ACTIVITY 4

# Reducing Error in Experimental Design

LABORATORY

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## ACTIVITY SUMMARY

**Students investigate local air quality by designing a lab to collect particulate matter data. They work to identify sources of scientific uncertainty in their experiment as they are formally introduced to random error and systematic error. By identifying errors, students consider how to reduce them and increase the certainty of their findings.**

ACTIVITY TYPE
LABORATORY

NUMBER OF
40–50 MINUTE
CLASS PERIODS
2-3

## KEY CONCEPTS & PROCESS SKILLS

1 Uncertainty in data is often a result of errors. Scientific errors can be random or systematic and can lead to conclusions that are less likely to be correct.

2 Scientific methods can reduce sources of uncertainty. Techniques to reduce random error include taking repeated measurements and averaging across many samples. Techniques to reduce systematic errors include calibrating equipment more carefully and designing investigations to control for other factors that could influence the results (*confounds*).

**NEXT GENERATION SCIENCE STANDARDS (NGSS) CONNECTION:**
Consider limitations of data analysis (e.g., measurement error, sample selection) when analyzing and interpreting data. (*Science and Engineering Practice: Analyzing and Interpreting Data*)

CONCEPTUAL TOOLS

## VOCABULARY DEVELOPMENT

**random error**

a difference between an observed and true value that has no consistent pattern and is caused by chance and/or unpredictable factors

**systematic error**

a difference between an observed and true value in a consistent direction, often caused by experimental equipment or design

## TEACHER BACKGROUND INFORMATION

### Types of Scientific Error

Scientifically accepted values are scientists' current best approximations, and they are affected by two types of errors: systematic and random. Systematic error results in measurements that are consistently different from the true value in nature, due to limitations of either the measurement tool or the procedure. It is often caused by instruments that consistently offset the measured value from the true value, like a scale that always reads 2 grams too high.

Random error occurs due to chance. There is always some variability when a measurement is made. Random error may be caused by slight fluctuations in a measurement tool, the environment, or the way a measurement is read. It does not cause the same error every time. To address random error, scientists repeat a measurement many times and take the average.

Error cannot be completely eliminated, but it can be reduced by being aware of common sources of error and designing an experiment or making a measurement to reduce the amount of error that might occur. As information and technology improve and investigations are refined, repeated, and reinterpreted, scientists' understanding gets closer to describing what actually exists.

### Systematic Error and Random Error

Systematic errors lead to measurements that are different from the true value by a set amount in one direction. In contrast, random errors lead to measurements that are different from the true value by a random amount in either direction. Although both types of error result in an inaccurate measurement, they must be corrected for in different ways.

Random errors are often caused by chance fluctuations in an instrument or the environment that lower the precision of a measurement. The more variability from trial to trial, the less certain one can be of where the true value lies. However, because these types of errors cause measurements that are randomly higher or lower than the true value, they can be dealt with by running more trials and averaging the results. If the measurements are less reliable, there will be more variability in the data set, and more trials will be needed to bring the average closer to the true value.

Systematic errors do not affect the precision or reliability of a measurement. When a systematic error is present, it is possible for measurements to be very precise, with little variability, but also inaccurate because the measurements are shifted in a predictable way. Systematic errors cannot be corrected for by collecting more trials and averaging. These types of errors can only be dealt with by discovering the source of the error and eliminating it (e.g., recalibrating an instrument or removing a factor from the environment that was not controlled for). Alternatively, if it is impossible to remove the factor, and the size of its effect is well established, it can be subtracted from the measurement to estimate the true value.

## MATERIALS & ADVANCE PREPARATION

FOR THE TEACHER

- VISUAL AID 4.1 "Guidelines for Safety in the Science Classroom"
- BLEACH SOLUTION
- DISPOSABLE GLOVES
- PROTECTIVE EYEWEAR
- LAB COAT

FOR EACH GROUP OF FOUR STUDENTS

- MICROSCOPE (OR STEREOSCOPE)
- 9 PETRI DISHES
- PETROLEUM JELLY
- TAPE
- 9 INDEX CARDS
- PERMANENT MARKER
- GRAPH PAPER
- DISPOSABLE GLOVES OR FINGER GLOVES (OPTIONAL)

FOR EACH STUDENT

- 2 STUDENT SHEETS 4.1 "Frayer Model" (OPTIONAL)
- STUDENT SHEET 1.3 "Unit Concepts and Skills" (OPTIONAL)

Preview a 7-minute 30-second video titled *Statistical and Systematic Uncertainty* (on the topic of systematic and random error) produced for the college course Sense and Sensibility and Science, from which this high school course is adapted. Note that the script was written and narrated by 2011 Nobel Prize in Physics winner Dr. Saul Perlmutter.

There are numerous ways in which to design a classroom lab to collect particulate matter, including using index cards and packing tape if petri dishes are not available, purchasing Carolina® Biological Airborne Particulates paper, or even building a classroom air quality sensor. The activity in the Student Book provides one suggested method. Determine which method is most feasible for you, given your classroom resources and student population, and adjust the procedure accordingly.

Review any safety-related guidelines provided by your district and look over Visual Aid 4.1, "Guidelines for Safety in the Science Classroom."

Set up microscopes (or stereoscopes) for student use.

Prepare for disposal of all materials used in the activity. Petri dishes can be placed in a disinfecting bleach solution prior to reuse. Wear appropriate safety equipment, including protective eyewear and a lab coat, prior to handling bleach. Follow the directions on the bleach bottle for preparing a diluted bleach solution. If your bottle does not have directions, you can make a bleach solution by mixing 5 tablespoons (⅓ cup) of bleach per gallon of room temperature water or 4 teaspoons of bleach per quart of room temperature water.

While the petroleum jelly can be spread in the dish, using a clean finger, you may want to reduce contamination by providing students with disposable gloves or finger gloves (a tubelike cap that covers the end of a finger).

# TEACHING NOTES

Suggestions for **discussion questions** are highlighted in gold.

Strategies for the **equitable inclusion of diverse students** are highlighted in mint.

## GETTING STARTED (15 MIN)

1 **Introduce the concepts of random error and systematic error.**

- Ask students to share examples of errors that they have seen in scientific experiments, either experiments they have conducted or observed. Make a list of these examples on a whiteboard or projected screen.
- You may wish to show students the video segment titled *Statistical and Systematic Uncertainty.* It explains both statistical uncertainty (random error, or precision) and systematic uncertainty (systematic error, or accuracy). Review how the language used in the video corresponds to the concepts presented in this course.
- Use the Student Book Introduction to highlight the concept of random error and systematic error, which are formally defined in Procedure Step 13. Point out that systematic errors are consistent errors that tend to skew the data in one direction.
- Work together to identify examples of systematic errors in the student examples of errors in scientific experiments, which may include miscalibrated equipment (such as a scale that always reads too low), someone routinely pressing on a scale while taking the mass of a material, or an experiment that is designed with systematic error (such as routinely taking a person's temperature while they are talking or placing an air quality sensor near an outdoor dryer vent). Do the same with random errors, which are less predictable and, therefore, more difficult to address when designing an experiment.
- To support the development of new vocabulary and concepts during the activity, consider using a Frayer Model with students as shown on optional Student Sheet 4.1, "Frayer Model." For the concepts of random error and systematic error, the Frayer Model can be provided at the beginning of the activity, filled out as the activity unfolds, and reviewed at the end of the activity. For more information about the Frayer Model, see Appendix 1: Literacy Strategies. A sample student response for the Frayer Model for the terms *random error* and *systematic error* can be found at the end of this activity.
- If you have begun a word wall, support students, particularly emerging multilingual learners, in sensemaking and language acquisition by adding the terms *random error* and *systematic error.*

**2 Review classroom safety expectations.**

- Use Visual Aid 4.1, "Guidelines for Safety in the Science Classroom," to remind students to follow all classroom safety rules. Highlight the Safety Note in the Student Book.

## PROCEDURE (40–60 MIN + 3 DAYS to conduct experiment outside of class)

**3 Groups set up a control.**

- Depending on your student population, you may need to review the elements of good experimental design, including a clear hypothesis, well-defined independent and dependent variables, a control, control of extraneous variables, and proper data collection and analysis.
- In order to familiarize students with the laboratory materials and setup of the investigation and to guide their experimental designs, groups begin by setting up a control. Depending on your student population, it may not be necessary to conduct this step in advance.
- If students are not familiar with the term *control*, remind them that a control is a basis of comparison for checking the effects of an experiment. Comparing the experimental results with the control allows them to see if the variable they changed in the experiment caused any effect. In this lab, a control dish that is not exposed to air indicates that the particulates came from the vaseline or were already in the dish.
- In this unit, laboratories and card-based investigations use hands-on materials to support student learning. Certain student populations—including girls, gender nonconforming students, and introverted students—often take on roles in which they do not directly engage with hands-on materials, such as recorder and observer. Incorporate strategies to ensure that all students participate over time. For example, in activities such as this one in which students conduct the investigation in groups of four, one strategy is to assign roles (such as group leader, recorder, observer, and timekeeper) ahead of time and then rotate them periodically. Another strategy is to create specific groupings of four that might encourage greater participation. Decide which strategy you will use to best support your student population.

**4 Groups work together to design an experiment to test one factor related to local air quality.**

- Students should begin by discussing locations in which to place petri dishes and what question could be investigated, such as potential differences in air quality near and far from a highway or major road, indoor vs. outdoor, homes with or without pets, distance from a heating/air conditioning vent, street vs. backyard, distance from trees and plants, and so on.
- Students should consider the weather forecast when considering outdoor data collection.

**Sample Student Response, Procedure Step 3**

*The purpose of our experiment is to determine outdoor vs. indoor air quality in homes by measuring the PM2.5 levels. We hypothesize that the outdoor air will contain higher PM2.5 levels. Our group's procedure is to place open dishes containing a thin layer of petroleum jelly both outside and inside each of our 4 homes for 3 days. Our control will be a dish that is left unopened at school. We will monitor all the dishes to make sure they are left undisturbed. We will examine the results under a microscope to count the relative number of particles in the outdoor vs. indoor dishes and compare them to the control.*

- Students can record their experimental designs in their science notebooks.

5 **Groups brainstorm possible sources of random error and systematic error in their experimental designs.**

- While responses will vary based on the type of investigation that is being conducted, some sample responses are provided here.
- Procedure Step 3 lists several questions to help students design their experiments. A sample student response is provided.

**Sample Student Response, Procedure Step 4**

**Possible Random Errors**

- *Someone moved a petri dish during data collection.*
- *An open petri dish was dropped while bringing it back to class for analysis.*
- *A petri dish went missing.*
- *Counting dust on the objective lens of the microscope (or stereoscope) vs. particulate matter in the dish.*
- *Accidentally touching the objective lens into the petroleum jelly and reducing visibility, yet counting and recording data.*
- *Removing eyeglasses before using the microscope (or stereoscope) but not being able to see clearly through the objective lens.*

**Possible Systematic Errors**

- *Not using enough magnification on the microscope (or stereoscope) so the particulate matter is not visible and measurable.*
- *Using too high a magnification on the microscope (or stereoscope) so only a very small area of particulate matter can be seen and counted.*
- *Not using enough light on the microscope (or stereoscope) so the particulate matter is not visible and measurable.*
- *Designing an experiment to compare particulatet matter in an area with many trees (like a backyard) and a road (like the one alongside a front yard) without accounting for numerous trees in the front yard.*

- *Designing an experiment for homes with and without pets and placing the petri dish in an area that is not frequented by the pet, like a basement or a stairwell.*
- *Designing an experiment to test the particulate matter near a vent for a system that has been turned off for the season.*

- After identifying possible sources of random error and systematic error, students should plan to address them in their designs to reduce their likelihood, if possible.

6 **After conducting their experiments, groups examine their dishes and make conclusions.**

- When having students examine their collected data, you may need to review the use of microscopes (or stereoscopes) and appropriate rules for handling microscopes.
- If a petri dish contains too many particles for students to count individually, Figure 4.3 in the Student Book provides a sampling method. By using the same template for each dish, groups can count and then compare the number of particulates collected in different dishes. Note that two different templates are shown (Figure 4.3a and 4.3b); each group should only use one template for their data collection.
- In Procedure Step 12, students are instructed to analyze their data and make conclusions. Depending on your student population, you may need to provide additional support for this step. A sample student response is provided.

**Sample Student Response, Procedure Step 12**

*Our conclusion is that the indoor air quality was better than the outdoor air quality. On average, we observed a greater number of particles in the outdoor dishes (10–35 per square) and fewer particles in the indoor dishes (0–14 per square). There were more particles in the outdoor dishes. This supported our hypothesis.*

## SYNTHESIS OF IDEAS (20 MIN)

7 **Students discuss the results of their investigations and the role of random error and systematic error.**

- You may wish to have students compare their results and discuss random errors and systematic errors in their designs. Direct each student from a group to pair up with a student from another group who investigated the same variable. Have each student present their experimental results, conclusions, and sources of random error and systematic error. The two students can then discuss the similarities and differences in their groups' findings. Emphasize the value in comparing multiple data sets, as reproducibility is a key element of reliable scientific investigations and reduces error.

- Possible random errors and systematic errors are described in Teaching Step 5 and include consistent errors in observing or counting particulate matter, as well as errors in design that could result in consistent overcounting or undercounting.
- Have groups share their results with the class.
- Use Build Understanding item 1 to review the idea that addressing sources of error is a way to reduce uncertainty in scientific findings. Scientific studies are designed to reduce sources of scientific uncertainty by improving the accuracy of measurements, compensate for the imprecision of instruments, prevent outside factors from influencing the results, and ensure that there is enough representative data collected. Some of this should occur before data collection—for example, when designing an experiment—and some should occur after data collection, such as averaging.

8 **Revisit the Guiding Question.**

- To conclude the activity, evaluate whether your students are able to answer the Guiding Question, *How do you design a study to reduce scientific error?* Use this as a chance to revisit and summarize the key concepts and process skills of the activity.
- You may wish to have students revisit optional Student Sheet 1.3, "Unit Concepts and Skills," and add information about the concepts of random error and systematic error.

## EXTENSION (10 MIN)

9 **Use the Extension as an opportunity for advanced learning.**

The Extension suggests that students investigate other methods of assessing local air quality and compare their findings with the results of their experiments. You may find it helpful to look at some suggested approaches at the AirGradient website (https://www.airgradient.com/blog/8-student-experiments-to-measure-air-quality/). Have students conduct another air quality investigation and then discuss which approach is less likely to have random errors and/or systematic errors and why.

# SAMPLE STUDENT RESPONSES

## BUILD UNDERSTANDING

① **Review your experimental design and your results.**

**a What were possible sources of systematic error in your experiment?**

*It was predicted to rain for one of the three days of our experiment. We covered the outdoor dishes for several hours during the rain but did not do the same for the indoor dishes. The dishes were not left exposed for the same amount of time.*

**b How did you address these possible sources of systematic error in your experimental design?**

*We were careful to address possible sources of systematic error in observing and counting our data. We cleaned the objective lenses and made sure we were using the right magnification and light levels. We had one member of our group count particles and another person check their observations.*

**c What possible sources of systematic error did you not address in your experimental design? Given more time and resources, how could you address them?**

*We compared indoor air quality in four different homes. We placed one dish in each home but in different rooms. Two were placed in bedrooms, one in a kitchen, and one in a living room. We could repeat the experiment and make sure we place the dishe indoors in similar places to reduce systematic error.*

② **The graph in Figure 4.4 shows annual average PM2.5 air quality in the United States over a 24–year period. PM2.5 levels have decreased by 37% during that time. A person living near an area of frequent wildfires complains that their PM2.5 levels have increased during the same period.**

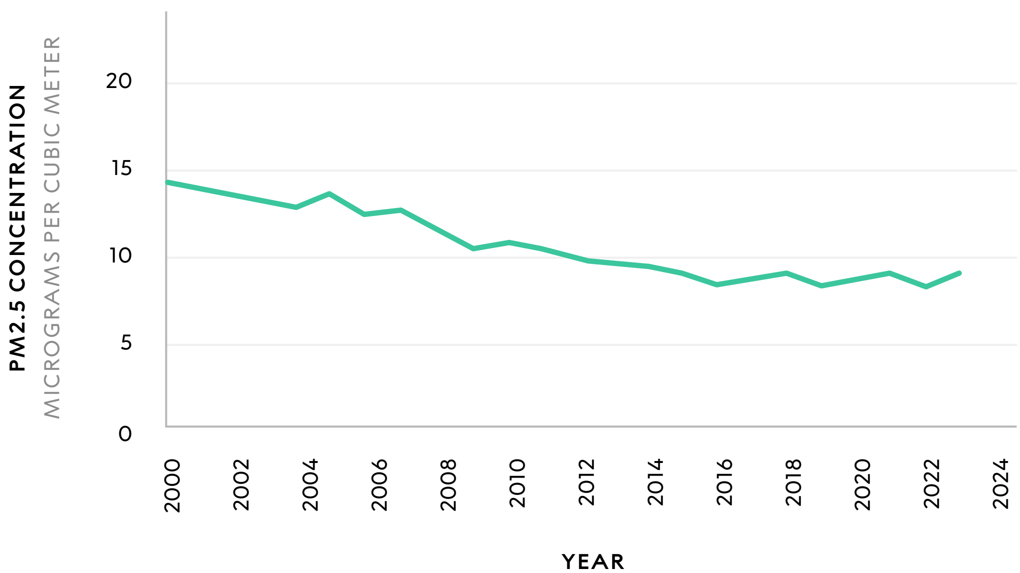
**a Explain how this could be true.**

*The overall air quality could be better on average across the whole country, but it could have gotten a bit worse in certain areas, or it could have gotten worse for short periods of time that are not reflected in the annual average. The average doesn't always reflect every place or all time periods that are part of the average.*

**b Figure 4.4 is from the U.S. Environmental Protection Agency, which addresses systematic and random error in its data. Explain one possible systematic error that could affect such data and how it could be addressed to reduce scientific uncertainty.**

*Air quality monitoring equipment may not be collected from the same communities from year to year. Placing air quality sensors in a regular pattern in different types of communities (urban, suburban, rural) spread evenly across the United States and collected from the same sites over time could reduce systematic error.*

**FIGURE 4.4**
PM2.5 Air Quality in the United States, 2000–2023




## CONNECTIONS TO EVERYDAY LIFE

③ **Like a scientific procedure, a recipe provides a list of steps to follow in order to produce an intended outcome, such as a batch of cookies. Imagine you are in a cooking class where eight groups each baked a batch of chocolate chip cookies using the same recipe. Some of the cookies came out chewy and thin, while others were thick and dry. What are some possible sources of (a) random error and (b) systematic error?**

*Possible sources of (a) random error include human error in measuring ingredients, inconsistent mixing techniques, and environmental factors such as temperature and humidity. Possible sources of (b) systematic error include an incorrectly calibrated measuring tool, inaccurate oven temperature, and slight differences in the quality of ingredients from one brand to another.*

④ **Janeen wants to improve her running speed, so she decides to experiment by running the same 1-mile route every day for a week to see if she gets faster. By the end of the week, her mile time had improved by 30 seconds. The following things happened during her experiment. Explain whether they are related to random error or systematic error and how each might have affected her results.**

- **a Janeen starts her stopwatch a little bit early because she needs to secure her phone in her pocket before she starts running.**

*This is a systematic error that would reduce her running speed because it would add time during which she is not running.*

**b** **Midway through the week, Janeen starts drinking an electrolyte drink 20 minutes before her run.**

*This is a systematic error that might increase her running speed if it provides her with more energy during her run.*

**c** **Each time she runs, her speed varies slightly due to factors such as how much energy she has, random distractions (like a car honking), or even slight changes in the weather. Some days, she feels tired and runs a little slower.**

*These are sources of random error. Being tired or distracted would likely reduce her running speed. The way in which weather affects her running speed would depend on the specific changes in the weather (for example: extreme heat or rain might reduce her running speed, while a cool overcast day might increase her running speed).*

⑤ **How might you redesign Janeen's experiment from item 4 to reduce sources of scientific uncertainty in her data?**

*I would recommend that she follow the same procedure and path each time prior to and during her run, that she not change her diet prior to running, and that she ask someone else to time her run so she has more accurate data about her running speed.*

## REFERENCES


A., Carisa. (February 16, 2020). *8 student experiments to measure air quality*. AirGradient. https://www.airgradient.com/blog/8-student-experiments-to-measure-air-quality/

Greenwald R., Sarnat J. A., & Fuller, C. H. (January 31, 2024). The impact of vegetative and solid roadway barriers on particulate matter concentration in urban settings. *PLoS One 19*(1): e0296885. https://doi.org/10.1371/journal.pone.0296885

| DEFINITION | CHARACTERISTICS |
| --- | --- |
| WORD | |
| EXAMPLES | NON-EXAMPLES |

### DEFINITION

*a difference between an observed and true value in a consistent direction, often caused by experimental equipment or design*

### CHARACTERISTICS

- *data affected in a predictable way*
- *graph or data points shifted in a consistent direction*
- *getting rid of the error gets rid of the shift in the data points*

### WORD

*systematic error*

### EXAMPLES

- *miscalibrated scale always reads too high*
- *air sensor is placed somewhere windy so the readings are always lower than the true value*

***Everyday example***
*Reading a measuring tape incorrectly by always aligning the zero mark slightly off*

### NON-EXAMPLES

- *random changes in the environment that cacuse fluctuations in the data that are not in a consistent direction*
- *data that has natural variation in the measurements*

***Everyday example***
*Getting slightly different measurements of your weight by weighing yourself at different times of the day on different days*

## DEFINITION

*a difference between an observed and true value that has no consistent pattern and is caused by chance or unpredictable factors*

## CHARACTERISTICS

- *data affected in unpredictable or inconsistent ways*
- *data points can fluctuate or be higher or lower than the average*

## WORD

*random error*

## EXAMPLES

- *getting slightly different measurements using the same instrument*
- *unexpected weather leads to unpredictable data measurements*

***Everyday example***
*Getting slightly different measurements of your heart rate after different activities on different days*

## NON-EXAMPLES

- *an instrument that always measures too high or always measures too low*
- *a factor that affects an experiment, shifting the data consistently in one direction*

***Everyday example***
*Using a measuring cup that measures incorrectly, shifting the data consistently in one direction*

## BEFORE THE INVESTIGATION

- Listen carefully to your teacher's instructions and follow any steps recommended when preparing for the activity.
- Use only the materials and chemicals needed for the investigation.
- Know the location of emergency equipment such as a fire extinguisher, a fire blanket, and an eyewash station.
- Tie back or remove dangling or bulky items such as long hair, jewelry, sleeves, jackets, and bags.
- Do not wear open-toed shoes in the science lab.
- Let your teacher know if you wear contact lenses or have allergies, injuries, or any medical conditions that may affect your ability to perform the lab safely.
- Make sure that both the work surface and the floor in your work area are clear of books, backpacks, purses, and any other unnecessary materials.

## DURING THE INVESTIGATION

- Follow all written and spoken instructions.
- Read the activity procedure carefully.
- Don't eat, drink, chew gum, or apply cosmetics in the lab area.
- Wear safety goggles when using chemicals.
- Do not wear contact lenses when using chemicals. If your doctor says you must wear them, notify your teacher before conducting any activity that involves chemicals.
- Read all labels on chemical bottles and be sure you are using the correct chemical.
- Keep all chemical containers closed when not in use.
- Do not touch, taste, or smell any chemical unless you are instructed to do so by your teacher.
- Mix chemicals only as directed.
- Use caution when working with hot plates, hot liquids, and electrical equipment.
- Follow all directions when working with live organisms and microbial cultures.
- Be mature and cautious and don't engage in horseplay.
- Report any accidents to your teacher immediately.
- Not sure what to do? Ask!

## AFTER THE INVESTIGATION

- Dispose of all materials as instructed by your teacher.
- Clean up your work area, wash trays, replace bottle caps securely, and follow any special instructions.