Metrology: The Science of Measurement
Companion Lesson to X-STEM All Access Episode Art + Science in Engineering

Grade/ Grade Band: Middle and High School	**Topic:** General Science: Biology, Chemistry, Physics, Earth Science, Marine Science

Brief Lesson Description:
Students explore the hands-on world of measurement and metrology.

Performance Expectation(s):

NGSS-HS0-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

NGSS-MS-PS3-1: Construct and interpret graphical displays of data to describe the relationships of kinetic energy to the mass of an object and to the speed of an object. [Clarification Statement: Emphasis is on descriptive relationships between kinetic energy and mass separately from kinetic energy and speed. Examples could include riding a bicycle at different speeds, rolling different sizes of rocks downhill and getting hit by a wiffle ball versus a tennis ball.]

Specific Learning Outcomes:
1. Understand the importance of measurement in scientific inquiry and engineering design.
2. Develop skills in using a variety of measurement tools and techniques with precision and accuracy.
3. Identify different units of measurement and different measurement tools used in metrology.
4. Conduct precise measurements and compare the accuracy of different measurement tools.

Narrative / Background Information

Prior Student Knowledge:
-Students have a basic understanding of estimating and measuring.
-Students can follow a simple procedure to conduct an investigation.

Science & Engineering Practices:

Analyzing and Interpreting Data
Analyzing data in 6–8 builds on K–5 and progresses to extending quantitative analysis to investigations, distinguishing between correlation and causation, and basic statistical techniques of data and error analysis.

- Construct and interpret graphical displays of data to identify linear and nonlinear relationships. (MS-PS3-1)

Constructing Explanations and Designing Solutions

Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles and theories.

Design a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and trade off considerations. (HS-ETS1-2)

Disciplinary Core Ideas:

PS3.A: Definitions of Energy
Motion energy is properly called kinetic energy; it is proportional to the mass of the moving object and grows with the square of its speed. (MS-PS3-1)

ETS1.B: Developing Possible Solutions

When evaluating solutions it is important to take into account a range of constraints including cost, safety, reliability and aesthetics and to consider social, cultural and environmental impacts. **(HS-ETS1-3)**

Crosscutting Concepts:

Scale, Proportion, and Quantity

Standard units are used to measure and describe physical quantities such as weight, time, temperature, and volume. (HS-ETS1-3)

Proportional relationships (e.g. speed as the ratio of distance traveled to time taken) among different types of quantities provide information about the magnitude of properties and processes. (MS-PS3-1)

Connections to Nature of Science

Scientific Knowledge Assumes an Order and Consistency in Natural Systems.

Science assumes consistent patterns in natural systems.

Possible Preconceptions/Misconceptions:

1. **Understanding Units and Scale**: Students often struggle with the concept of different units of measurement and their appropriateness for different contexts (e.g., using millimeters instead of meters for small objects).
2. **Precision and Accuracy:** Grasping the distinction between precision (the closeness of two or more measurements to each other) and accuracy (how close a measurement is to the true value) is challenging.
3. **Tool Selection and Use**: Properly selecting and using measurement tools (rulers, calipers, balances, etc.) can be difficult.
4. **Estimation**: Students often lack confidence in estimating measurements and understanding the importance of estimation in scientific inquiry and everyday life. Developing a sense of scale and an ability to estimate can help students check the plausibility of their measurements.
5. **Dimensional Analysis and Unit Conversion**: The process of converting between units, especially within the metric system and between the metric and imperial systems, can be challenging. Dimensional analysis, while a powerful tool for solving physics and chemistry problems, often confuses students.

*This video might help: Dimensional Analysis Problems + Conversion Factors

Teacher Note: All of these misconceptions will be directly addressed in the sections below.

LESSON PLAN – 5-E Model

ENGAGE: Opening Activity – Access Prior Learning / Stimulate Interest / Generate Questions:

It is recommended that teachers do the SEL portion of the lesson first, and then proceed, in order, with the 5E portion of the lesson. Students will be measuring (with and without scientific instruments), estimating, working cooperatively, and reflecting on metrology and measurement in their lives and the world around them.

Begin by having students watch the following video highlighting various phenomena related to measurement and metrology. It is one minute long, you can keep it on repeat, much like an extended version of a GIF. Each individual clip is numbered. After watching the first time, have students construct a SEE / THINK / WONDER table in their notes. Continue the video on repeat while the students add to their table. When finished, have students pair share and add a few additional ideas from their partners onto their own tables.

Students can write down some of their thoughts from SEE / THINK / WONDER on a collective class document (this can be a class whiteboard, post-its in a designated area, or in an online space). What other measurement and metrology phenomena and examples can you think of?

Video Link: Measurement Phenomena

Show the X-STEM Episode "Art and Science in Engineering".

Metrology Quotes to share with students. Share with students and ask them to share which one they think is most interesting.

1. "Measure what is measurable, and make measurable what is not so." - Galileo Galilei
2. "Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it." - H. James Harrington
3. "To measure is to know. If you cannot measure it, you cannot improve it." - Lord Kelvin

EXPLORE: Lesson Description – Materials Needed / Probing or Clarifying Questions:

Students will explore metrology and measurement in the science classroom.

1. Assemble as many measurement tools as possible. *See materials list.
2. Set up as many stations as possible, using the different tools. Teachers can arrange rulers, scales, meter sticks, calipers, balances, beakers, flasks, etc throughout the room. Give students time to walk around and touch and explore the gear. Have them fiddle around and see how things work.
3. Depending on what equipment is present, teachers should set up a series of stations for students to rotate through and complete a measurement task. See "Measurement Mania" pdf for examples. Additionally, if equipment is limited, teachers could simply share the pdf and have students do stations virtually. Choose a variety of measurement types and scales.
4. Have groups rotate through the stations, recording their measurements in a data table.
5. Teachers can project an online timer to keep track of time.

Teacher Notes on Activity:

6. Emphasize proper technique when measuring and share with students the importance of accurate measurements. One area

where students often struggle is with how precise to make their measurements. Have students measure to one uncertain digit. Teachers can help students apply this by choosing different types of tools and equipment. (e.g., different degrees of graduated cylinders)

EXPLAIN:

We want students to connect their prior knowledge to new ideas about measurement.

1. Students are to watch these two short videos from TED-Ed.
    a. Why the Metric System Matter: TED-Ed
    b. What's the Difference Between Accuracy and Precision: TED-Ed
2. Students then pair share their thoughts on the questions below.
3. Teachers can then lead a class discussion based on student responses.

Questions:

1. How does this historical context help you understand the importance of standardized measurements in today's global society, especially in science and engineering?
2. Why do you think precise and consistent measurement is crucial for scientific discovery and innovation? How does collaboration among scientists across different countries play a role in this evolution?
3. Why do you think precise metrology is essential for technological innovation and safety? Provide an example of a technological device or system that relies heavily on accurate measurements. **Connect back to our video example.*
4. Explain how the story of William Tell helps illustrate the difference between accuracy and precision? Can you think of a real-life scenario where precision is achieved without accuracy, or vice versa?
5. Imagine you are leading a project where increasing precision by 10% would double the project's cost. Justify how you would decide whether the increase in precision is worth the additional expense? What factors would you consider in making this decision?

ELABORATE: Applications and Extensions:

In this section students will apply what they've learned to a new, but similar situation. The goal is for them to expand upon knowledge gained earlier in the lesson.

1. Hand out a copy of "Measurement Olympics" to all students. Complete instructions can be found on the hand out.
2. Randomly assign students to groups of three.
3. NOTE: teachers may need to adapt the activity to fit their school and environment. Outside on a track and field is ideal.
4. Special emphasis should be given to the initial estimates for each event.
5. Encourage students to apply their newly gained skills from the earlier parts of the lesson.
6. Students will complete the data table - estimation, actual measurement, and the calculation for % error.

EVALUATE:

Formative Monitoring (Questioning / Discussion):

Participation in discussions and group activities from the sections above will provide teachers with insights into students' understanding.
Teachers should pay close attention to questions posed during discussion and during activities.
Teachers should encourage students to think about how improving measurement techniques can lead to advancements in technology and science.

Summative Assessment (Quiz / Project / Report):

Accuracy and completeness of measurements and data recorded during the lesson.
Discussion and reflection questions embedded into the 5E and SEL sections of the lesson.
End the lesson with a reflection session where students share what they learned about the importance of measurement and how they can apply this knowledge in their daily lives and future careers.

Elaborate Further / Reflect: Enrichment:

Students can do further reading, listening, and research on the links and topics below. Teachers can also gain deeper insights and generate interesting class discussions based off of these links. Additionally, students and teachers can explore the Interdisciplinary Connections/Ideas section below.

NPR How Did the Meter Get Its Length?
Scientists Introduce New Kilogram On World Metrology Day
Who Invented the Metric System
Beyond Measure: Book Review

SOCIAL EMOTIONAL LEARNING ACTIVITY

Teacher note: This section of the lesson can be done first as an introduction to measurement and metrology.

This section is designed to highlight the importance of precision in measurement and the value of collaboration and communication. Using just paper and a common classroom object as a reference, students will work together to replicate an object's length as accurately as possible.

SEL Competencies:
Collaboration: Working effectively in small groups, sharing responsibilities, and valuing each member's input.
Responsible Decision-making: Making thoughtful decisions about personal and collective actions.
Social Awareness: Demonstrating empathy and respect for others' opinions and work.

Introduction:

1. Students will first estimate and then precisely measure the length of a chosen object. To do this, they will only use a piece of paper. No rulers or meter sticks will be used.
2. Randomize the class and divide into groups of three.
3. Teacher note: You might consider doing groups of different sizes and see how that impacts interactions and discussions.
4. Highlight the SEL focus of collaboration and making collective decisions to achieve a common goal.

Estimation:

5. Without using any measuring tools, each team will estimate the length of the object and cut a piece of paper to the exact size they believe matches the object's length. NOTE: students are not allowed to touch or directly measure the object.
6. Teams discuss their estimation strategies and decide together on the final cut.

Precision Measurement:

7. Allow each team to measure (and touch) the object accurately with their hands or another piece of paper.
8. Teams then cut a second piece of paper based on their more precise measurement.
9. Discuss as a class the difference between estimating and measuring precisely.

Reflection and Discussion:

10. Teams present their estimated and precise measurements, reflecting on the challenges and strategies they used.
11. Facilitate a discussion on the importance of precision and how collaboration contributed to their approach and outcomes.
12. Prompt students to reflect on how they communicated and made decisions within their teams.

Reflection Questions:

1. Collaboration and Communication: Reflect on how your team worked together during the activity. What strategies did you use to ensure everyone's opinions were considered, and how did effective communication impact your team's performance?
2. Responsible Decision-making: Think about the decisions your team made during the estimating and precise measurement phases. How did you decide whose method to use or how to combine different approaches?
3. Social Awareness and Empathy: During the activity, how did you demonstrate empathy and respect for your team members' ideas and feelings, especially if there were disagreements or mistakes?

INTERDISCIPLINARY CONNECTIONS/IDEAS

- **Mathematics:** Utilize trigonometry and calculus in analyzing and solving problems related to measurement and conversion.
- **Technology:** Explore the development of measurement technology and its impact on scientific discovery and innovation.
- **Societal Impact:** Discuss the role of accurate and precise measurements in medicine, environmental science, health, and safety standards.
- **Mathematics:** Use of geometry and algebra in calculating areas, volumes, and dimensions from measurements.
- **History/Technology:** The evolution of measurement tools and units of measurement.

Materials Required for This Lesson/Activity	
Quantity	**Description**
1 per student	PDFs of connected activities
As many as possible	Measurement tools (determined by what is available in each classroom):
	Ruler, tape measure, balance, scale, caliper, micrometer, flask, beaker, graduated cylinder, etc
2 pages per group	Sheets of paper
1 object per group	Classroom objects (books, water bottles, pencils, etc.)

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