practices, things like modeling phenomena, making and testing hypotheses, and paying attention to error and bias, are especially important for the students in this course. Most of the students in Physics 108 are pursuing a career in the medical field (see Appendix D), a place where they will use these scientific skills daily. This context makes gaining both an understanding of physics principles and gaining experience in scientific thinking important student objectives in this course. As we train students to think scientifically, they will become more adept at navigating biases, errors, hypotheses, and results, skills that will help them become better medical professionals.

1.2 The Physics 108 Lab Course

Physics 108 is a lab course that covers topics in electricity, magnetism, and optics, whose target audience is mainly students planning on studying medicine. It is taught in conjunction with Physics 106, its lecture-based counterpart. During Physics 108, students complete ten labs covering the concepts they are taught in the lecture course. The course has existed for over 50 years [3], and while many of the labs have changed with respect to content, current instructors of the course say that the course has always taken the traditional approach to labs, that is, following a set of instructions, completing pre-designed experiments, and reinforcing lecture content.

The course description for Physics 108 in the BYU course catalog gives four learning goals for Physics 108: Students will learn to use scientific modeling, design and conduct experiments, obtain and understand data, and communicate results [4]. These goals reflect the shift from traditional lab goals to the American Association of Physics Teaching's (AAPT's) recommended lab goals [5].

Current labs in Physics 108 are not designed to meet these goals. Current labs consist of a set of instructions that students follow to complete a set of activities that reinforce lecture content. These labs include some scientific modeling and communication elements, for example, students learn about mental models in some labs and write their thoughts about experiments in the lab notebook.

Students occasionally design experiments, but rarely perform them. For example, a student might be presented with a hypothetical situation where a “friend” believes voltage drops in parallel branches of a circuit are different. The lab would then require the student to devise an experiment that would show whether the friend is right or wrong, but not ask them to perform the experiment. Students rarely collect data in these labs, instead mostly using physical observations to confirm science principles. This lab structure does provide some opportunities for students to practice scientific thinking, but it is not the main focus of the labs.

1.3 The Research

AAPT’s suggested learning goals [5] and Etkina and colleagues’ ISLE labs and research [6] heavily influenced the current lab goals for Physics 108. These publications show that allowing students to design experiments helps students to learn to think like a scientist. We wanted to create labs that encourage students to design experiments and scientific models to help Physics 108 students become more familiar with science practices.

Current literature lacks information about how these new labs affect specific science practices. We decided to write new labs and focus our study on how these new labs affect scientific modeling, one of the science practices we are interested in improving in the Physics 108 course. This will allow us to create labs in the future that will target specific science practices like scientific modeling and others.

Modeling is an abstract concept for many students, and we wanted to help students use scientific modeling in a lab where students designed their own experiment. We tested how requiring students to create, revise, and communicate their own models of an unfamiliar phenomenon helps students to model at a more sophisticated level.

Chapter 2

Methods

This chapter will discuss the methods we used to measure the impact of model revision and model communication on student modeling. It will discuss our motivations for creating the labs the way we did, how we created the new labs, and how we administered the new labs. It will also discuss how we collected data and analyzed the data from the study.

Because of the non-invasive structure of the study, we collected and analyzed the data only after the experiment was complete. We did not observe the students during their lab sessions. We did not gather survey data about the specific labs or conduct interviews. Instead, we collected students' lab submissions and analyzed them for specific modeling elements. This method allowed us to assign "modeling levels" based on which modeling elements students included. These levels indicate how well each student did scientific modeling during a given lab [7].

We created a coding rubric, to analyze the labs, a document that has instructions for converting students' lab submissions into useful data. This rubric allowed us to quickly determine whether specific modeling elements like "sense-making" or "limitations" were present in a given student's lab submission. Using this rubric, we coded a lab submission from labs each of the three labs studied for every student group in the class, giving us data that indicated how well students modeled across the control lab and both of the new ones.

2.1 Changes to Physics 108

A group of five people worked together to change the Physics 108 course. These people were professors, most of whom had taught or were currently teaching Physics 108; and myself, an undergraduate student. The goals of this group were to improve Physics 108 as a whole, replacing old "cookbook labs" with newer labs that were more engaging [8], encouraged higher levels of student autonomy [9], and better met the course description [4]. The group met three times during the semester to discuss the direction of our research and the quality of our methods.

We organized our first meeting to decide how to modify Physics 108. Together we decided on two labs to replace that were particularly confusing and rigidly structured. These two labs were chronologically situated right before a lab called "The Optics of the Eye", a lab that instructors noted was a student favorite, likely because of its explicit ties to the body and the medical field. A new lab about the thin lens approximation was proposed as an introduction to the Optics of the Eye lab. Because the lens of an eye does not obey the thin lens approximation, the lab would be about the limitations of the thin lens approximation. Students would study specific limitations of the thin lens approximation and then create models to describe the phenomena they were observing. The group then decided to create a second lab that would be an extension of the first that would allow students to revise their original models and present them to their classmates. The lab would be more autonomous and have a stronger emphasis on scientific modeling than any of the labs in Physics 108 up to that point.

2.1.1 Lab Creation

Dr. Adam Bennion and Carson Chandler wrote the new labs. Though they changed the underlying structure of the lab, they formatted the new labs like the old labs so that formatting did not affect the way the students interacted with the lab. They created the labs were based on current physics education research [5] and ISLE labs [10], emphasizing student autonomy and scientific modeling.

The first lab, "Limitations of the Thin Lens Equation" (see Appendix B) included an introductory section on reflection and refraction and then presented students with a choice of what to study [11]. Students could choose which limitation of the thin lens equation they wanted to study from three options: rotation of a lens, different colors of light, and changing aperture. We hoped this would give students some ownership of the lab [7]. The lab then required students to devise an experiment to explore their chosen phenomenon and create a scientific model of it.

The second lab, "Revisions and Explanations of Findings" (see Appendix C), to be done the following week, began by requiring students to revise their original model. We made the equipment from the first lab available to students so they could change their experimental setup or collect more data if needed. After students revised their models, the lab required students to create and present a poster of their experiment and model [6].

Once the two labs were written, they were reviewed and edited. Each member of the group reviewed the labs and made suggestions, and we trained the Physics 108 teaching assistants to administer the labs. After some minor changes like formatting and wording edits the labs were complete.

2.1.2 Lab Administration

Once the labs were written, the teaching assistants administered the labs the same way they administered the other labs during the semester. Students were aware that some changes had been made to the labs, but to our knowledge were unaware of our study. They followed the normal weekly lab procedure. None of the researchers involved participated in the labs in any way. Students then submitted their labs as usual, and after names were redacted from their lab submissions, copies of their lab submissions were made available for our study.

2.2 Data Collection

Once students' names were redacted from the lab submissions, we sorted them by lab numbers, 3, 7, and 8. We used Lab 3, "DC Circuits and Electrical Measurements" (see Appendix A) as a control lab because it is not a self-directed lab, but it has a high emphasis on scientific modeling. Instead of asking students to develop their own model, most of the lab asks students to identify how certain phenomena fit into pre-defined models.

ECLASS data [1] was also collected at the end of the semester from the beginning and end of class surveys. We used this data to get the demographics of the students in this study. It will also be used in future studies.

Source	Available	Used	Description
ECLASS data	2	2	Survey about how much students think like scientists
Lab 3 submissions	210	56	Regular lab used as control
Lab 7 submissions	214	56	New lab focused on autonomy and modeling
Lab 8 submissions	202	56	New lab focused on model revision and presentation

Table 2.1 Data sources. Note that different numbers of each lab were available because some students did not submit a lab. 56 submissions from each lab were used because there were 56 lab groups in the course.

Rather than using all of the students' submissions, we sorted the data to find a representative sample. Each 108 class is divided into groups of three to five students, so we sorted the lab submissions into their respective student groups. We then assumed that the groups stayed roughly the same throughout the semester and chose one student from each group to represent that group's work on each of the labs. We chose the representative based on whether or not they had submitted all 3 of the labs we needed to analyze. The first student we found in each group that had submitted all 3 labs was chosen to represent their group. This narrowed our sample to 56 lab submissions per lab, and we analyzed that sample.

2.2.1 Rubric Development

We extracted quantitative data from the students' lab submissions to analyze the labs. This was done with a grading rubric that helped us determine whether or not certain elements of scientific modeling were present in the lab submission. This rubric also allowed us to see what level students modeled at on a scale from 0 to 5, with 0 representing no modeling elements present in the lab report, 3 representing introductory college-level modeling indicated by the modeling elements present in the lab submission, and 5 representing sophisticated college-level modeling indicated by the modeling elements present in the lab submission.

We based the rubric on Dr. Adam Bennion's dissertation work [12], the Next Generation Science Standards (NGSS) for high school-level science courses [13], and the American Association of Physics Teachers (AAPT) college-level modeling standards [5]. From these standards, we identified nine modeling elements we would look for in each lab, shown in Table 2.2. These correspond to both high school and college-level modeling elements in order to evaluate the relative level at which students are modeling.

Student examples were also included in the rubric along with descriptions of each element based on their original sources. These student examples were selected based on how well they fit the description of the lab element.

We then created criteria to determine what level students were modeling at based on which modeling elements were present in their lab submissions. We based these criteria on AAPT modeling criteria and previous research by Dr. Adam Bennion.

Origin	Element	Description
NGSS	Scientific Principle	Describes a scientific principle that links aspects of the model to the real-world phenomenon
NGSS	Relationships	Shows relationships or patterns in data
NGSS	Predicts	Model makes predictions about phenomena (after the hypothesis has been tested)
NGSS	Limitations	Identifies limitations
NGSS	Sense-Making	Students approximate and determine whether their results are reasonable
AAPT	Assumptions	Students address assumptions and biases they have/made
AAPT	Multiple Models	Students address multiple models
AAPT	Complete Analysis	Students apply multiple models to give complete analysis
AAPT	Systematic Error	Students discuss how systematic error and biases introduced by instruments affect their model

Table 2.2 Simplified grading rubric. Lab submissions were analyzed for the presence of these nine modeling elements and then. Each element comes from either NGSS or AAPT in the left column, with a description of the element on the right. Student examples were also included in the rubric, but have been excluded here. For the full rubric, see Appendix E.

2.2.2 Lab Coding

The labs were then coded according to the rubric we created. The labs had one grader for the sake of consistency. The labs were coded using a Google Form and a rubric which together contained all of the information needed to properly code the labs based on the rubric.

We took a selective approach to coding the labs because of their length. Each lab had sections that were likely to contain modeling elements and sections that were not. We identified these sections by coding three lab submissions from each lab completely and then identifying which sections of each lab included modeling elements. We coded all subsequent labs using only these sections. The chosen sections can be seen in the Google Form included in Appendix E that we used to code the labs. All of the elements present in lab 7 were automatically coded into lab 8, being that lab 8 was an extension of lab 7.

We used a Google Form to code the rubric grading into a format that we could easily analyze in excel. In the Google Form, the grader was asked to provide the student's lab ID number and was then given three separate lists of the nine modeling elements, one for each lab. The grader would then analyze each lab submission (3, 7, and 8) for the student, checking off each element present in the lab in its respective list. This grading process allowed us to export the data acquired from the Google Form to excel to run analytics and organize the data.

2.2.3 IRR

We used percent agreement, a widely used IRR (inter-rater-reliability) method to verify the reliability of our study. Because lab grading is not automated, the resulting data can be dismissed as biased. IRR methods determine the reliability of the data.

To calculate percent agreement, two graders graded the same lab submissions independently and compared the data they acquired from the lab submissions. They then calculated the "percent agreement" of their data by taking the ratio of how often they agreed in their grading to how often they disagreed in their grading about whether a certain element was present in the lab. This resulted in a value that shows how well the two graders' data agree with one another. Accepted values of percent agreement are generally between 85 and 100 percent. A value in this range indicates that the grader is consistent with the rubric [14].

Element	**Percent Agreement**
Scientific Principle	100
Relationships	83
Predicts	33
Limitations	100
Sense-Making	50
Assumptions	83
Multiple Models	50
Complete Analysis	100
Systematic Error	67

Table 2.3 Percent agreement between independent graders using the same rubric. Some elements ("Scientific Principle," "Limitations," and "Complete Analysis") were graded more consistently than others ("Predicts," "Sense-making," and "Multiple Models").

2.2.4 Limitations

Education researchers usually do IRR in the initial stages of grading so that graders can approach agreement before the bulk of the data is generated, leading to higher percent agreement. However, we did most of the lab grading without considering IRR, so we did not have a high percent agreement for some elements. This means that the data in this study is valuable as preliminary data, but is not reliable as a full-scale study.

Chapter 3

Results and Conclusions

Once we had the lab data, it became apparent that student modeling was slightly better in lab 7 than in the control lab, and even better in lab 8, the follow-up lab to lab 7. Graphing the data from each of these labs helped us identify which modeling elements students included more often in labs 7 and 8 to cause the improvement in overall modeling. Once analyzed, the data indicates that time spent on model revision and model communication is not only a good use of lab time, but is an essential element of labs if we expect students to elevate their modeling skills.

3.1 Data Analysis

The data from lab 3 indicates that students exhibited satisfactory modeling at the NGSS level (elements A-E in Fig. 3.1), the level we expect them to model at after graduating high school. This is expected because up to this point, students have not had any training in college-level modeling. Indeed, this college-level modeling is something that we hope to develop in the Physics 108 course, however, many of the existing labs in Physics 108 do not require elevated student modeling, hence the base-level modeling observed in lab 3.

In lab 7 (Limitations of the Thin Lens Equation) data shows that students began to exhibit

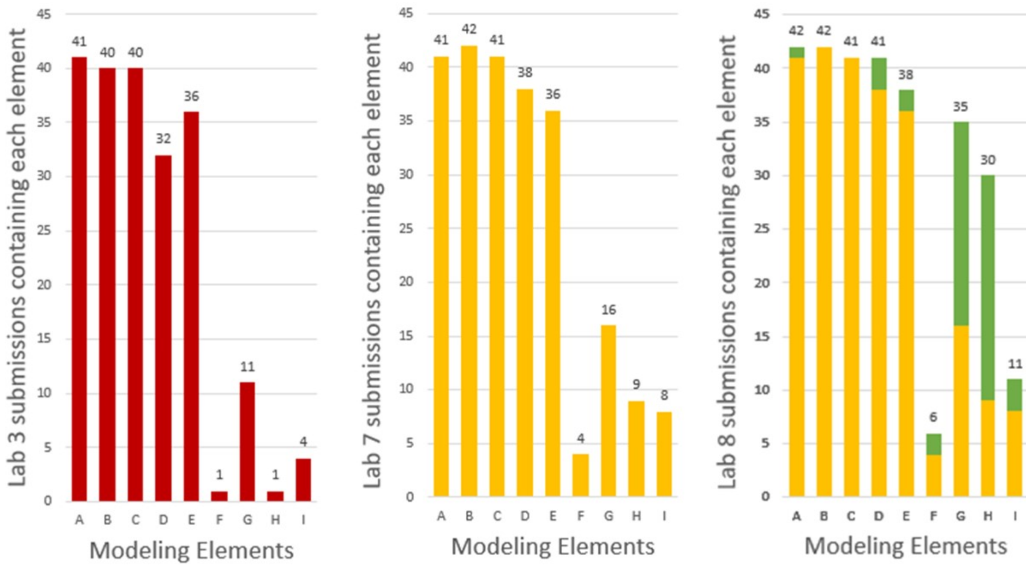


Figure 3.1 Modeling elements observed (in order from left to right) in lab 3, "DC Electrical Circuits and Measurements", lab 7, "Limitations of the Thin Lens Approximation", and lab 8 "Revisions and Explanations of Findings"; organized by number of lab submissions containing each element. Note that in labs 7 and 8, more students exhibit collegiate-level modeling skills (F-I). Modeling elements A through I respectively: Scientific Principle, Relationships, Predicts, Limitations, Sense-making, Assumptions, Multiple Models, Complete Analysis, and Systematic Error. The graph of lab 8 includes all of the elements seen in lab 7 in yellow and the ones seen in lab 8 on top in green as lab 8 was an extension of lab 7.

AAPT-level modeling skills more frequently (elements F-I in Fig. 3.1), likely because of the autonomy and modeling opportunities introduced in this lab as these are the main difference from lab 3. This was expected, and this result corroborates current research about student autonomy in collegiate lab courses [7].

Data from lab 8 (Revisions and Presentation of Findings), shows that students exhibit higher-level modeling with even greater frequency in lab 8. As this lab was an extension of lab 7, this data includes all of the modeling elements observed in lab 8 and lab 7. Lab 8 required students to revise their model and communicate it to other students, so we conclude that this higher-level modeling came as a product of the time allotted for model revision and communication.

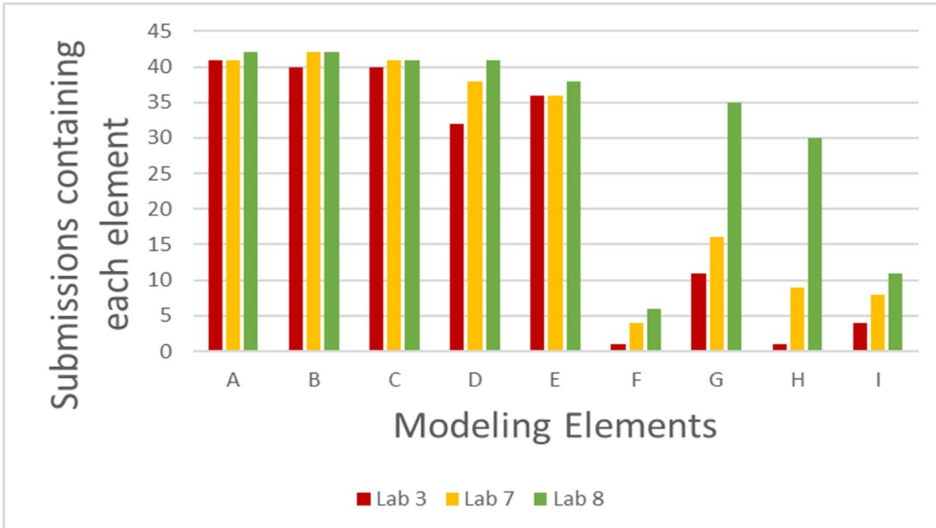


Figure 3.2 A condensed comparison of the three bar graphs in the figure above. Upon examining upper-level modeling elements (F-I), it is apparent that the autonomous structure of lab 7 somewhat helped students meet higher-level modeling benchmarks, and that when presented with an opportunity to revise and communicate their model in lab 8, students elevated their modeling even further.

Although students exhibited an overall increase in modeling quality, some modeling attributes were less affected by the labs than others. In Figure 3.2, element “F”, “Assumptions” was rarely present in any of the students’ lab submissions. Element “I”, “Systematic Error”, was also observed infrequently, present in about 1/5 of lab 8 submissions.

Elements G and H, “Multiple Models” and “Complete Analysis”, however, improved drastically in lab 8, likely because students were required to create a presentation to explain their results to the class. This explanation component meant that students were more likely to explain things in multiple ways; graphically, mathematically, and as an analogy. This explanation component also meant that students were more likely to demonstrate a more complete understanding of the subject in their model, as they were required to explain it to one another.

Most of the NGSS-level modeling skills were consistently present across all three labs. Element “D”, “Limitations” is an exception, likely because students were given more time to think about

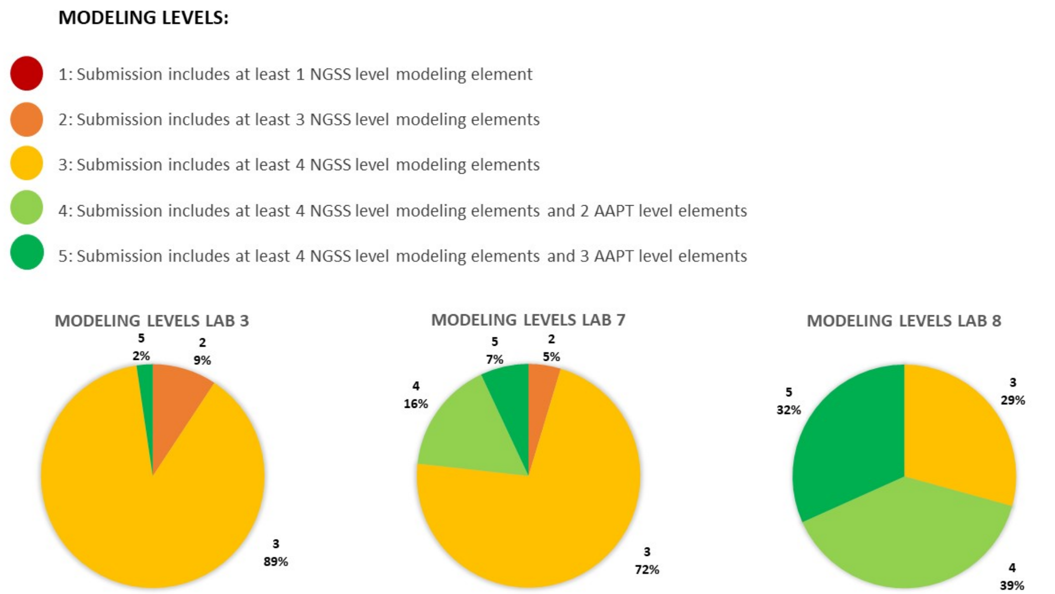


Figure 3.3 Student modeling levels by lab. Each complete circle represents all of the lab submissions for a given lab and each slice represents the percentage of lab submissions that meets certain level criteria. Level criteria are displayed in the top right. Note that lab 7 submissions showed slightly higher level modeling when compared with lab 3, but lab 8 submissions showed significant improvement with 71 percent of students modeling at a level 4 or higher.

and revise their model rather than simply identify limitations. This meant that students were more likely to find meaningful limitations to their experiment so they could improve upon them in the next iteration of their experiment.

We created an arbitrary scale for student modeling from 1 to 5 to better understand how the labs elevated overall student modeling, seen in the top left of Fig. 3.3. We expect students to be modeling at a level 3 at the beginning of the course, and by the end of 108, we expect them to be modeling at a level 5, implementing all of the college-level modeling elements. This data shows that we can help students reach level 5 modeling by requiring them to create, revise, and share scientific models with their classmates, seeing that it elevated students' modeling overall.

3.2 Conclusions

This study indicates that when students are required to revise and communicate their scientific models in a two-week lab format, they are more likely to model at a collegiate level. Students in this study included more modeling elements in labs that provided time for model revision and communication than in a control lab that did not. The study shows that these labs had an especially large impact on AAPT-level modeling elements, showing that model revision and communication help students develop college-level scientific modeling skills.

3.3 Scope and Applications

According to the results of this study, changing the format of more of the labs in BYU's Physics 108 course to allow time for model revision and communication will better help students meet the learning objectives of the course. In the future, we plan to change all of the labs in Physics 108 to follow a 2-week structure of exploration followed by revision and communication.

The data we have collected indicates that students in BYU's Physics 108 course exhibit higher-level modeling skills when the labs provide require students to develop, revise and communicate scientific models. It does not show whether this would work if we changed the whole course to follow a two-week format or if we tried this in other lab courses. More studies can be done in this regard in the future.

Although labs 7 and 8 increased high-level modeling from the students, we do not know how they affected students in other areas. Lab submissions from this study could also be analyzed for concept understanding, sense-making, problem-solving, experimental procedure, and science practices. We can also study the effects of future two-week labs on different science practices. Assuming they are formatted the same way, we can conclude that the benefits we get from the future two-week labs will also apply to the current two-week labs.

We also administered Boulder's ECLASS survey to this semester's students, a survey with a strong reputation that measures how well students think like scientists [1]. We hope to use this semester's ECLASS data in the future to track how gradually switching to a two-week format that focuses on model building, revision, and communication impacts students' ability to think like scientists.

Appendix A

Lab 3

See following pages for Lab 3 used in this study.

Name: ______________________________ Section: ________

DC Electrical Circuits and Measurements

In this lab, you will learn to measure and analyze circuits. You will then use these skills to experiment on and evaluate models of circuit behavior. We expect that the models will help you develop a deeper understanding of how circuits work.

Learning Outcomes

1. Explain the rules of current in parallel and series.
2. Explain the rules of voltage in parallel and series.
3. Calculate the power of each part of a circuit and a circuit as a whole.
4. Solve circuits using Kirchhoff's Junction Rule and Ohm's Law
5. Identify parts of a circuit physically and in a schematic.
6. Describe what current and voltage are and how to measure them.
7. Construct knowledge of circuits through experiment.

Rubrics for this lab

In each lab we will focus on learning and following a set of rubrics that should help you improve your experimental habits and skills. As the semester continues you are expected to continue to follow rubrics from past labs even though a new set of rubrics is listed for the given lab. Make sure that you are assessing yourself on the rubrics below:

Scientific Ability		Missing	Inadequate	Needs Improved	Adequate
D2	Is able to design a reliable experiment to accomplish the goal	The experiment does not solve the goal	The nature of the design is unlikely to lead to accomplishment of the goal (*i.e.*-no reliable data or solution likely).	The nature of the design leads to only a moderate chance in accomplishing the goal (*i.e.*-only partial data or solution likely).	The experiment is very likely to lead to reliable results that are relevant to accomplishing the goal (*i.e.* – leads to conclusive judgement or reliable solution).
D5	Is able to describe how to use available equipment to make measurements	At least one measurement cannot be made with the available equipment.	Each measurement can be made, but no details are given about how it is done.	All measurements can be made, but the details of how it is done are vague or incomplete.	All chosen measurements can be made and all details of how it is done are clearly provided.
C1	Is able to devise an explanation for an observed pattern or phenomenon	No attempt is made to explain the observed pattern or phenomenon.	An explanation is vague, not testable, or contradicts the pattern or phenomenon	An explanation contradicts previous knowledge or the reasoning is flawed.	A reasonable explanation is made. It is testable and it explains the observed pattern or phenomenon.
A1	Follows the instructions and/or procedures carefully and accurately (this applies to self-designed procedures).	No attempt to follow the instructions and/or procedures was made	Significant mistakes and/or oversights were made.	An attempt was made to follow the instructions and/or procedures but not all steps were completed carefully and/or accurately.	Carefully and accurately followed the instructions and/or procedures.

DC Circuits and Measurements Pre-lab Assignment

I. Required Reading/Watching

Previous page

Circuit vocabulary: https://www.khanacademy.org/science/physics/circuits-topic/modal/v/circuits-part-1

Circuits: https://courses.physics.illinois.edu/phys102/sp2018/handouts/handout7.pdf

II. Resources for completing the pre-lab quiz and lab activities

Current: https://cnx.org/contents/Ax2o07Ul@13.1:3ct4v3c5@7/Current

Resistance: https://cnx.org/contents/Ax2o07Ul@13.1:peIFjTvw@11/Resistance-and-Resistivity

Series and Parallel: https://cnx.org/contents/Ax2o07Ul@13.1:FLqArfdc@7/Resistors-in-Series-and-Parall

Include an overview of a topic you were interested in and would like to investigate in the lab. Include a brief description of the method you would use to investigate it:

____
____
____
____
____

DC Circuits and Measurements Lab

I. Qualitative analysis of circuits

Caution: The light bulbs will burn out if there is more than 3.2 V across them.

A. **Observational Experiment:** Use a battery, one wire, and one light bulb. Try different arrangements of these elements to make the light bulb glow. You may unscrew the bulb and/or remove the battery from their holders, if desired. Find a pattern.

B. **Observe:** Build the following circuits, and observe the relative brightness of the light bulbs. Each circuit below will use two batteries in series (~1.5 V each) as the voltage supply.

Circuit description	**Draw the circuit diagram**	**Relative brightness**
1 light bulb		
2 light bulbs connected in series with each other (You cannot make a path through the circuit without going through both bulbs.)		
2 light bulbs connected in parallel with each other. (You can make a path through the circuit that goes through only one or the other of the bulbs.)		

C. **Observe:** Observe the relative brightness of a single light bulb.

Circuit description	**Draw the circuit diagram**	**Relative brightness**
1 battery		
2 two batteries with the positive terminals connected to each other and the two negative terminals connected		
2 two batteries with the positive terminal of one connected to the negative terminal of the second		

D. **Explain:** Batteries and DC power supplies (like the one you will use later in this lab) maintain a constant potential difference across two points. Based on your observations from this and other labs you have completed so far, explain what the battery must do in order to maintain a constant potential difference.

E. **Develop Model:** Develop an analogy for the circuit. The analogy should be consistent with observations.

II. Conceptualizing the observed behavior

A. **Develop Model:** Use your observations from the previous section and your understanding of conductors and batteries to develop analogies for electrical circuits. Do this by first filling in the table with any similar components to a system that you identify.

Circuit element	Water system analogy	Busy ski slopes
Moving electrons		
Connecting wires	Pipes with water in them.	
Battery		
Light bulb		Narrow trail

B. **Explain:** Now use your analogies to describe what the observed properties of the particular system would be.

Electric circuit	Water system	Busy ski slopes
Bulbs in series are dimmer than bulbs in parallel		
Bulbs in parallel each have the same brightness		
When batteries are in series, the bulbs glow brighter		
When two batteries are in parallel, the bulbs glow the same amount as with one battery		

III. Quantitative measurements of circuits

From this point forward you will be using the DC (Direct Current) Power supply instead of the batteries. The power supply can maintain a constant voltage that is set by the user. **Warning: Be careful not to set the voltage above the recommended value as it could damage equipment.** You will be measuring quantities of the circuit by using a multimeter. In voltmeter mode, the meter measures the difference in potential between the post labeled with a V and the one labeled with a COM. In ammeter mode (you will use this later), it measures the current running through the meter.

A. **Observe:** Measuring the voltage of a parallel circuit

1. Build the circuit shown below with your power supply set to about 3 volts (do not exceed 3.2 V). Take care to build it correctly to ensure accurate measurements.
2. Set your multimeter to the voltmeter setting.
3. Place the negative end of the multi-meter (wire connected to COM) at the star.
4. Place the positive end of the multi-meter at each successive dot to measure the voltage (with reference to the COM position) at that location.
5. Record your findings for each dot. (Be sure to check the units on the voltmeter.)

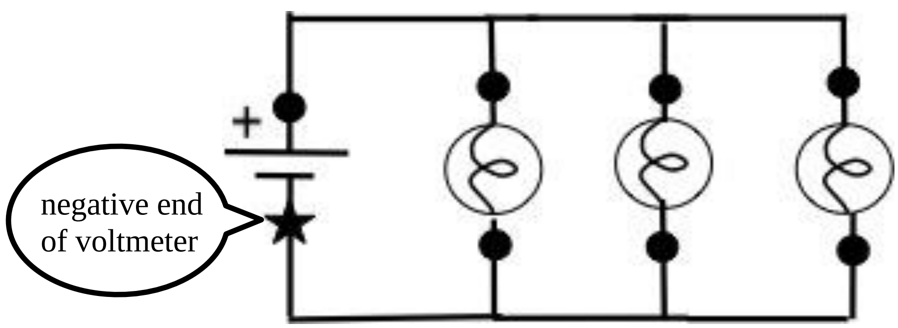


Figure 1

B. **Represent:** Some values you measured are only slightly different from each other. You may consider similar values to be the same in this case. Other values that you measured are significantly different. Use the colors in the list below to color code the wires of the circuit above. Regions with the same voltage should be the same color. Don't color the bulbs.

Color	Levels of voltage found within the circuit
Red	High
Orange	Moderately High
Yellow	Normal
Green	Moderately Low
Blue	Low

C. **Analyze:** What patterns do you see in the data? Include uncertainty in your analysis.

D. **Develop Model:** Consider your answers and the exercise you just completed. Use your observations to further develop your analogies.

Electric circuit	Water system	Busy ski slopes
Voltage		

E. **Explain/Design:** You saw in part A-C that the voltage difference across each of the bulbs and the battery were the same. One of your friends says that that the voltage across the light bulbs is only the same because the light bulbs are identical and that if one of the light bulbs were more resistive, the voltage across each bulb would be different. Based on the analogy you have developed, explain why you agree or disagree with your friend. Suggest an experiment to test your prediction using only the given equipment.

Explanation:

Experimental design:

F. **Testing Experiment:** Use the procedures below or your own design to test your friend's idea.

1. Mark dots on the schematic to illustrate where you will take measurements to test the prediction from part E.

2. Build the circuit using 3 volts as your input. Take care to build it as illustrated.

3. Start from left to right when building the circuit. Take care to build it correctly. It may help to start from the positive end of the power supply and build it clockwise.

4. Measure the voltages and label them on the schematic.

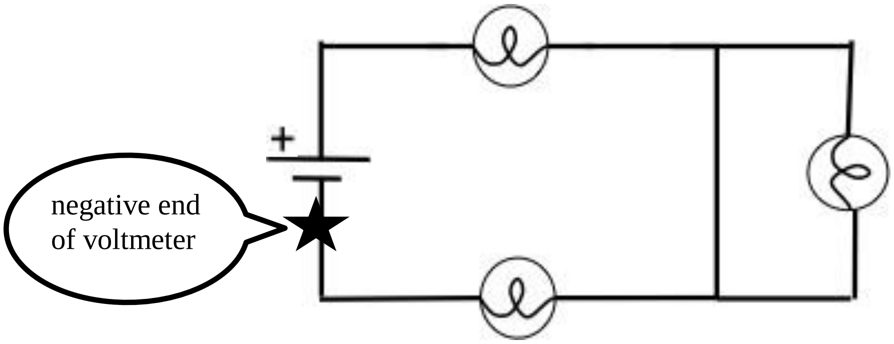


Figure 2

Include observations, analysis, and conclusions. Also, respond to the questions: What do you observe that helps respond to your friend's prediction? Is the voltage drop across parallel paths the same? What is required to light a bulb? What do you notice about the bulbs in series?

IV. Measuring Current

In this part of the lab, you will set your meter to the ammeter setting (A). Recall that in this setting the meter will tell you how much current is running through the meter. Note: There are two differences in how this measurement is performed, including attaching the wire to a different port of the meter and the attaching the wire in a different way on the circuit.

A. **Explain:** Fill in the table below.

Electric circuit	Water system	Busy ski slopes
Current through a wire		

****Study the slide show that compares voltage and current to a water pipe analogy.****

B. **Predict:** Based on the water analogy, predict a set of rules that you expect current to follow in both parallel and series configurations.

Prediction (include hypothesis it is based on):

C. **Observe:** Use the procedures below.

1. Using the same circuit from the previous section. Set you multimeter to measure the current by setting the dial to the A and plugging the positive wire into the hole labeled 10 A.

2. For each measurement, disconnect the circuit wire at the location where you intend to measure the current and connect one side of the meter to each disconnected point. The paired stars and dots on the schematic are there to help you identify how and where to connect the meter. Make sure the positive side of the meter (10 A) is on the star side.

3. Record all of your measurements in the space provided. (Units are amps).

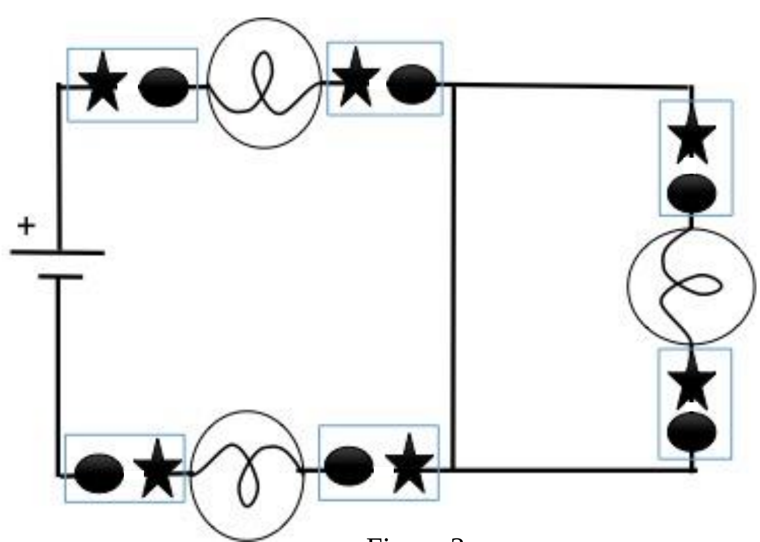


Figure 3

D. **Analyze:** Based on your observations. Discuss and respond to the following prompts.

Compare the current going into the circuit with the current through the other parts of the circuit. What pattern(s) do you notice?

Does the observed pattern match your prediction? What can be concluded based on the observed results in comparison to your expected results?

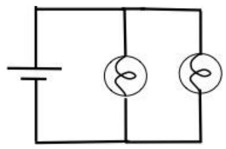
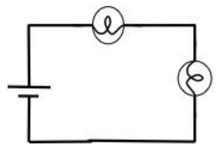
What do you expect the current to be in the extra wire? Why?

E. **Explain:** A friend says that when the power supply is set to a certain voltage (say 3 V) it will always emit the same amount of current. Based on this your friend predicts that removing the wire that is in parallel to the second (unlit) bulb will cause the second bulb to light up without affecting the brightness of the other two bulbs. Explain whether you agree or disagree with your friends assumptions and why.

F. **Observe:** Remove the wire and record your results.

Current into the circuit	Brightness of first bulb	Brightness of second bulb	Brightness of third bulb	Current into second bulb

G. **Analyze:** Record the generalizable rules you discovered in the table.

	Voltage	Current
Parallel 		
Series 		

The behaviors that you observed agree with **Kirchhoff's Junction Rule.** The rule explains what happens when there is a junction in a circuit. Simply put, current must be conserved. There is an activity that models this concept in the review section. It may help you remember this rule.

V. Resistance in a circuit

The concepts you investigated above are foundational concepts for understanding other rules and laws of circuits. There is one more concept that we may not have been explicit about but that you are likely familiar with, *V=IR*. This equation states that if a voltage is applied, current will flow at a rate that is determined by how much the circuit elements resist the flow. Using the foundational concepts in combination with this equation, one can derive equations to explain how combinations of resistors affect a circuit. As you may know, they are:

$$R_{series} = (R_1 + R_2 + R_3 + \ldots + R_n)$$

$$R_{parallel} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}\right)^{-1}$$

You should become familiar with how they can be used in a circuit as you complete the remaining sections. If you want more practice on this topic later, go to:

- Series circuits: http://www.physicsclassroom.com/class/circuits/Lesson-4/Series-Circuits
- Parallel circuits: http://www.physicsclassroom.com/class/circuits/Lesson-4/Parallel-Circuits
- Combo circuits: http://www.physicsclassroom.com/class/circuits/Lesson-4/Combination-Circuits

At this point in the lab we are going to start using resistors instead of light bulbs. While bulbs resist flow and give us a nice conceptual view of what is going on, they are more complicated than resistors because their resistance changes depending on their temperature.

A. **Predict:** Use the following table to predict the voltage, current, and resistance in two circuits. Both circuits use a 3 V power supply and have two resistors (500 Ω and 1000 Ω). The difference is that in one circuit the resistors are connected in series and the other they are connected in parallel. Note: this is similar to what we did in the first section with light bulbs.

Type of Circuit	Total Voltage	Total Resistance	Total Current
2 Resistors in series			
2 Resistors in parallel			

Your predictions should follow **Ohm's law** below:

total voltage = total current x total resistance

V = I x R

volts (V) = amps (A) x ohms (Ω)

B. **Observe:** Use voltage and current to determine the resistance of the resistors. Use Ohm's law.

C. **Observe:** Measure the resistance of resistors in series and parallel. Use Ohm's law. Does the resistance of the circuit follow the equations described on the previous page?

Observations (series):
Observations (parallel):

VI. Feel the Power?

The amount of power in a circuit and in the individual pieces of a circuit is:

Power = Current x Voltage

P = I x V

Watts = Amps x Volts

These equations should make sense if you remember that:

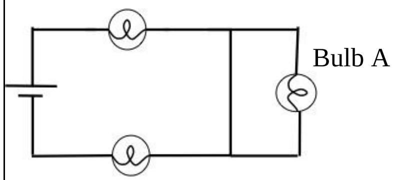
V = Potential Energy per unit charge,

I = charge per unit time, and

P = Energy per time.

The equation for power makes sense if you consider that the potential energy lost by a single charge moving from one potential to another is PE = qV. Since, current is charge per time, power is just a measure of how many charges lose potential energy per time.

A. **Analyze:** Using the values you measured earlier, calculate the power for bulb A.



B. **Explain:** A friend says that the circuit in Figure 7 below will use more power than the one in Figure 6 because the voltage is the same but Figure 7 will have more current. Do you agree with your friend and why.

C. **Testing Experiment:** Find the total power and the power in each resistor for the following circuits. (Include units) Make measurements and calculations to complete the tables. You may save yourself time if you think about the rules you identified for current and voltage in series and parallel.

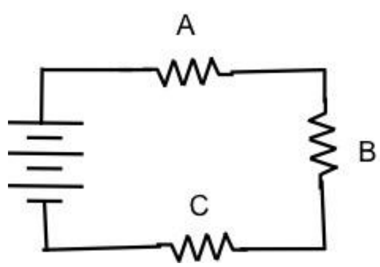


Figure 6

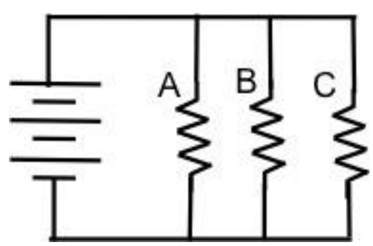


Figure 7

Figure 6	Resistance	Voltage	Current	Power
Resistor A	500 Ω			
Resistor B	1000 Ω			
Resistor C	1500 Ω			
Total		3 Volts		

Figure 7	Resistance	Voltage	Current	Power
Resistor A	1500 Ω			
Resistor B	1000 Ω			
Resistor C	500 Ω			
Total		3 Volts		

V. Review, Conclusions, and Applications

A. **Predict** how the brightness of the of the remaining two bulbs will be affected if one of the bulbs is removed from the circuit shown below. Explain your reasoning.

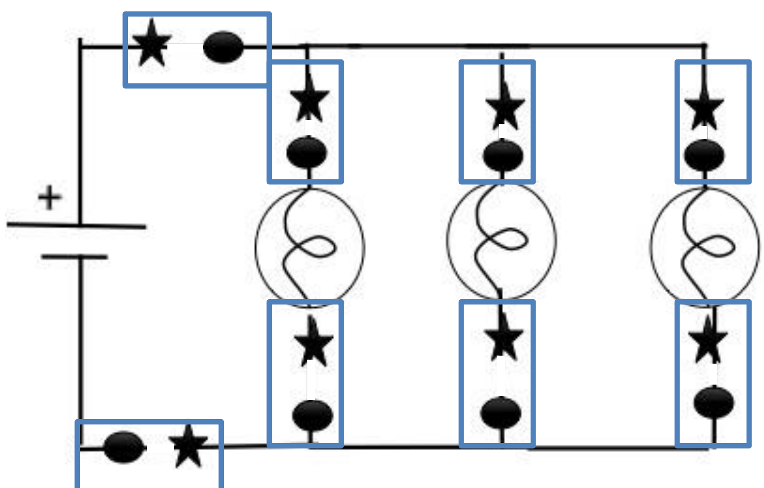


Figure 4

B. **Observe/Analyze:** Perform the experiment. Record your results. What affects the brightness of the bulb?

C. **Represent:** Visualizing current with string

1. Find the group of strings that are tied together at one end. The combined strings together represent the total current from the power supply. (Note: The total current for each figure may be different.) Each individual string represents a fraction of the total current. So, 3 out of 6 strings would be 1/2 the total current, 2 out of 6 would be 1/3 the total current, etc.

2. Place the knot at the positive voltage input of Figures 3 or 4.

3. Use the strings to illustrate how much current is present at different parts of the circuit.

4. Label each figure with symbols like the ones in Figure 5. The number indicates how many strings and the arrow indicates the direction of the current.

Figure 5

Explain how this representation of current agrees with water being pumped through pipes. For instance, what does the term conservation of current mean?

D. **Observe:** Use the figure below to determine the proper order for calculating the equivalent resistance of a circuit with resistors in both parallel and series.

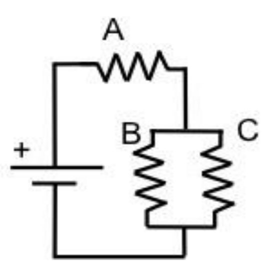


Figure 8

Figure 8	Resistance	Voltage	Current	Power
Resistor A	1500 Ω			
Resistor B	1000 Ω			
Resistor C	500 Ω			
Combo B & C				
Total		3 Volts		

Explanation of method for determining equivalent resistance:

Name: ____________________________ Section: ________

Complete this page and then condense your answers into a concise lab summary to submit online.

What was this lab about?

What was the most important thing that you learned in this lab? Why was it important?

What question do you still have after completing this lab?

What activity from this lab was the most beneficial? Why was it beneficial?

What activity from this lab was the most enjoyable? Why was it enjoyable?

Appendix B

Lab 7

See following pages for Lab 7 used in this study.

Name: ___________________________________ Section: _________

Light, Optics, and the Thin Lens Approximation

It is easy to get the sense that we have a good understanding of light and optics because it is something that we experience every day. However, these daily experiences can actually hinder our understanding and can allow us to overlook some simple yet fascinating phenomena. In this lab, you will investigate light and imaging at a fairly fundamental level and test some of the limits of the thin lens approximation. You will develop models to describe your observations and then test them.

Learning Outcomes

1. Develop models based on experimental observation.
2. Describe the effect of different optical elements such as lenses and prisms on the path of light rays.
3. Predict the location of the formation of images using lenses.
4. Test a limitation of the Thin Lens Approximation.
5. Explain the results of your experiment using evidence based justifications.

Light, Optics, and the Thin Lens Approximation - An Introduction

Most people observe light and use optics daily. In this lab, you will develop a practical model for how light behaves and will test the limitations of an approximation used to understand lenses.

I. Behavior of Light -- Laser Ray Box

A. **Observe:** Locate the “laser lens kit” on your table and pick an object from the kit to use for this activity. Each member of your group should have a different object from the kit. Trace the object you chose in the box below. Then, turn on the “laser light ray box”. Set it to shine multiple lasers by switching the toggle switch to “⌋⌋⌋” on the box. *Be careful not to stare into the laser beams.Be careful not to shine the beams into anyone’s eyes.* Shine the laser beams into your object. Trace the paths that the laser beams take before, within, and after the object. Pay attention to the different paths the lasers take with the other objects people in your group chose.

Object and laser paths:

B. **Explain:** Explain what happened for three of the objects your group chose. Why did the light rays follow the paths you saw? At each air/glass interface, explain the observed changes in the paths. Remember, "explaining" requires both a description of what happened, and why it happened. Illustrations are often helpful. Discuss your answers with your group.

Object 1

Object 2

Object 3

C. **Predict:** As a group, take two of the objects you used previously and predict the path that the light will take if the parallel light rays were to pass through both of them, one after the other. Trace the objects in the box below. Draw your prediction for at least two parallel light rays *using a colored pencil or pen*. Have a TA check your prediction before the next step.

D. **Observe:** Test your prediction in the box above by shining one laser ray from the "laser ray box" through both objects and drawing the actual path the lasers take *with a black pencil or pen*. You should draw the actual path of the laser on the sketch you made your prediction with. You can generate a single laser beam by switching the toggle switch to the middle of the laser ray box.

E. **Explain:** In the box below, explain what might have caused any differences we see between the predicted path and the observed path of the light *or* why the actual path matches your predicted path.

Light, Optics, and the Thin Lens Approximation - The Lab

The thin-lens equation ($\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$) gives a relationship between the focal length (**f**), the object distance (**p**), and the image distance (**q**). This equation, like many equations in physics, is an approximation and has limitations. In this part of the lab you will explore one limitation of the thin-lens equation and develop a model to explain your observations.

II. Testing the Thin Lens Approximation

A. Develop a Hypothesis:

The thin lens equation is a standard mathematical model. Your group will choose a limitation of the thin lens equation to explore: color, lens angle, or aperture size. Talk to a TA to sign up for a limitation to study and get the equipment for your experiment. Once you have decided which limitation to explore and obtained your equipment, you will create a hypothesis that shows how you think your limitation will change the relationship between focal length, image distance, and object distance.

Circle the limitation your group signed up to study:

Varying aperture at the lens   *Varying angle of incidence at the lens*   *Focal length for different colored light*

PREDICTION:

What do you expect to happen?

____

____

HYPOTHESIS:

Turn your prediction into a hypothesis by (1) adding some reasonable motivation or explanation for your prediction and (2) making sure your prediction is one you can test.

____

____

____

B. **Design:** After you have made your hypothesis and thought about how you will test it, you're ready to design your experiment. Good experiments do the following:

- Control variables
- Have the potential to disprove the hypothesis
- Have a reliable way to collect data
- Include error analysis
- Can be repeated

In your group, design an experiment to test your hypothesis. Your goal is to develop a reliable approach for determining the limitations of your specific parameter (color, lens angle, or aperture) places on the thin lens equation. Organize your experimental procedure below in an orderly manner using bullet points, paragraphs, sketches, etc. as needed.

C. **Observe:** In the space below, organize the data you have collected and write your observations.

D. **Analyze:** In the space below, analyze the data you collected. This could include mathematical operations, description of patterns, graphs, plots, ray diagrams, sketches, or anything else that makes it easier to interpret the data you have collected. Be sure to consider the error in your experiment as well. Your analysis should be sufficient to determine whether or not you can reject your hypothesis based on your experiment.

E. **Model:** A model is a representation of a concept or phenomenon that allows you to better predict what will happen in a given situation. Using the data from your experiment and your analysis, you will create a working model for your limitation. This could be a mental model, a written model, an illustration, or something more mathematical. It should be an accurate way to relate focal length, object distance, and image distance within your chosen limitation.

- How does the limitation you studied affect the focal length of the lens?
- How could you use a light ray diagram to aid in your model?
- What are some different ways you could model your observations?
- Which do you think could be most easily understood by someone outside your group?

The above questions are simply to help you think about your model, and do not need to be answered explicitly, although we recommend discussing them in your lab group. The space below is for the model you and your group came up with.

F. **Evaluate your Experiment:** As a group, discuss the questions below. On your own, write a reflective statement about your experiment. Your statement does not need to answer the questions explicitly.
- What went according to plan?
- What didn't go according to plan?
- How much error was there in your experiment?
- What were the limitations of your experiment?
- What do you like about your experiment?
- How could you improve your experiment?

EVALUATION:

Appendix C

Lab 8

See following pages for Lab 8 used in this study.

Name: ___________________________________ Section: _________

Revisions and Explanations of Findings

Many times when an experiment is done for the first time, things don't go as planned. As scientists perform their experiments, they notice things they can improve about their experiment, so they iterate their experiment, performing it many times in many different ways. Then, when scientists have perfected their experiment and found their results, they communicate their results to the scientific community, and sometimes to the general public as well. In this lab you will focus on iteration and communication in science.

Learning Outcomes

1. Collect, analyze, and interpret real data from observations of phenomena.

2. Develop abstract representations of real systems studied in the laboratory, understand their limitations and uncertainties, and make predictions using models.

3. Analyze and display data using statistical methods and critically interpret the validity and limitations of these data and their uncertainties.

4. Present results and ideas with reasoned arguments supported by experimental evidence.

Revisions and Explanations of Findings Lab

Last week we did a lab about limitations of the thin lens approximation. We practiced designing experiments and created our own models based on what we observed. One of the most important parts of being a scientist is being able to clearly communicate your findings with the scientific community and the general public. In this lab, you will review your findings and your model, and then you will present your findings to your peers in a conference poster format.

I. Refining the Model

A. Review your experiment:

At the end of the last lab, you built a preliminary model that could explain the results of your experiment in order to give clarity to one of the limitations of the thin lens approximation. In part I of today's lab you will return to your model and collect additional data to refine and improve it.

Original Model:

Write up the details for your original model. Make sure to include any figures and explanations that are salient to the model:

What are some of the limitations of your current model?

B. Plan for Revision: Considering the lab work you did last time and your current limitations, what can you do to improve your model? What additional data could you collect? What additional analyses could you do?

C. **Observation/Analysis:** Following your above plan, organize your new data or analyses.

D. **New Model:** Use this space to illustrate your new model. Make sure to include all of the relevant details, illustrations, and explanations.

Reflection: How is your current model different from the original? What are some of the limitations of this version? If you had more time or resources, how could you iterate on this model further to improve it?

II. Communicating Your Results

A. **Know Your Audience:**

Communicating with a community of scientists (or your classmates) is very different from communicating with the public. What do you think some of those differences may be?

B. **Create a presentation for the scientific community (your classmates):**

Using your final model, create a one-slide presentation (a virtual poster) that you can display on the classroom monitors using the provided template. This slide will include your hypothesis, your experiment, your analyzed data, and your model. It should be detailed and put together as if you were to present these results at an academic conference.

C. Share your results:

The last 45 minutes of class will be separated in three 15 minute rounds. You will need to divide your lab group into three "presenter groups" (one for each round). During the presentation time, one "presenter group" will remain with your poster to answer questions and describe your model while the other members of your group move around the classroom learning about what your fellow classmates discovered. You will switch the "presenter group" each round.

In the space below, take notes on the things learned from the other groups' models:

Appendix D

ECLASS

See following pages for ECLASS data taken in this study.

Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS)

Thank you for participating in the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS). We hope you find this report helpful for learning more about how your students think about experimental physics. On this tab of the report, you will find an overall summary of your students' responses and comparison data from similar level courses. For more information on how to read this report, or how this report was analyzed, see the "How to Read This Report" and "How This Report was Analyzed" tabs. The final tab provides a list of questions as well as the "expert-like" responses for each.

If you have questions about the survey or the results, or if you would like to make suggestions to improve the usefulness of the survey and report please email your questions or thoughts directly to our research team at: (mailto:eclass@colorado.edu)eclass@colorado.edu

Sincerly,
Heather Lewandowski

Overall Results for your class

Number of valid pre-responses	168
Number of valid post-responses	147
Number of matched responses	119
Reported number of students in class	210
Fraction of class participating in pre and post	0.57

TABLE 1. Summary of class participation. For a description of what qualifies as a valid response, see the "How to read this report" tab.

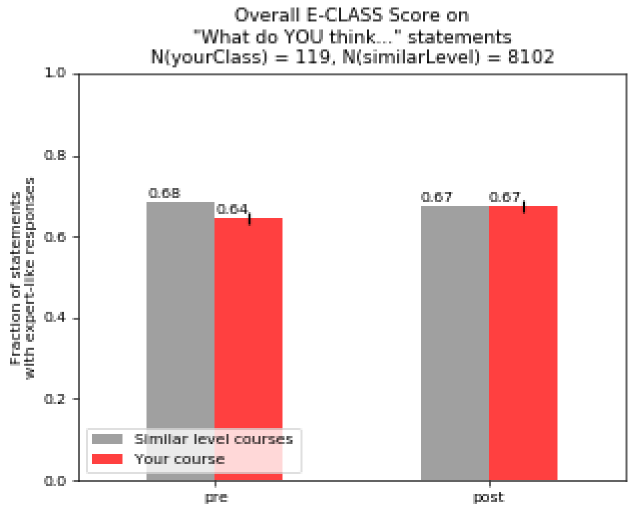


FIGURE 1. Comparison between overall pre and post scores for students' personal views on What do YOU think when doing experiments for class? Your class (Red) is compared with all students in similar level classes (Grey), (i.e., either introductory- or advanced-level physics labs). The overall mean shown here averages over all students and all statements on the survey. **The error bars represent one standard error of the mean.**

How do students' personal views change in your course compared to other courses?

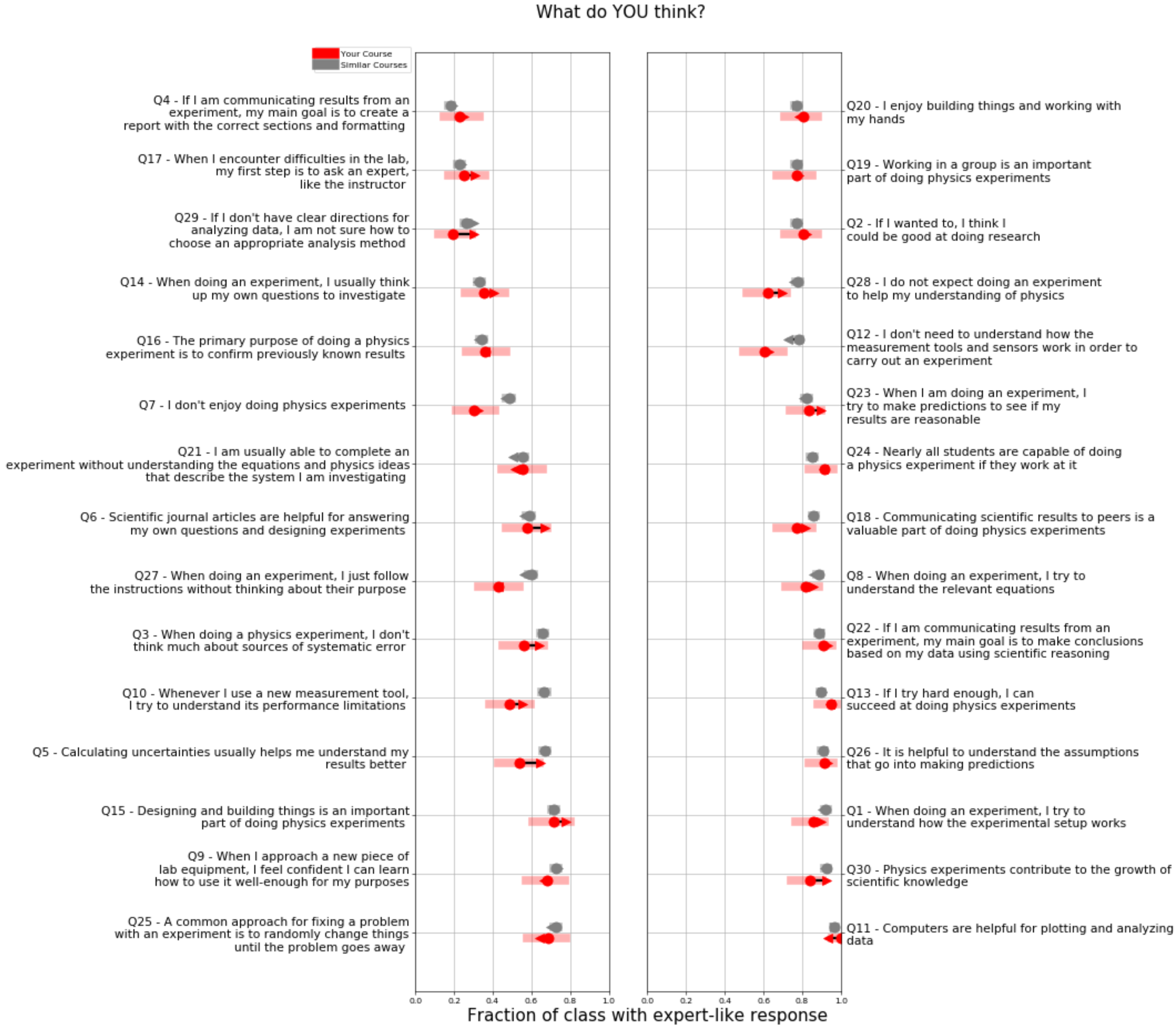


FIGURE 2. Pre/Post changes in students' personal views about "What do YOU think when doing experiments for class?" for your class (Red) and all students in similar level classes (Grey). The circles show the pre-survey values. The arrows indicate the pre to post changes. The shaded bars indicate a 95% confidence interval. The responses are ordered by the expert-like fraction in the pre-survey from similar level courses. Questions which show up on (or shift towards) the right side of the graph are "good" as they indicate a large (or increasing) fraction of students with expertlike views.

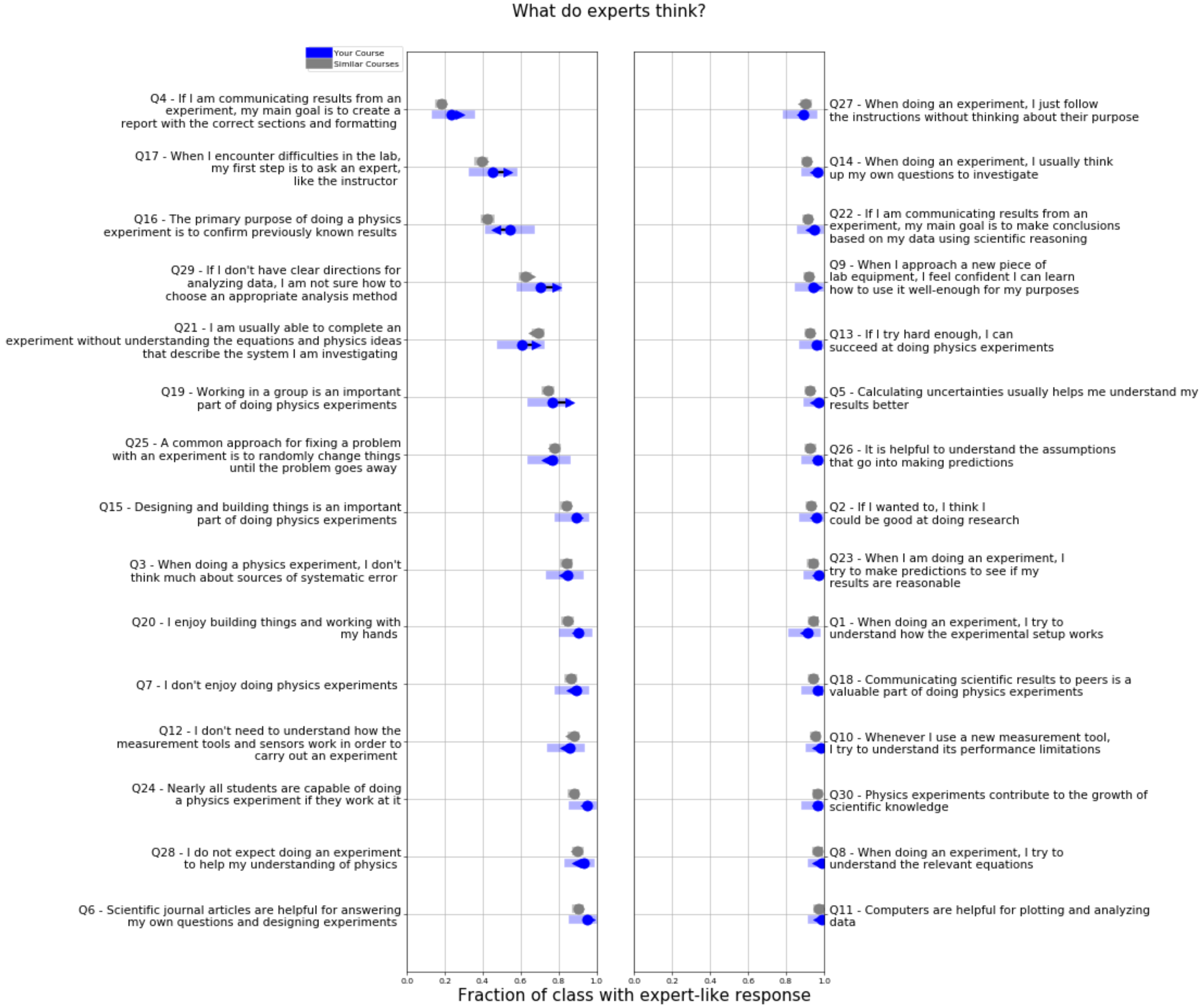


FIGURE 3. Comparison for your class (Blue) between changes in the students' views about professional physicists and students in similar level classes (Grey). The circles show the pre-survey values. The arrows indicate the pre to post changes. The shaded bars indicate a 95% confidence interval. The responses are ordered by the expert-like fraction in the pre-survey. Questions which show up on (or shift towards) the right side of the graph are "good" as they indicate a large (or increasing) fraction of students with expertlike views.

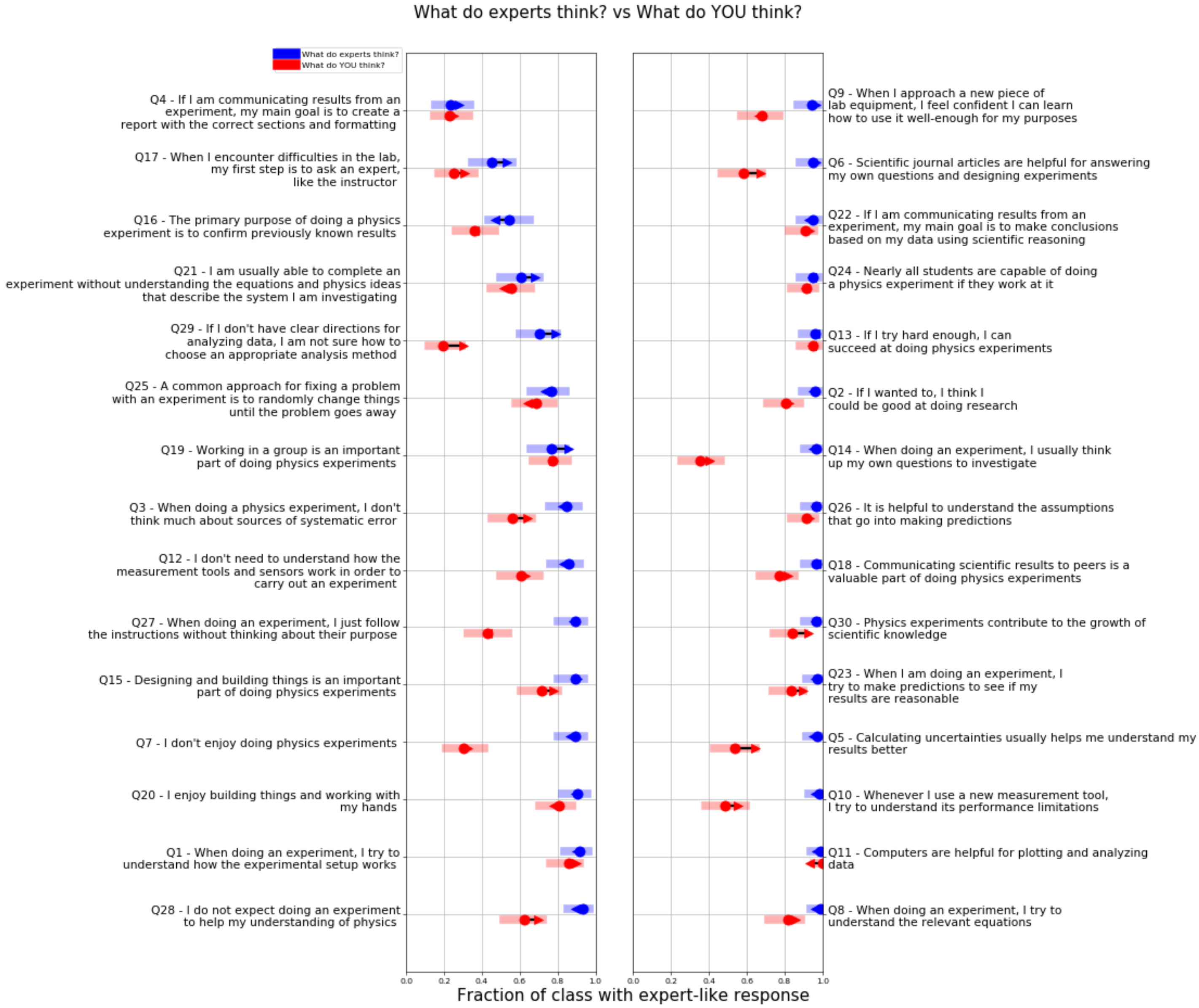


FIGURE 4. Comparison for your class between changes in students' personal views versus their views about professional physicists. What do YOU think... (Red) shows the change in students' response to "What do YOU think when doing experiments for class?" This red data is the same as the red data in Figure 2. "What would experimental physicists say..." (Blue) shows the change in students response to "What would experimental physicists say about their research?" The circles show the pre-survey values. The arrows indicate the pre to post changes. The shaded bars indicate a 95% confidence interval. Questions which show up on (or shift towards) the right side of the graph are "good" as they indicate a large (or increasing) fraction of students with expertlike views.

What did students think was important for earning a good grade in your course and other similar courses?

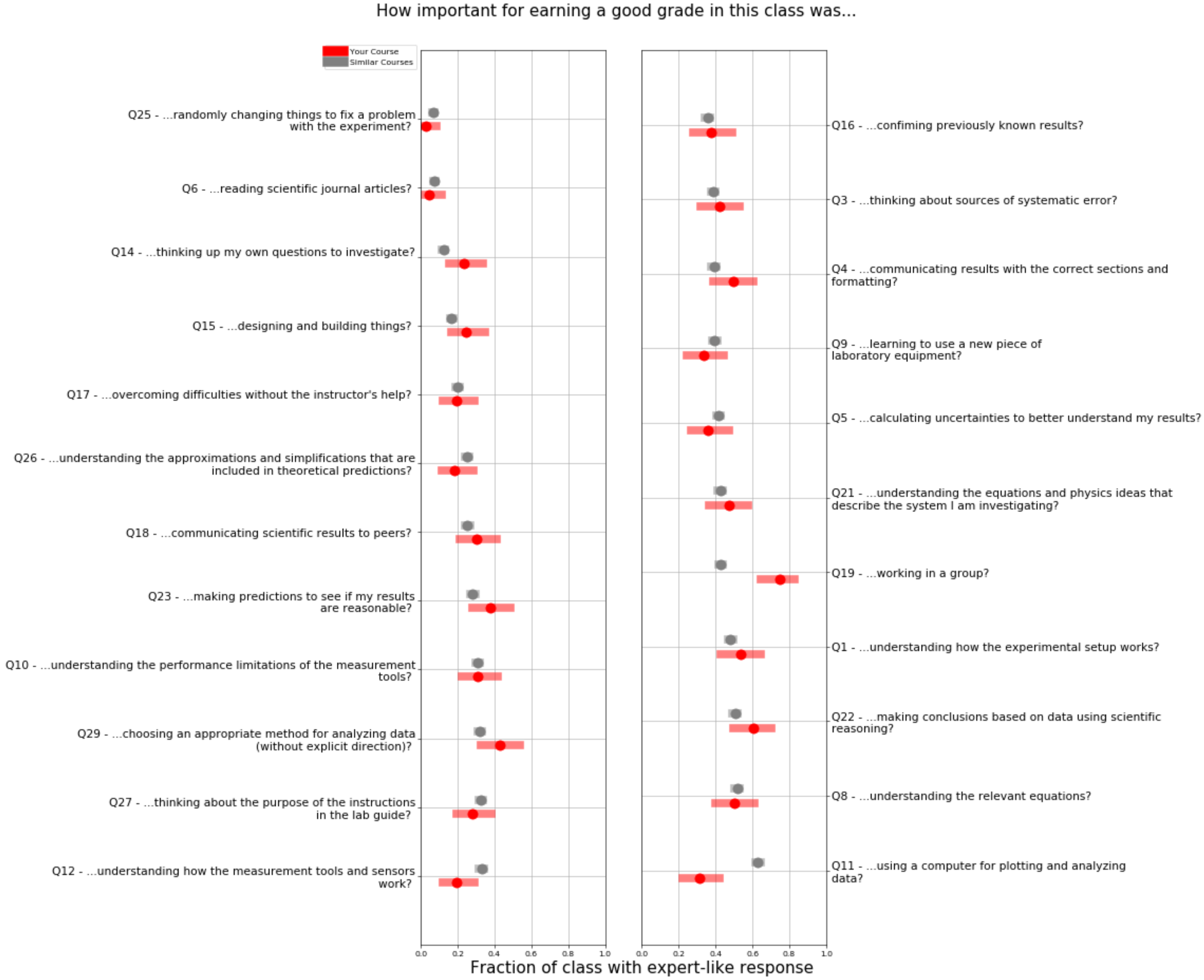


FIGURE 5. An ordered plot of students' views of importance of different activities for earning a good grade in your class (Red) and in similar level classes (Grey). The circles show the pre-survey values. The arrows indicate the pre to post changes. The shaded bars indicate a 95% confidence interval. Questions which show up on (or shift towards) the right side of the graph are "good" as they indicate a large (or increasing) fraction of students with expertlike views.

Follow-up questions about course interest and career plans

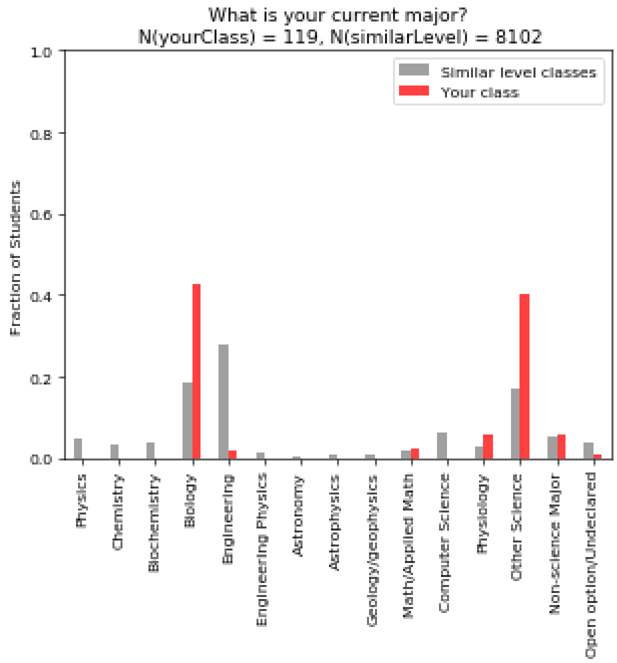


FIGURE 6. Distribution of students by current declared major for your class (Red) and similar level classes (Grey).

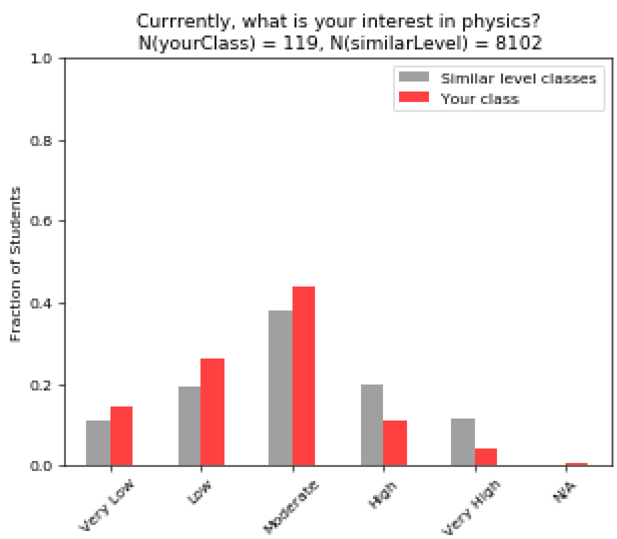


FIGURE 7. Students' current interest in physics for your class (Red) and similar level classes (Grey).

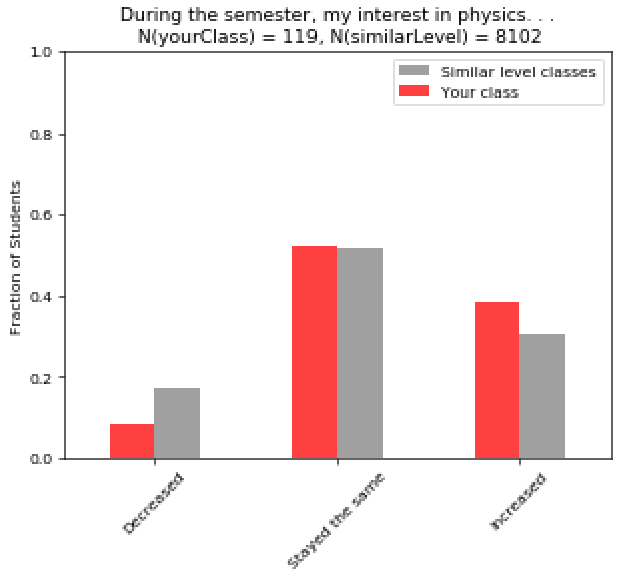


FIGURE 8. Change in students' interest in physics for your class (Red) and similar level classes (Grey).

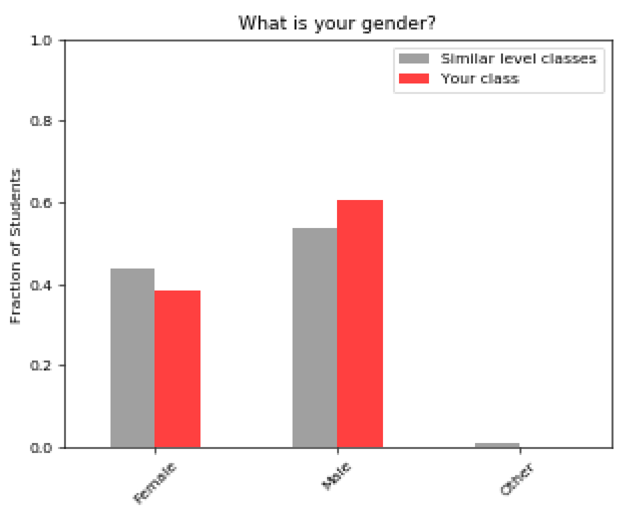


FIGURE 9. Gender distribution for your class (Red) and similar level courses (Grey).

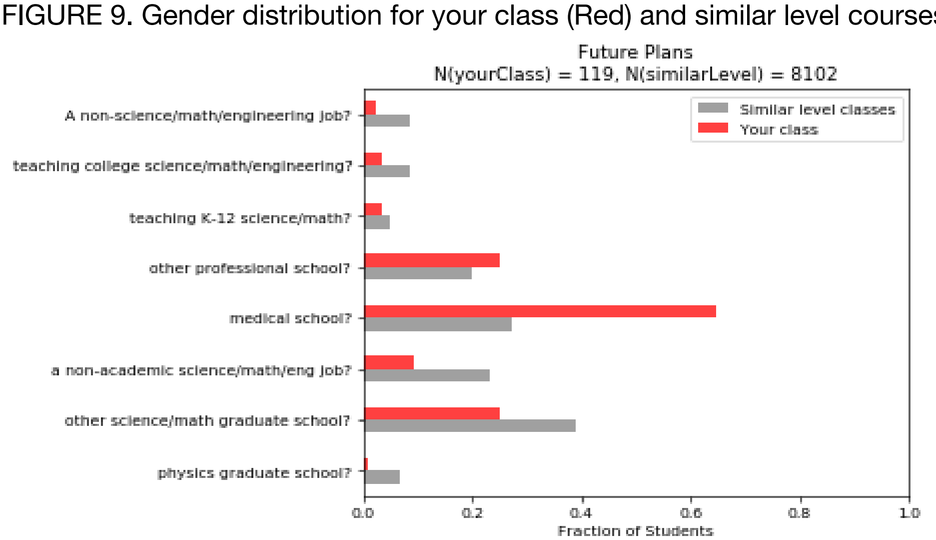


FIGURE 10. Future plans reported by your students (Red) and by students in similar level courses (Grey).

Appendix E

Coding Tools

See following pages for grading rubric and Google Form used to code lab submissions.

OFFICIAL RUBRIC

		Modeling Benchmarks	Criteria	Examples
NGSS	A1	Scientific principle	Describes a scientific principle that links aspects of the model to the real-world phenomenon	"An analogy we could use is a tube of water…The resistance is a bottleneck" (1111_Lab3) "diffraction with different colors is like a car turning onto grass. The more wheels it has, the more affected it will be by the change from pavement to grass"
	A2	Relationships	Shows relationships or patterns in data	"As we added more resistors, the volage drop stayed the same" "When we made the angle bigger, the focal point was closer to the lens" Any graphs
	A3	Predicts	Model makes predictions about phenomena (after the hypothesis has been tested)	"It looks like when we add resistors, the voltage will drop less over each one." "Our data indicates that even if we change the color, the focal point will stay the same."
	A4	Limitations	Identifies limitations	"some sources of uncertainty are our tools that could be more precise" "The light was on in the room and it felt subjective deciding where the focal point was"
	A5	Sense-Making	Students approximate and determine whether their results are reasonable	"This makes sense because the battery was getting hotter" "Just like in a camera, when you close the aperture you have a larger field depth, so it makes sense."
AAPT	B1	Assumptions	Students address assumptions and biases they have/made	"we assumed the wires had no resistance" "I don't know if it's right, it's just the equation"
	B2	Multiple Models	Students address multiple models	"I think it makes sense if you think of it like marbles in a pipe or like water in a stream."
	B3	Complete Analysis	Students apply multiple models to give complete analysis	"Conceptually I think of it as a car turning onto grass, and mathematically you can see that that's true on the graph we made"
	B4	Systematic Error	Students discuss how systematic error and biases introduced by instruments affect their model	"If we were able to more accurately identify the focal length, this graph would probably be a lot more linear." The wires made it so that there actually was a larger voltage drop across the first bulb, but if the wires had no resistance, we would have seen that the voltage drop across every bulb is the exact same.

Lab grading

Let's do some IRR science!

1. Who are you?

Mark only one oval.

- Adam
- Riley
- Carson

Getting started!

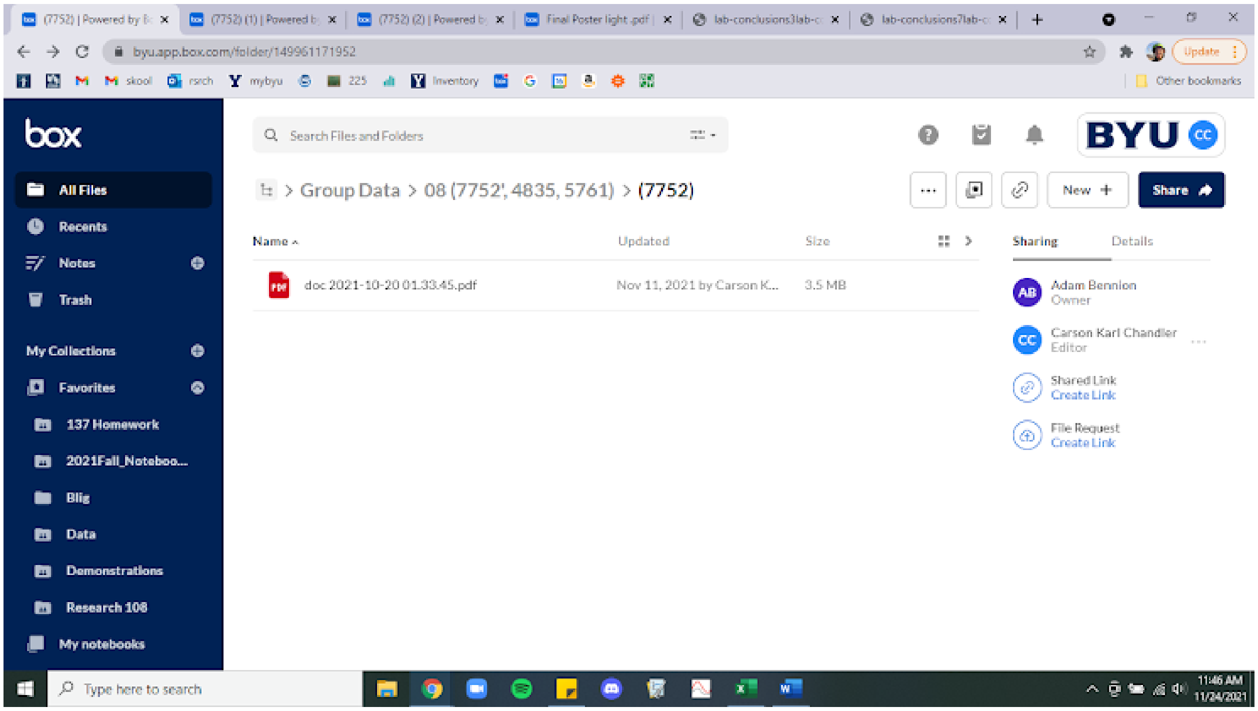
Please read all of the instructions in this box before you start.

Start from the "Group Data" box folder: https://byu.app.box.com/folder/151310863829

Each of these "group folders" contains data from a different student group. Open a "group folder". Each folder contains labs 3, 7, and 8 from a student in the group and the group's presentation. Open each of these in a different tab. You should have four tabs open.

At the bottom of the "Group Data" folder there are two PDFs. You should download them and open each of them in a new tab. You should now have 6 tabs open.

Example of those 6 tabs open. The four tabs on the left are from group 8's group folder, and the two on the right are the downloaded lab conclusions.



2. Which student's labs are you grading? All of the folders in the group folder will be labeled with a student number. Enter the 4 digit student number below. Ex. for the picture above I would enter 7752.

____

Grading

Each lab has two documents to analyze. If a student meets a benchmark described in the rubric in either document, check it off in the google form.

Lab 3

Open the student's Lab 3 on box. It's the one about circuits. Look at setions 1e, 3c, 3d, 3e, and 3f. Then open the lab conclusions PDF for lab 3 ("lab-conclusions3lab-conclusion_1"). Use Ctrl F and the student's number to find the student's final lab report. These often meet benchmarks.

3. Benchmarks hit in Lab 3

Check all that apply.

- [ ] Scientific Principle
- [ ] Relationships
- [ ] Predicts
- [ ] Limitations
- [ ] Sense-Making
- [ ] Assumptions
- [ ] Multiple Models
- [ ] Complete Analysis
- [ ] Systematic Error

Lab 7

In lab 7, look over 2C, D, and E. Use Ctrl F and the student's number to find the student's final lab report in the pdf "lab-conclusions7lab-conclusion_1".

4. Benchmarks hit in Lab 7

Check all that apply.

- [ ] Scientific Principle
- [ ] Relationships
- [ ] Predicts
- [ ] Limitations
- [ ] Sense-Making
- [ ] Assumptions
- [ ] Multiple Models
- [ ] Complete Analysis
- [ ] Systematic Error

Lab 8

In the form below, check every benchmark hit in Lab 7 and then look at Lab 8 only for additional benchmarks hit. This will save you a lot of time. For this lab, you'll want to look at everything but the communications sections at the end. In this case, the group poster is the lab conclusions document. It usually meets a few extra benchmarks, so be sure to analyze it thoroughly.

5. Benchmarks hit in Lab 8

Check all that apply.

- [ ] Scientific Principle
- [ ] Relationships
- [ ] Predicts
- [ ] Limitations
- [ ] Sense-Making
- [ ] Assumptions
- [ ] Multiple Models
- [ ] Complete Analysis
- [ ] Systematic Error

Thank you!

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Google Forms

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Index