Teacher's Preparatory Guide

Is measuring an art or a science?
What is "to measure"? Accuracy and precision in nano-measurements.

Purpose:
The purpose of this lesson is to help students understand the concepts of accuracy and precision and how they are important in measurements at the nano-scale.

Overview: Nanotechnology occurs on the scale of 1-100 nanometers (in one direction). There have been numerous predictions about the growth in nanotechnology production and its impact on manufacturing in the near future. Manufacturing and commercial exchange of nano products will create a need for high-quality measurement technology. This lesson introduces students to the concept of measurement and how important and difficult such measurement is at the nanoscale.

Time Required: (1) 50 minute class period

Level: high school; community college: general science, physical science, Intro to Engineering

Teacher Background:

Measurements are part of our everyday life, but have we stopped to think about what "to measure" means? When we measure, we actually compare a magnitude (length, weight, etc.) with a standard accepted to be the measuring unit. This comparison implies to count how many times this measuring unit fits our object being measured. To measure implies to compare and read a scale.

It is fairly easy to confuse the physical dimensions of a quantity, with the units used to measure the dimension. Only a few physical quantities are needed to fully describe natural events and our surroundings. We usually consider quantities like *mass*, *length*, *time*, etc. as fundamental *dimensions*. We then express the dimensions of other quantities like *speed*, which is *length/time*, in terms of the basic set of fundamental dimensions.

There are seven fundamental or base dimensions to express what we know of the natural world:

1) Length	5) Electric Current
2) Mass	6) Amount of Substance
3) Time	7) Luminous Intensity
4) Temperature	

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With the help of these fundamental dimensions, we can derive all other necessary physical quantities.

Units give the magnitude of some dimension relative to an **arbitrary** standard. While the standard size chosen is entirely arbitrary, it becomes very useful for comparing measurements made in different places and times. Several national laboratories are devoted to maintaining sets of standards, and using them to calibrate instruments. The National Institute for Standards and Technology (ww.nist.gov) is the leading agency for these standards. The National Nanotechnology Initiative also has publications on nanoscale standards (www.nano.gov) resulting from workshops on metrology (the science of measurement) and nanotechnology.

In contrast to dimensions, of which only a few are needed, there is a multitude of units for measuring most quantities. It is always necessary to attach a unit to the number. Without units, a number is at best meaningless and at worst misleading to the reader.

There are several systems of units being used today. For example the International System (SI or metric), the British Gravitational System (BGS), and the U.S. Customary System (USCS). In the SI system the units of the fundamental dimensions are:

1) Length — Meter
2) Mass — Kilogram
3) Time — Second
4) Temperature — Kelvin
5) Electric Current — Ampere
6) Amount of Substance — Mol
7) Luminous Intensity — Candela

Most of the time engineering and scientific measurements are real numbers. Real numbers require an infinite number of digits to describe them. We can not handle numbers that are infinitely long, but we can always approximate them. Measurements are also the product of human observation; this can generate some discrepancies in their reading. The use of the approximations and observations mentioned before, will introduce some error in the reported measurement. It is important to identify the source of your errors to obtain a good value of your measurements. Why is this important? In trade, no supplier wants to deliver more than what was agreed upon, and no customer wants to receive less than agreed. In industry, we need processes that are more efficient with less waste produced. For example, in today's markets different components of products are manufactured in different plants, even in different countries; yet these parts should always fit together during assembly. You cannot have components from different manufacturers that do not fit together in the final assembly. For example, NASA lost the $125 million Mars Climate Orbiter because the Lockheed Martin engineering team used English units of measurement while the NASA team used the metric system.

Measurements need to be comparable, precise (reliable) and accurate. Let's introduce some definitions:

- **Accuracy** is the degree of closeness of a measure or calculated quantity to its actual (true) value. Systematic errors result from a measurement method that is inherently wrong. Sources of systematic error may be imperfect calibration of instruments, changes in the environment which interfere with the measurement process, and sometimes imperfect methods of observation. Error is the difference between the reported value and the true value. Error results from systematic errors and describes the lack of accuracy.

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- **Precision**, also called reproducibility or repeatability, is the degree to which further measurements or calculations show the same or similar results. Random errors are errors in measurements that lead to measured values being inconsistent when repeated measurements are taken. Uncertainty results from these types of errors and describes the lack of precision.

In summary, we need good measurement tools that will be both accurate and precise. How do we achieve this? First, to have good accuracy we need instruments that are properly calibrated (i.e. they have been properly compared to the standards).

In order to improve the precision, we need tools that have good repeatable and reliable resolution (e.g., fineness to which an instrument can be read). Here, a ratio between the uncertainty and the measurement has to be as large as possible to improve the quality of the measurements.

When we talk about measuring things at the nanoscale, we are talking about measurements in the range of 1 to 100 nm (i.e. 10^{-9} to 10^{-7} meters). As mentioned before, the ratio uncertainty/measurement has to be as large as possible therefore the need of instrumentation that can handle really small numbers is a must. This leads to the use of techniques of measurement that are different to classic metrology techniques. All tools have limitations; therefore different tools are better for different purposes. Choosing the right tool is essential in the field of nanotechnology.

Some of the instruments used in the nano-field are the following:
1) Atomic Force Microscope (AFM)
2) Scanning Electron Microscope (SEM)
3) Transmission Electron Microscope (TEM)
4) X-Ray Diffraction
5) Profilometer
6) Small-Angle X-ray Scattering

These instruments are used for measuring different features and different materials. Some are better under certain circumstances while others are better under different ones. To really be able to obtain reliable measurements, it is crucial to understand what each of these techniques does, because each one of them uses different physical properties to operate.

The next question is how does one calibrate an instrument used at the nanoscale? We need calibration to obtain more accurate measurements. Some standards are released by the National Institute of Standards and Technology (NIST) to calibrate sizes of different objects in the nanoscale, e.g. gold nanoparticle sizes. These reports are far from being precise (see NIST Reference Material 8011, 8012, and 8013) challenging the understanding of the size measurements at this very small scale.

In order to improve precision, researchers from MIT have been trying to create a nanoruler, which is a ruler of tiny proportions, made of a silicon crystal lattice structure (http://web.mit.edu/newsoffice/2004/nanoruler.html). Since it can accurately measure fractions of nanometers, it could help standardize the future nanotechnology industry. Since the characteristics of silicon are well understood, the distance between one crystal lattice line to another is well known. Therefore, counting these lines can reveal a fairly accurate measurement.

In conclusion, to answer the question that gives name to this lesson, we can say that it is a little bit of both, some science and some art. We understand that we need to make several measurements to have a statistically meaningful number (more precise). We also need to calibrate the instruments to have measurements that are as close as possible to the true value (more accurate). But it is undeniable that each experiment we do is unique and requires a full understanding of the instrumentation to be used that comes only with years of experience. But sometimes we don't understand completely what we are doing but like a good artist, a good scientist has to have the "feeling" on which instruments to use for each specific situation.

Sir William Thompson, Lord Kelvin, explained the importance of measuring in these two quotes: "To measure is to know" and "If you can not measure it, you can not improve it."

Materials:

- Squares template (attached)
- Circles template (attached)
- 4 Rulers (included)
- Plastic rectangle with high index of refraction (example: Flinn Scientific Index of Refraction Plate #AP9329)

Advance Preparation:
Print out and laminate the templates and rulers so that you have a set for each group of 4 students.

Safety Information: None

Directions for Activity:

1) Distribute materials and student sheets.
2) Have students read through background information in the student sheet. Answer all the questions about the terms or concepts before students begin activity.

Resources:
National Institute of Standards and Technology: http://www.nist.gov/
Metrology: http://en.wikipedia.org/wiki/Metrology
National Nanotechnology Initiative: http://nano.gov
Search metrology for publications related to measurement technology and applications
NIST Reference Materials on Gold Nanoparticles:

- https://srmors.nist.gov/view_detail.cfm?srm=8011
- https://srmors.nist.gov/view_detail.cfm?srm=8012
- https://srmors.nist.gov/view_detail.cfm?srm=8013

National Science Education Standards
Content Standard A

- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

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Content Standard E

- Understanding about science and technology

Content Standards G

- Nature of scientific knowledge

Principles and Standards for School Mathematics

Measurement

- Understand measurable attributes of objects and the units, systems, and processes of measurement
- Apply appropriate techniques, tools, and formulas to determine measurements

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