Unit 1: Pendulum for Pros

**Course-wide Learning Goals:**

By the end of the three-course intro lab sequence, students should be able to:

1. Collect data and revise the experimental procedure iteratively, reflectively, and responsively,
2. Evaluate the process and outcomes of an experiment quantitatively and qualitatively,
3. Extend the scope of an investigation whether or not results come out as expected,
4. Communicate the process and outcomes of an experiment, and
5. Conduct an experiment collaboratively and ethically.

### Objectives:

By the end of these activities, you should be able to:

* Conduct an experiment to confidently evaluate whether the angle of amplitude affects the period of a pendulum
* Identify sources of statistical uncertainty, instrumental precision, and systematic effects
* Decide what and how much data are to be gathered to produce reliable measurements given the set of concerns above
* Define and calculate the mean, standard deviation, and the standard uncertainty in the mean of a set of data
* Compare measurements with uncertainty by calculating the difference in units of uncertainty
* Propose and carry out follow-up investigations or revisions in light of the data and model, particularly to improve the reliability of the data

**Pre-Lab Activity I (Due the day before your lab section during the week of Insert Date at 11:59pm):**

*Answer the following questions using your own opinions, experiences, and knowledge. Please do* ***not*** *use outside resources.*

1. What is a measurement? Thoroughly explain your definition of a measurement.
2. In your previous courses with lab components (e.g., biology, chemistry, physics), in what ways have you used and/or explored measurements?
3. Two engineering teams are measuring the distance from one riverbank to the other as part of the development process of plans for a new bridge. Both teams use the same procedure and apparatus. One team finds that the distance is and the other finds that the distance is . In what ways can they compare their measurements of the distance? Do their measurements agree or disagree?
4. Your lab partners are in an argument over the mass of a cart that you’re using in the physics lab. One lab partner is convinced that the cart’s mass is . However, your other lab partner argues that the mass is . Your TA is kicking you out since your lab period is ending, so there’s no more time to take additional measurements of the cart’s mass. How are you going to reconcile their argument? Why?
5. You and your friend decide to measure the acceleration due to gravity in Ithaca. After carefully developing an experiment that minimizes the effect of any forces other than gravitational force (i.e., measuring the acceleration of an object in free fall), you measure the acceleration due to gravity to be . However, when you look up the value for Ithaca, you find that it is listed in a textbook as (W.D. Henderson, *Physics in Everyday Life*, p. 27, 1921). Which measurement do you think is better? Explain your reasoning. What additional information would enable you to make a better judgment?
6. How do you know if an experimental result is acceptable or trustworthy? What gives you confidence that your data is trustworthy?

**Pre-Lab Activity II (Due the day before your lab section during the week of Insert Date at 11:59pm):**

1. Use the provided data on LabArchives to compare the period of the pendulum at 10 degrees and 20 degrees. Describe the decisions you make to compare the periods. Describe at least two new ways to improve the provided measurements. Discuss how you plan to improve your own results during this week’s lab period and describe why you chose that plan.
2. Reflect on your findings and process from last week. What did and didn’t go as expected? How did you respond? What new questions do you have as a result of your investigation? What will you do next? How will you improve your measurements?

Week 1 Warm Ups (5-10 minutes):

Warm-ups are intended to start class-wide discussions to set the stage for a student-centered environment where the instructor is the facilitator rather than the provider of information. Facilitate a whole class discussion about students’ answers to the pre-lab questions. Through this discussion, don’t provide students with definitive answers but encourage all students’ answers. Facilitation questions may include:

* How did you all compare the engineering teams’ measurements? Did they agree with each other? What should their next steps in the project be?
* What ideas did you all have about the lab group? How would you handle that situation? What would you do during lab if there had been more time?
* Which measurement of the gravitational acceleration in Ithaca was better? Why? What else did you want to know?

Prompting groups to “respond” rather than volleying the conversation between instructor and individual students may shift the conversation over to the students.

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| **Instructor Time Stamp: 45 minute maximum Activity I: Introduction to Measurement** |

Whenever we collect data, it’s always important to make sense of the data. There are a lot of ways and tools to do this. Today, we’re going to talk about making sense of data through comparisons. First, let’s get some data to play with:

1. **Thinking about measurements**

As a class, individually measure the period of the same pendulum by recording the time for the pendulum bob to move through a single period starting from its highest position. Record your measurement for the period on the board. Do this again, this time recording the time for the bob to move through a single period starting from its lowest position. Record this measurement as well, keeping the two data sets separate.

1. **Making pictures**

Use one pendulum. Place the pendulum in an easily accessible area of the room and set it swinging at a small amplitude. Have students make measurements of the period of the pendulum at its highest and lowest position. Every student must record one or two measurements at each position on the board in a single column.

NOTE: For comparison, measurements need to be from the same pendulum during the same swing. Using a small angle reduces the chances of student concern that the amplitude changes over time. BUT the fact that later periods may be different from earlier periods would be a good discussion if it comes up.

If precision has emerged as a discussion in the warm-ups, you may begin this activity by asking students to predict whether their measurements of the period will be more precise when starting at the highest or lowest position. Defining precision and accuracy is not always necessary at this point in the lab but should be addressed later on.

Having students actively taking measurements allows the class to begin a conversation of what was "easy" or "difficult" about taking the measurement from each location. You ask the class to consider whether measuring from the highest or lowest point will be more precise. They develop a “reliability index” later, so you should not provide a definitive answer. Students can perform the calculation with the index.

Work in pairs to invent a way to **graphically** **compare** the period of the pendulum in the two cases, using the data that the class collected. There is more than one way to do this, so be creative! Sketch your pictures on a board and briefly describe how you came up with the representation and what it tells you.

We will have a group discussion about everyone’s inventions.

Try to encourage students to be creative rather than leading them to a particular representation of the data. Key phrase: "There is no bad idea or wrong answer." Use whiteboards to make it seem less formal. Having a multitude of representations will allow you to engage the whole class in a discussion of the affordances and limitations of each representation.

After groups have developed rough sketches, pause the class for a whole class discussion. Begin with discussing affordances of representations. Students need to feel that class conversations are productive rather than critical. Praise groups who are especially creative to establish classroom norms where creativity is appreciated and applauded. Use this discussion to guide students to the idea that a histogram is often a productive way of looking at and comparing measurements. Histograms will be most helpful moving forward in this lab.

Common pictures:

Scatter plots - students invent an x-axis that is the order of the items in the table, and plot vs period on the y-axis. Pros: can see trends over time if ordering is meaningful (and not random), can get a sense of centrality. Cons: hard to see spread (especially depending on y-axis scaling), gets annoying with lots of data points, odd to compare data sets with very different numbers of measurements.

Box & whisker diagrams - x-axis = condition, y-axis = period. Mean or median are drawn as a line, then something like quartiles or stdev are the end points of the box, with full range drawn as the "whiskers". Pros: centrality and spread, concise. Cons: spread is very coarse, can't see amount of data (e.g. if one set has 3 data points and the other has 100, info is lost), can't see trends (if meaningful)...

Histograms - x-axis = period, y-axis = frequency. Pros: centrality, spread, amount of data, concise. Cons: can't see trends (if meaningful)

Number line - x-axis = period (no y-axis), each period measurement is marked on the number line. Pros: centrality and spread (sort of). Cons: hard to compare

**C. Quantifying our pictures**

Now that you have created a graphical representation of the pendulum data, a decision needs to be made concerning which measurement method is the most reliable (i.e., consistent). Invent a **quantitative** procedure for calculating a ‘reliability index’ for each of the methods to determine how **reliably** they measure the pendulum period.

The goal, once again, is to be creative. Write down your procedure and calculate the ‘reliability index’ for each group using the class’ data. The only rules are that:

1. You use the data collected from Part I and the graphical representations.
2. Each measurement set gets a single ‘reliability index’.
3. The same procedure must be used for each data set to determine its ‘reliability index’ and make a fair comparison.
4. A small ‘reliability index’ implies that the measurements are more reliable.

Instructors can take a step back from involvement with students' initial experimental design. If students have questions, answer in a way that will allow them to take ownership of the experimental design process. For example, you can say "you all are the scientists, and those are your decisions" or "I evaluate you on your process rather than your results, so record your reasons for making these decisions and reflect on your results to improve the experiment".

Encourage creativity in this quantitative activity. If some groups are struggling, it may be helpful to pause groups to have students develop a list as a class of the factors they are considering when developing their quantitative procedure of reliability. If all groups appear to be converging on a quantitative procedure, then ask several groups to explain their procedure to the class. Develop a list of "features" that need to be considered (e.g., number of data points, how far data are from each other, keeping things positive). From students' contributions and their quantitative procedures, develop the expressions for the standard deviation and the standard uncertainty in the mean.

Suggested segue between standard deviation to standard uncertainty in the mean: The stdev tells us, on average, how far are the data points from the average. So if we took another data point, it will likely fall within the stdev from the mean. That means that the uncertainty on any single measurement is the stdev.

* What do you trust more though: a single measurement or the average of a collection of measurements? {the average} Why? {Because there's more data}
* So we want the uncertainty in the mean to be smaller or bigger than the uncertainty in a single data point? {smaller} An easy way to do that is to divide by the number of points, but we divide by the square root of the number of points (because statistics...)

Carefully distinguish between use of standard deviation and standard uncertainty. See statistics summaries for the definitions that we are using in these courses.

Please do NOT use "error" in your language; we are consistently avoiding language that includes "error" in these labs to avoid students' conflation of mistakes and uncertainty.

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| **Activity II: Investigating Period of a Pendulum** |

The goal of this activity is to evaluate whether the period of a pendulum depends on the angle of amplitude of the swing.

1. **Initial investigation**

Write down a plan for a high-precision measurement of the period of a pendulum at amplitudes of 10 degrees and 20 degrees. Include a clear description of how you will determine the uncertainty in your measurements. Use the earlier discussion and even the data collected to inform your decisions.

Carry out your plan to measure and compare the period of the pendulum at 10 and 20 degrees using the methods discussed at the end of Activity I. What does the comparison mean or suggest?

**B. Quantifying comparisons**

Now that we have a statement about the reliability of a data set and high-precision measurements of the period of a pendulum, we want to determine whether the period of the pendulum is the same at 10 degrees and 20 degrees, or if one is systematically different from the other.

Work with your group to come up with a way to **quantitatively compare** the period of the pendulum at each amplitude. Focus on inventing a method to quantify how **distinguishable** the two data sets are. To get started, come up with a list of features of the data that are important to consider in making this comparison.

Begin by having students determine the mean and standard uncertainty of the two sets of pendulum period measurements. Ask them to develop a way to quantitatively compare the two measurements of period. Ask students to extend their quantitative comparison to include any measurements by sketching the [contrasting cases](http://sqilabs.sites.olt.ubc.ca/files/2015/07/Comparing-measurements.pdf) on the board (graphs on next page). With the contrasting cases your students may recognize that the number of samples within each distribution needs to be the same to create distributions with comparable standard uncertainty in the mean. Choose the "N" to be the same number of students in the class so your "N" is equal to the "N" from the period of the pendulum.

The contrasting cases line from above contains all information needed about the t'-score, which we will use to compare measurements in this course. If some groups struggle with the task, pause the class and begin to solicit qualitative descriptions of important features that need to be quantified. For example, the "distance" between the means is required, as is the spread of the distributions. As groups finish quantifying their index to compare measurements, ask several groups to share their invention and reasoning with the class. By the end of a whole class discussion a quantitative index to compare two measurements emerges. Define t' to be the quantity that we use to make comparisons between two measurements.

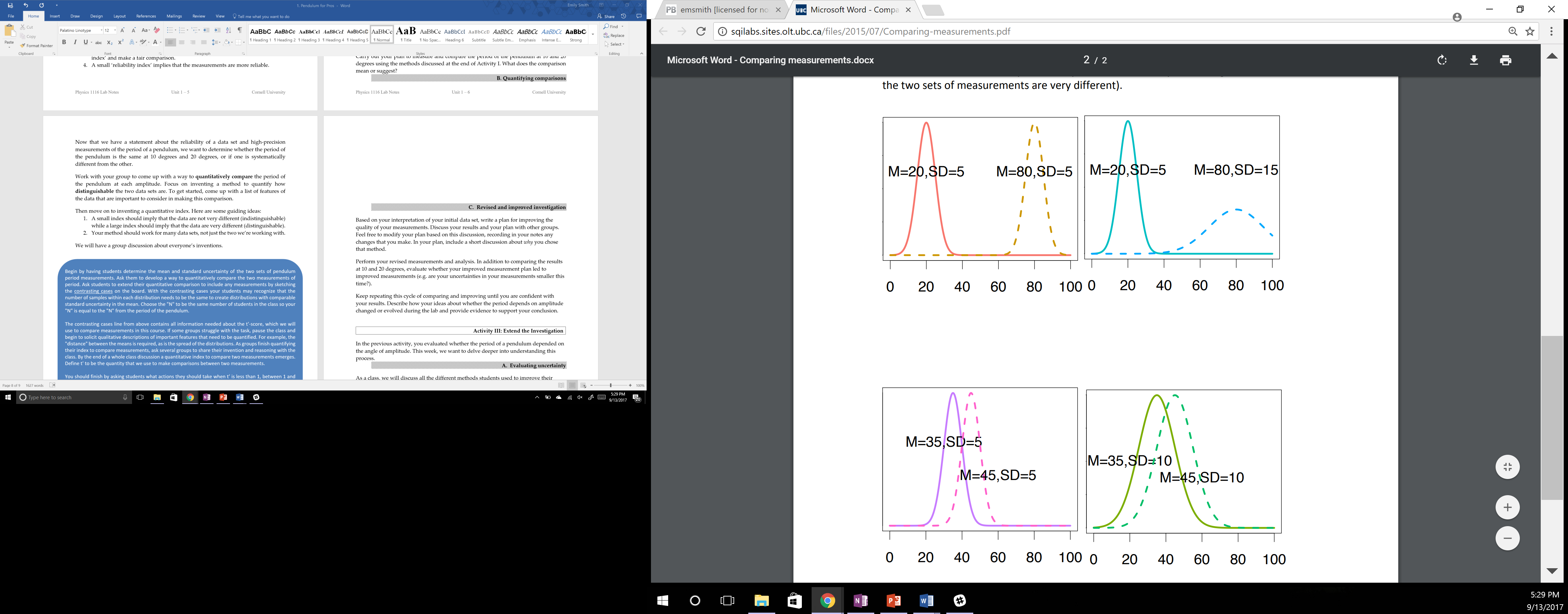
You should finish by asking students what actions they should take when t’ is less than 1, between 1 and 3, and greater than 1. In all cases “improve your measurements” should be emphasized as the “answer”. When t’ is less than 1, the uncertainty may be overestimated. When t’ is greater than 3, uncertainty may be underestimated or there may not be enough data to determine the “true” means.

Then move on to inventing a quantitative index. Here are some guiding ideas:

1. A small index should imply that the data are not very different (indistinguishable) while a large index should imply that the data are very different (distinguishable).
2. Your method should work for many data sets, not just the two we’re working with.

We will have a group discussion about everyone’s inventions.

**By the end of Week 1, students need (at minimum) to have completed this activity and arrived at t’ for the statistic to compare two measurements. They will practice statistics in the pre-lab.**



1. **Revised and improved investigation**

Based on your interpretation of your initial data set, write a plan for improving the quality of your measurements. Discuss your results and your plan with other groups. Feel free to modify your plan based on this discussion, recording in your notes any changes that you make. In your plan, include a short discussion about *why* you chose that method.

Perform your revised measurements and analysis. In addition to comparing the results at 10 and 20 degrees, evaluate whether your improved measurement plan led to improved measurements (e.g. are your uncertainties in your measurements smaller this time?).

Keep repeating this cycle of comparing and improving until you are confident with your results. Describe how your ideas about whether the period depends on amplitude changed or evolved during the lab and provide evidence to support your conclusion.

Allow students the chance to analyze and improve their data without extensive assistance. Encourage students to discuss their ideas with other groups and provide assistance to groups that are struggling to improve their data. Because this is early in the lab experience, many students may be hesitant or reluctant to share their ideas. Encouraging students to provide multiple ideas and approaches, then discussing the pros and cons of each of the ideas as a group may help students shift to viewing their ideas as part of a collective effort rather than an individual attribute. As an instructor, it may be helpful to keep asking "what else?" until students seem to exhaust all of their ideas before shifting to evaluation of ideas. This way, a list is built that contains either ideas from every group member or ideas that cover a large range from a single group member, but all members are involved in evaluating how to proceed.

They will find that increasing the number of swings, multiple measurements, and ??? will decrease the uncertainty in the measurement of the period. The damping should not have a large effect on measurements, and students may decide to test this by determining the amount of damping at set numbers of swings.

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| **Activity III: Extend the Investigation** |

**Instructor Time Stamp: At minimum, the final 30 minutes of Week 2 should be devoted to this activity. Some students may move on earlier than others, which is okay!**

In the previous activity, you evaluated whether the period of a pendulum depended on the angle of amplitude. This week, we want to delve deeper into understanding this process.

Lead a class discussion on evaluating the sources of uncertainty that groups identified in the first activity. It may be helpful to begin by asking groups to develop their own lists of sources of uncertainty and having them share these lists with the class. You can track the frequency with which each source of uncertainty is brought up by groups. This can lead to a whole class discussion of why certain sources of uncertainty were the largest contributors and the various ways in which groups minimized those contributions. Attempt to maintain a student generated discussion by asking students to respond to other's ideas; this is often achievable by calling on groups rather than individuals if no individual students are offering responses.

If there is a sea of confused faces and students are not able to contribute to the conversation, it may be helpful to ask students "How can I help you?" or "In your groups, come up something that you would like me to better explain or ask" before moving forward with the whole class conversation. As a facilitator, it can be helpful to keep asking questions or prompting responses rather than providing students with definitive conclusions. After the whole class discussion, provide a summary of what students determined and you can provide a judgment. This judgment could be agreeing with the student conclusions, identifying a source of tension among students' discussions and asking them to pursue a test to resolve this tension, or providing a brief, clarifying lecture.

1. **Evaluating uncertainty**

As a class, we will discuss all the different methods students used to improve their uncertainty in the previous activity. What was the main source of uncertainty in the measurement? Based on this discussion, describe the best ways you can reduce the uncertainty in the measurement of the period of a pendulum.

1. **Uncertainty in the amplitude dependence**

Many students found that the period of the pendulum was different at the two angles. Work with other groups of students to come up with possible explanations for why these two measurements were different. The rest of the lab will involve designing and carrying out experiments to test these explanations.

An important thing to consider as you design your experiment is: what evidence will you need to come up with a convincing argument one way or another? For example, what quality of uncertainty will you need and how can you achieve it? What comparisons between data can you make?

Many of the groups will determine from the previous activity that the period of a pendulum is different at 10 and 20 degrees, however, this result contradicts the model. Students must then try to test explanations for why there is a difference in the period of a pendulum at different angles. Emphasize the process of iterative experimentation rather than students' arrival at the "correct" answer. If students are quickly able to come to a conclusion with evidence to support that the model assumes the angular displacement is small, then urge students to explore the limits of their findings, which might include evidence to determine how small is "small enough", whether changing the length of the string affects "small enough", etc.

As with the last activity, after coming up with and testing an initial plan, evaluate your data and find a way to improve based on your comparisons. Record all of your decisions in your lab notebook.

The goal, by the end of the lab, is to have confidence in an explanation for why (or whether) the periods of the pendulum were different that is supported by evidence. (This can also involve evidence that shows that an explanation is not correct.)