Are You Certain?

Teaching error analysis and other experimental skills in the physics classroom

David Bonner

Conducting labs isn't a new way to teach physics, but labs have become increasingly prevalent with the rise of inquiry. Physics students collect mostly quantitative data, often represented by graphs or tables. Interpreting this data can be a challenge for students, especially when it comes to experimental error. To address this issue, this article describes a way to teach error analysis and other important experimental skills in the classroom.

The purpose of experiments in learning

From a learning perspective, experiments serve one of two purposes—verification or discovery. Verification experiments are application based and reinforce concepts that students have already learned. Discovery experiments are inquiry based; in these experiments, students pursue answers to questions. Both types of experiments are important in the science classroom, but this article focuses on how to use discovery experiments to maximize learning.

The role of experiments in teaching

From a teaching perspective, experiments serve as either teaching structures or curricular objectives. As a teaching structure, experiments offer a hands-on way of learning science content. For example, we can teach the concept of acceleration by having students investigate the motion of a marble rolling down an inclined track. As a curricular objective, an experiment has the purpose not of teaching acceleration or some other scientific concept but teaching how to do experiments. In physics, one important aspect of that is learning how to assess experimental error by conducting or analyzing repeated identical trials.

Error analysis: A critical skill

Students must learn how to conduct discovery experiments, and teachers must scaffold and support the development of the necessary skills throughout the year. One skill that should be mandatory for all students to develop is error analysis.

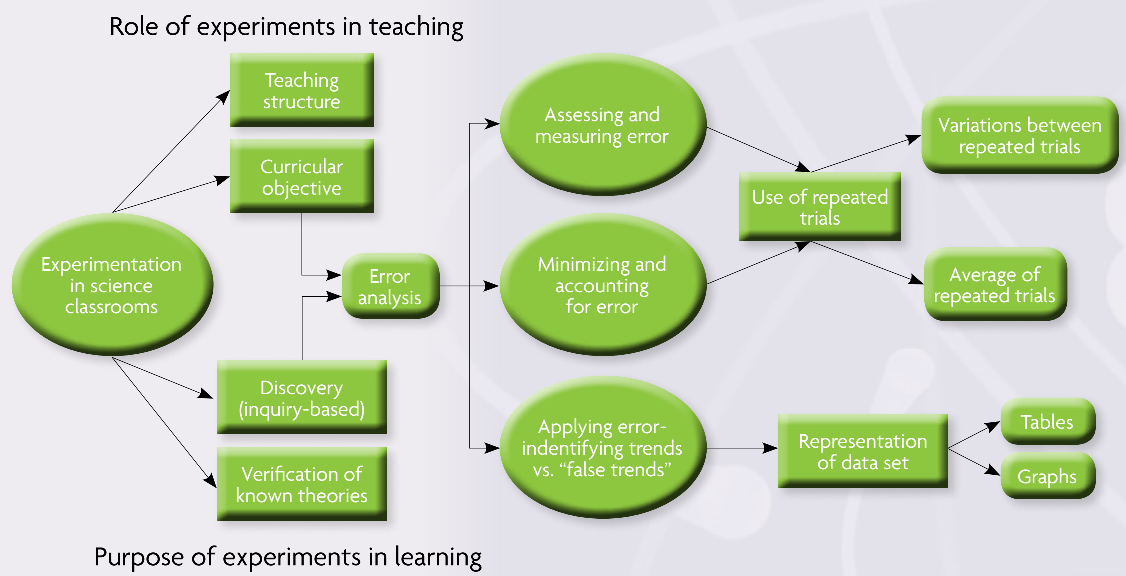
Giving students hints to minimize error isn't enough; they must learn to reduce and interpret error on their own. As shown in Figure 1, there are three fundamental aspects of error analysis:

1. assessing and measuring error (i.e., quantifying error),
2. minimizing or accounting for error; and
3. applying error (i.e., identifying the correct trend in data or distinguishing a true trend from a false trend).

From these, teachers can focus on several more specific skills that students need to conduct experiments and investigations. Teachers introduce these skills at the beginning of the year and then support and develop them

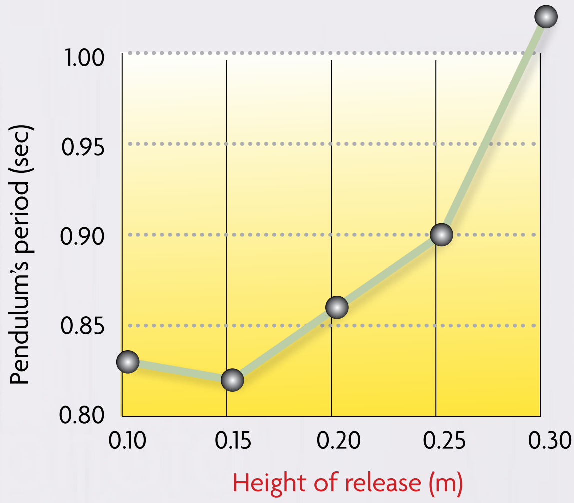
FIGURE 1

Experimentation in the science classroom.



Why teach error analysis?

Data set	
T (sec)	H (m)
0.83	0.10
0.82	0.15
0.86	0.20
0.90	0.25
1.02	0.30



Consider the sample data at right, collected from an investigation in which the period of a pendulum was measured when released from five different heights.

A student might have trouble interpreting the meaning of this data. For instance, without projecting any background knowledge onto the data, one might consider the relationship or trend to be either nonlinear or to have a linear trend with a slope of zero—indicating a noncovariant relationship (i.e., the independent variable doesn't affect the dependent variable). This example reveals three potential problems that arise in any pedagogical approach that encourages learning through experiments:

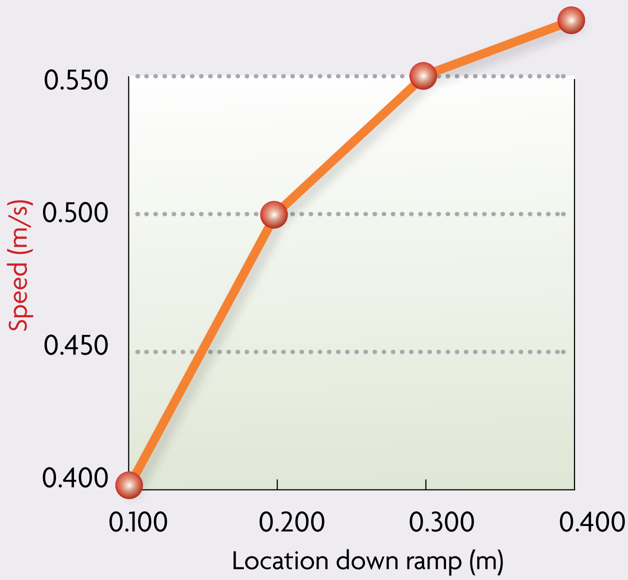
1. Any quantitative experiment data collected from measurements is subject to error that is unavoidable and at least partially unpredictable, especially when students are collecting data.
2. Students struggle to correctly discern true trends from false trends (Kanari and Millar 2004). This idea is exemplified in the graph above: It appears to have a nonlinear trend, but it actually represents a noncovariant relationship in which the nonlinear appearance is solely due to experimental error (random or systematic), or a false trend. The variation in this graph's period—the time value measured with a stopwatch—doesn't exceed 0.2 seconds. Therefore, the variation that appears to be nonlinear can be attributed to random error from using a stopwatch, which is a numeric value obtained from analyzing the variation in the repeated trials' data. In my experience, it is common for the difference between the largest and smallest stopwatch measurements within repeated trials at a single height to be approximately 0.3 seconds, which exceeds the variation within the data set plotted in the graph and justifies why this is a false trend. This presents a profound problem because it can actually reinforce student misconceptions instead of debunking them.
3. A low level of student autonomy in experiments limits the level of inquiry and sophistication used to learn scientific concepts. Correctly interpreting and applying error to data sets heightens students' level of autonomy and influences how open ended the level of inquiry can be. I've often heard from colleagues that open-ended lessons require too much instructional time and create confusion, causing students to disengage and become off task. However, teaching proper error analysis is part of teaching students how to do inquiry and can actually reduce off-task behavior and the time needed to conduct subsequent investigations. In any inquiry-based activity in which students collect and interpret numerical data (i.e., all quantitative experiments), the effects of error on data points, data sets, and relationships become significant and must be taught for the activity to be fully effective.

As students learn these skills, subsequent inquiry activities become not only more meaningful but also more efficient: Students are able to pursue their own inquiries in a coherent and systematic way. Applying experimentation skills, such as error analysis, increases the level of student autonomy in pursuing their inquiries through experiments and is therefore a primary determining factor in the debate over how open-ended inquiry lessons should be. The more student autonomy, the more open-ended, meaningful, and time-efficient an inquiry lesson can be; therefore, teaching scientific practices, such as error analysis, is integral to student inquiry and experimentation.

FIGURE 2

Sample test question.

A team of students measures the speed of a marble at different locations on a ramp, using a meterstick and a stopwatch. These measurements are all listed in the “Data set” table below. The team completes four trials at the 0.200 m location and plots the average value (0.560 m/s) in a graph (below). The values for the repeated trials at this location are shown in the “Repeated trials” table.



Data set

x (m)	Speed (m/s)
0.100	0.410
0.200	0.510
0.300	0.560
0.400	0.580

Repeated trials

Location (m)	Speed (m/s)
0.200	0.562
0.200	0.560
0.200	0.559
0.200	0.561
Average	0.560

The team then finds themselves in a disagreement. One student, Bob, argues that the curved trend isn’t actually a trend and may just be a change due to random effects of error. Another student, Sue, claims that the graph is a trend and is supposed to be curving; therefore, it would need to be fit with a curve. Who is correct?

throughout. In my physics classes, I teach three skills to address and minimize error:

1. maximizing the range of independent variables;
2. collecting many data points within that range; and
3. conducting repeated trials at a particular data point or points.

I teach these skills to increase students’ confidence when they are unsure what trend to expect in their data sets. That way, during experiments, when students question “Am I doing this right?” I can simply ask what they can do to increase confidence in their data.

Accountability and assessment

Teachers should treat experimentation skills as content—teaching and assessing them like any other curricular objective so that students can practice and develop their skills over time. One way to do this is to demand that students have confidence in their data patterns for each experiment. To gain confidence, students must consistently practice these skills, which requires a high level of engagement during and after experiments.

Assessment holds students accountable and measures their development. Sharing student groups’ results with the class in some manner, instead of merely grading written lab reports or handouts, can increase engagement. Students can also periodically perform a lab practicum in which they have to demonstrate—and are graded on—their experimentation skills.

Test questions that require students to apply these skills can also increase accountability and measure growth. These questions can be tricky to write: The key is to create a question that parallels the experiment, or how the experiment is done, and directly tests an experimentation skill. Figure 2 provides a sample test question from my physics unit on acceleration.

In my classes, students conduct repeated trials on at least one data point to estimate error. Though more sophisticated statistical methods exist, for simplicity’s sake, students describe error as the range between the highest and lowest values for the dependent variable. In reviewing the “Repeated trials” table in Figure 2, a student using this method would assess the error to be 0.003 m/s (the difference between the highest [0.562 m/s] and lowest [0.559 m/s] speed). By comparing this value with the amount of change in the dependent variable, as seen in the data set table or graph (lowest of 0.410 and highest of 0.580, which yields a change of 0.17 m/s), a correct student would say this trend is significant since the change in dependent variable (0.17 m/s) far exceeds random variations that could be caused by error (0.003 m/s).

FIGURE 3

Follow-up experiments.

Lesson planning

In lesson planning, allow the time and space for students to make and fix mistakes. Students will have error in their data sets—this is an unavoidable aspect of conducting experiments. Instead of giving students hints for how to set up or conduct the experiment to minimize error, help them learn general practices for increasing confidence in their data—this makes both the activity and the learning more meaningful.

Teachers should also provide follow-up experiments (Figure 3). These don't need to be exactly the same as the initial experiment, but they should provide an opportunity for students to put teacher feedback into practice. Don't allow too much time for the experiments—20 minutes is enough time to collect and interpret data. This is especially true for the first few experiments, when students are learning scientific practices and experimentation skills. During these initial experiments, students can become confused quickly. Provide feedback and support and then ask them to complete a similar follow-up experiment.

The need for follow-up experiments diminishes as students develop experimentation and error analysis skills. Once students acquire these skills, teachers can teach other science content through more open-ended inquiry. Figure 4, for example, outlines the first four days of the physics of waves unit in my junior-level physics class. Once my students have mastered error analysis, they conduct three experiments in four days that include data collection and interpretation, class discussion, and lecture notes.

FIGURE 4

Sample outline of waves unit.

Slinky Experiment I: Determine relationship between wave height and wave speed.

Day 1: Collect data (last 20 minutes of class).

Day 2: Analyze data and form a conclusion backed by evidence.

- Class discusses the results and teams share their results.
- Lecture notes summarize the experiment and its conclusions (underlying concepts).

Slinky Experiment II and III: Determine relationship between wave period and wave speed (half of the class) and slinky length and wave speed (half of the class).

Day 3: Collect data (last 25 minutes of class).

Day 4: Analyze data and construct conclusions backed by evidence.

- Class discusses the results and teams share their results.
- Lecture notes summarize the experiment and its conclusions (underlying concepts).

Conclusion

By the end of the first quarter, students can often fully demonstrate their analytical and experimental skills and form inferences and conclusions based on authentic evidence and data. Time devoted to developing these skills is well spent: Experiments are conducted more quickly, and less time is needed to reteach concepts from experiments that go awry. Good experimentation skills make teaching more efficient and allow for deeper conceptual understanding. Students learn to think critically about data, an important skill in any science investigation involving quantitative measurements. Implementing experimentation and error analysis as a curricular objective, and not just a teaching structure, can make all the difference. ■

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Reference

Kanari, Z., and R. Millar. 2004. Reasoning from data: How students collect and interpret data in science investigations. *Journal of Research in Science Teaching* 41 (7): 748–769.