Designing a First-Year Undergraduate Lab Course to Teach Authentic Experimentation Skills

TRAVIS MERRITT

DEPARTMENT OF PHYSICS
VIRGINIA TECH
(TMERRITT@VT.EDU)

VIRGINIA TECH™

WHAT IS A TRADITIONAL LAB?

- Traditional teaching laboratories are **highly structured** and serve to **reinforce** or **verify** lecture content.
  - **Highly-structured:** Students are given a step-by-step protocol to follow.
  - "…[students] follow a prescribed procedure to replicate a prescribed outcome." [1]

CONCERNING EVIDENCE ABOUT TRADITIONAL LABS

- **Recent Research**: Traditional labs have minimal impact on student learning of the lecture content but negative impacts on student attitudes and views of experimental science [2-4].

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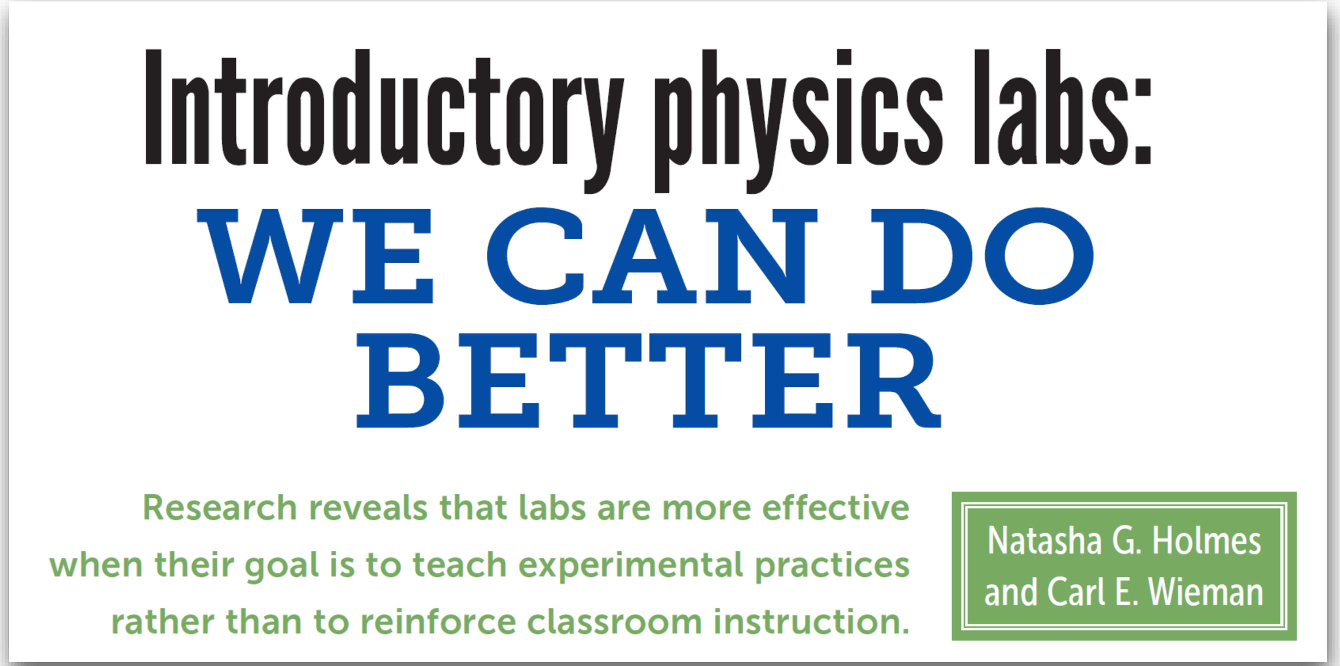


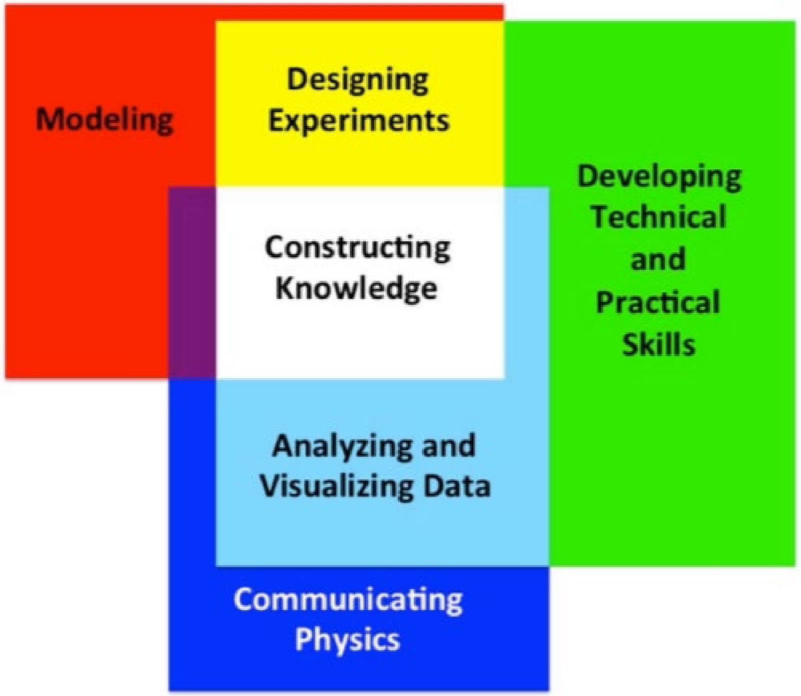
Introductory physics labs:
WE CAN DO BETTER

Research reveals that labs are more effective when their goal is to teach experimental practices rather than to reinforce classroom instruction.

Natasha G. Holmes and Carl E. Wieman

NEW STANDARDS FOR LABORATORY EDUCATION

- AAPT Recommended Learning Outcomes [8]
  - "Developing particular **habits of mind** (i.e., "Thinking like a physicist") and **constructing knowledge** of our physical universe pervades all of the recommended learning outcomes…. since the enterprise of physics is the construction of new knowledge."
  - Constructing Knowledge
    - "Through laboratory work, students should gain the awareness that they are able to do science; that is, students should be able to **collect, analyze, and interpret real measured data in an ethical manner as responsible scientists and draw meaningful conclusions from personal observations of the physical world.** The laboratory curriculum should get students to start thinking like physicists by constructing knowledge that does not rely on an outside authority…"



NEW LAB CURRICULUM: GUIDING PRINCIPLES

- At Virginia Tech, we are developing a new intro lab curriculum[1] to align with the AAPT's recommendations by
  - removing all verification goals,
  - simulating authentic scientific activities,
  - letting students engage in scientific decision-making,
  - making students and their data the source of investigative authority, and
  - providing formative feedback throughout course

[1] *Adapted from Thinking Critically in Physics Labs by Holmes et al.*

NEW LAB CURRICULUM: COURSE STRUCTURE

- **Overview**
  - During the semester, students complete a sequence of **lab units**.

Lab Session 1	
Before:	• Complete and submit a homework assignment related to the first session.
During:	• Design and conduct an experimental investigation that evaluates a specific research question. • Formally check in with your lab instructor.
After:	• Submit a preliminary version of your group's lab notes for the unit
Lab Session 2	
Before:	• Read your instructor's feedback on your preliminary submission. • Complete and submit a homework assignment related to the second session.
During:	• Conduct a more open investigation that extends your investigation from the first session. • Formally check in with your lab instructor.
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Unit 1: Introduction to Model Testing

High-precision Experiments and Pendulums

LAB UNIT 1: *FIRST HOMEWORK*

- **Homework 1.1**
  - Students complete a Mathematica-based guided tutorial about uncertainty
    - Develop a conceptual understanding of statistical uncertainty using simulations and invention activities
    - Learn how to quantify uncertainty in an individual measurement and mean measurement

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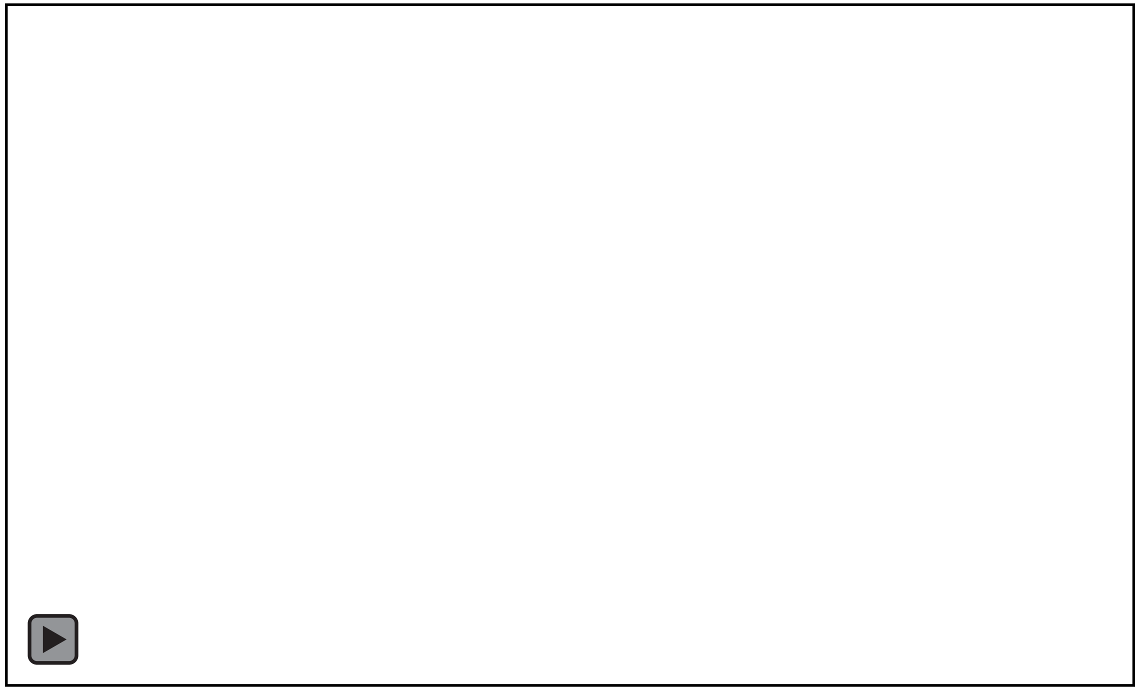

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- To estimate the uncertainty in the mean measurement using data from one experiment, we can use the following formula. (I will discuss the basis of this formula in Chapter 2 of the Statistics Handbook):
  - $\sigma_{\text{mean}} = \frac{\sigma_{\text{indiv}}}{\sqrt{N}}$
    - σ_{indiv} is the standard deviation in the individual measurements, and
    - N is the number of trials in the experiment (i.e., the number of measurements used to calculate the mean measurement)
  - **Example:** Suppose you drew 10 cards and the point values were {5,4,1,7,5,3,6,4,5,2}. According to the following calculations
    - The mean measurement is 4.2,
    - The uncertainty in the individual measurements is 1.81, and
    - The uncertainty in this mean measurement is 0.57.

```
In[70]:= exampleDataSetPointValues = {5, 4, 1, 7, 5, 3, 6, 4, 5, 2};

N[
 Mean[exampleDataSetPointValues]
]

N[
 StandardDeviation[exampleDataSetPointValues]
]

N[
 StandardDeviation[exampleDataSetPointValues] / Sqrt[10]
]

Out[71]= 4.2

Out[72]= 1.81353

Out[73]= 0.573488
```

LAB UNIT 1: *FIRST LAB SESSION*

According to your textbook, a simple pendulum behaves according to the **model**[3] below:

Simple Pendulum Model

For a simple pendulum, the period of the pendulum T depends only on its length L and the free-fall acceleration g:

$$T = 2\pi\sqrt{\frac{L}{g}}\ ,$$

This relationship assumes, among other things, that:

- the only forces on the pendulum are due to gravity and tension in the string,
- the pendulum string is massless,
- the initial angle of amplitude is small, and
- the pendulum bob behaves like a point mass.

LAB UNIT 1: *FIRST LAB SESSION*

- Confine **preliminary investigation**
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- Students design **follow-up investigation** through reflective decision-making
  - Should they improve their measurements?
  - Should they perform more trials?

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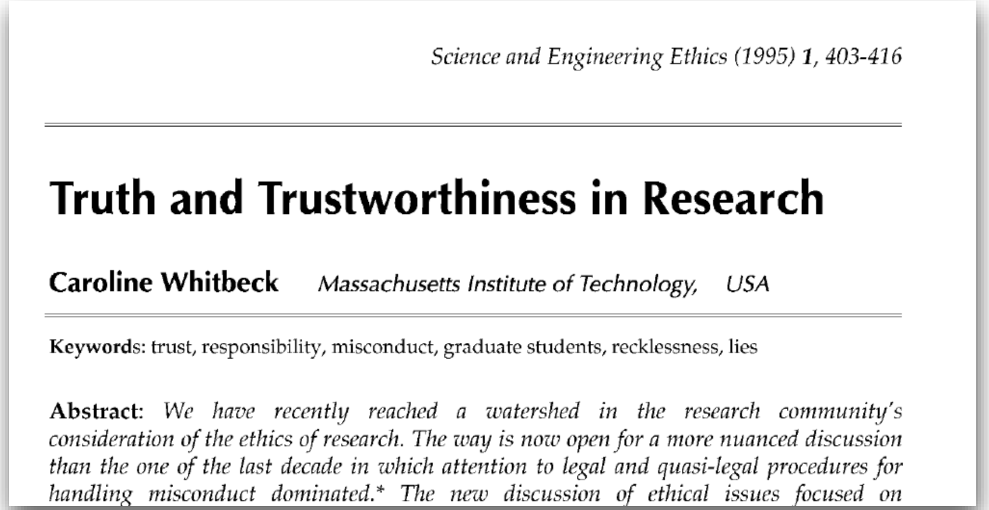
  - Should they improve their measurements?
  - Should they perform more trials?
- Use **confirmation bias** as a learning opportunity
  - Due to their previous experience with verification labs, some students will try to confirm the model.

LAB UNIT 1: *SECOND HOMEWORK*

- **Homework 1.3**
  - Students complete an **ethics tutorial**
    - Tutorial introduces an ethical framework for responsible research.
    - Students explore the ethical implications about confirmation bias and reflect on their experimental decisions.



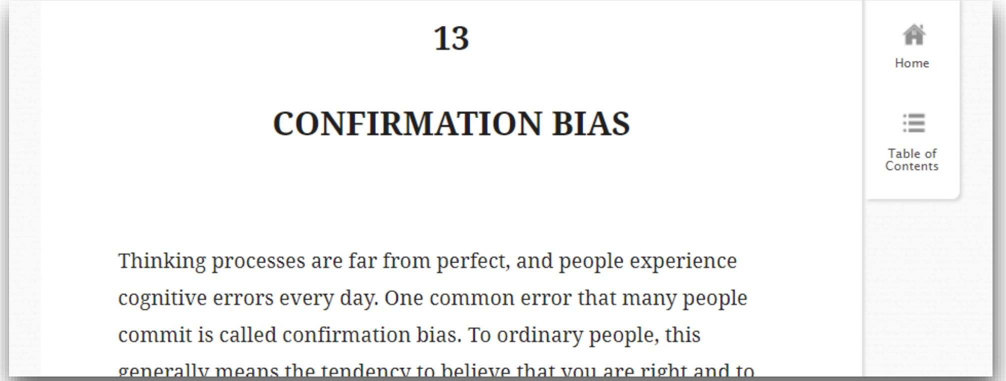
Science and Engineering Ethics (1995) **1**, 403-416

Truth and Trustworthiness in Research

Caroline Whitbeck *Massachusetts Institute of Technology, USA*

Keywords: trust, responsibility, misconduct, graduate students, recklessness, lies

Abstract: *We have recently reached a watershed in the research community's consideration of the ethics of research. The way is now open for a more nuanced discussion than the one of the last decade in which attention to legal and quasi-legal procedures for handling misconduct dominated.* The new discussion of ethical issues focused on*



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CONFIRMATION BIAS

Thinking processes are far from perfect, and people experience cognitive errors every day. One common error that many people commit is called confirmation bias. To ordinary people, this

LAB UNIT 1: *SECOND HOMEWORK*

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Question 4

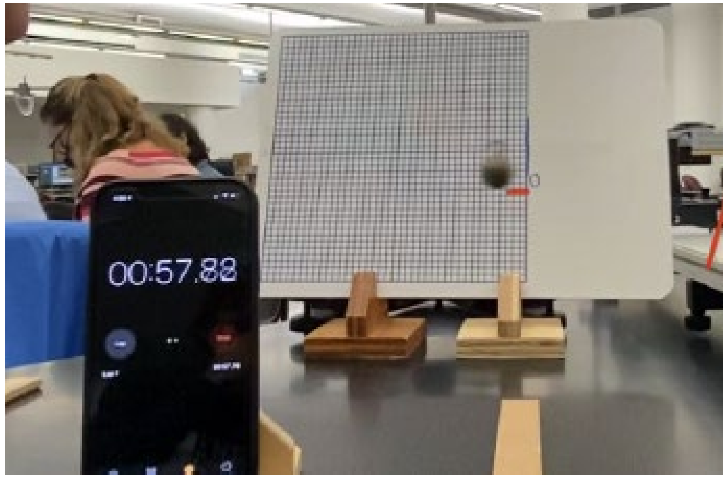
Was there anything about your expectations, the way the lab was presented, or your prior experience that you think made you more likely to look for confirming rather than disconfirming evidence? If so, what?

Question 5

Propose two actionable strategies you can implement in future lab activities to manage your expectations and mitigate biases. Explain how these strategies would mitigate bias and why you should implement them.
Your proposal and explanation should be between 75 and 150 words.

LAB UNIT 1: *SECOND LAB SESSION*

- Students develop actionable strategies to mitigate their biases.
- Investigate the limitations or assumptions of the model with high-precision experiments.
- **Example research questions**
  - *"Are the periods of the two angles distinguishable because of air drag?"*
  - *"Will measuring the period with video capture instead of a stopwatch result in higher precision?"*



Supplemental Material

Lab Check-ins, Rubrics, and Instructor Support

LAB UNIT 1: *LAB ASSESSMENTS*

- **Lab Assignment**
  - During the lab sessions, groups document all their experimental designs, data, analyses, and decisions in a digital **lab notebook**.
  - The **lab rubrics** specify the criteria on which the groups' lab notebooks will be assessed.
    - These criteria assess the groups' empirical skills and quantitative critical thinking abilities

Experimental Uncertainty (Mitigation) Is able to decide how much data to collect to obtain a desired uncertainty or range of measured values, and determine ways to reduce sources of uncertainty, systematics, or procedural mistakes L.O. 1.2.1	**5 pts** **Sufficient** The group's data collection decisions are clear and justified, and the group lists ways to reduce the sources of uncertainty. As they collect data, the group describes, justifies, and carries out reasonable ways to further reduce uncertainty. The group supports their justifications with data.	**3 pts** **Needs Improvement** The group's data collection decisions are detailed and somewhat justified, and the group lists ways to reduce the sources of uncertainty. However, as they collect data, the group does not attempt to reduce their uncertainty further; or, the group describes ways to reduce their uncertainty further as they collect data, but their data insufficiently justify their decisions.	**1.5 pts** **Inadequate** The group's decisions and data collection are sparsely detailed and rarely justified. As they collect data, the group does not attempt to reduce their uncertainty further.	**0 pts** **Not Yet Applicable** Groups will be asked to include this content in the next session of the unit.	5 pts

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Experimental Iteration Is able to iterate on an experimental investigation to progress the investigation forward to the next stage of inquiry L.O. 3.2-3.3	**10 pts** **Sufficient** The group proposes, conducts, and justifies follow-up investigations based on previous results and observations. Follow-up investigations creatively seek to explore, understand, and push the limits of the initial investigations. Or, they attempt to resolve obvious anomalies and problems with the initial investigation.	**6 pts** **Needs Improvement** The group proposes follow-up investigations, but they either do not conduct these investigations or do not justify them based on previous results and observations.	**3 pts** **Inadequate** The group does not propose or conduct follow-up investigations. Or, the group ignores obvious problems or anomalies in their initial investigation.	**0 pts** **Not Yet Applicable** Groups will be asked to include this content in the next session of the unit.	10 pts

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- **Lab Check-ins**
  - The lab instructors periodically check in with each group during the lab session and provide suggestions and feedback.
  - Instructors use a **check-in rubric** to formally assess each group's productivity, justifications, empirical scrutiny, responsiveness, sand overall teamwork.

Criteria	Ratings		Pts
Productivity	**1 pts** **Sufficient** The group appears to be keeping busy, moving along productively, and not wasting time.	**0 pts** **Insufficient** The group appears to be mostly off task or not working productively.	1 pts
Justification	**1 pts** **Sufficient** The group appears to understand why they're doing what they're doing.	**0 pts** **Insufficient** The group does not appear to understand or cannot clearly communicate why they are doing what they are doing.	1 pts
Empirical Scrutiny	**1 pts** **Sufficient** The group uses empirical methods to scrutinize a model, explanation, or claim effectively. For instance, the group attempts to reduce uncertainty to distinguish results or adjusts their data spacing to perform a more thorough examination in a specific data range.	**0 pts** **Insufficient** The group tries to scrutinize a model, explanation, or claim, but they use ineffective or ineffectual methods. Or, the group does not attempt to scrutinize a model, explanation, or claim.	1 pts
Responsiveness	**1 pts** **Sufficient** The group responds to interesting or unexpected results by changing their methods, exploring alternative explanations, or performing additional experiments. Or, the group responds to setbacks or issues positively and constructively.	**0 pts** **Insufficient** The group encounters interesting or unexpected results, but they overlook them or make no attempt to explore them further. Or, the group responds to setbacks in a non-constructive manner	1 pts
Teamwork	**1 pts** **Sufficient** The group is capitalizing on all group members (i.e., parallel processing). All students in the group can clearly and accurately answer their instructor's questions about the group's experiments and decisions.	**0 pts** **Insufficient** The group is not capitalizing on all group members. (For instance, one group member does all the work while the other members are not contributing.) Or, all group members cannot answer the instructor's questions about the group's experiments and decisions.	1 pts

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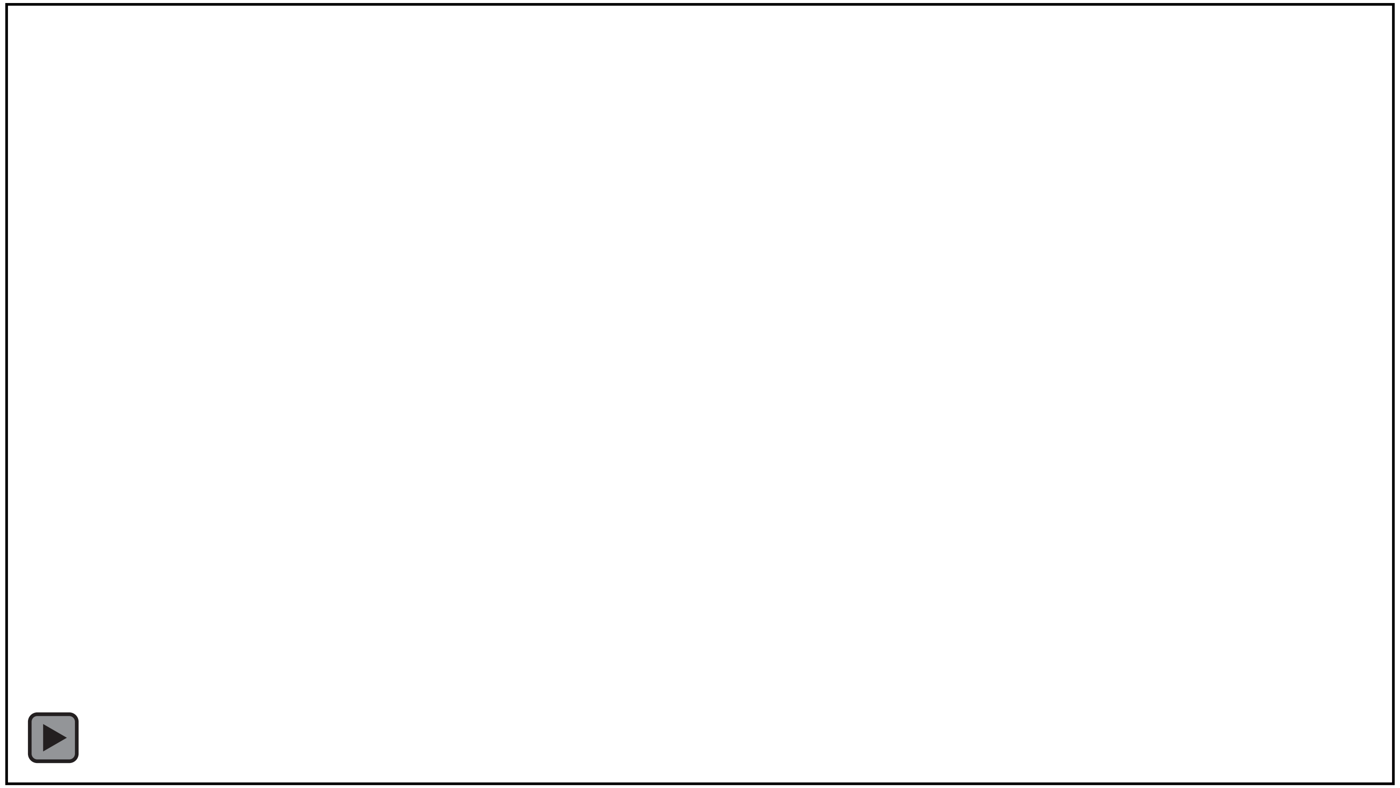

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+0:00-0:10 - Class-wide Discussion and Brief Announcement

+0:10-1:00 –Group Work: Sections 1.1.1-1.1.3; Lab Check-ins

+1:00-1:10 –Class-wide Discussion about Cycle of Experimentation

+1:10-1:50 –Group Work: Finish Unit 1.1; Finish Lab Check-ins

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1. Discussion: Lead a call-and-response about quantifying uncertainty and the mathematical tools they should use.

1. Discussion: Ask for 1-2 volunteers to discuss their high-precision experiments, their results, and how use their results to plan the next iteration of their experiment

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- [Teamwork and Productivity]

1. **What are you doing?**
   - Recommended Sub-Questions
     1. How have you been using all your team members to ensure that you can finish your experiments before the end of the lab session?
     2. Explain your experimental design for your high-precision experiment.

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- [Empirical Scrutiny]

  1. **How are you reducing your experimental uncertainty so that you can better scrutinize the model?**
     - Recommended Sub-Questions
       1. Are you trying to reduce your experimental uncertainty? Why should you try to reduce uncertainty?
       2. What methods are you using to reduce your experimental uncertainty?

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- How to challenge their **claims, explanations, and justifications**
  - Students will often make claims based on their prior beliefs. Any time a student makes a claim, demand that they provide evidence to justify their claim, preferably a quantified justification (e.g., the uncertainty in their mean measurement, the results of a t'-test test, etc.). For instance, ask them either, "Can you quantify that?" or "Show me the evidence."
  - The following statements are all quantifiable claims:
    - "This is/isn't working."
    - "This is a major/minor source of uncertainty."
    - "These measurements are/aren't distinguishable."

References

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