How do scientists study things that are too small to see?

(160 min, approximately 4 class periods of 40 min)

Authors

Leigh Metcalfe

Ashley Carter

SUBJECT/GRADE LEVEL

Subject Area: Science

Grade Level: Middle School

Materials

- Tools for measurement (see suggestions below)
- Pre-made Black Boxes or make (one per group)
- Ping Pong balls or marble (one per group)
- Square cardboard - 2 ft x 2 ft or or 1 ft x1 ft (one per group)
- Dowels (4 per group)
    - 1 in diameter cut into 4, 2 in tall pieces
    - *or* reclaimed paper towel or thread spools
- Cardboard or wooden simple shapes
    - (triangle, square, diamond etc)
- Blank copy or construction paper
- Optional:
    - additional plastic box (or any opaque box as long as the students can not see inside).
    - Cardboard or sponge shape (rectangle or triangle)
    - Masking tape (one per group)
    - Marbles (one per group)
- Optional/suggested measurement tools: (one of each tool per group)
    - Tools to measure distance- Student ruler (Inches), Metal scientific ruler (cm) yard stick, measuring tape, calipers
    - Tools to measure time: Wall clock, wrist watch, stopwatch with 100th of a second
    - Tools to measure fluids: measuring cup with cups and oz, beaker, graduated cylinder, pipette, micropipette
    - Tools to measure temperature: celsius, fahrenheit, infrared, digital thermometers
    - Tools to measure other less common elements: light (lumens meter), voltage (voltmeter), Wattage (Kill-o-Watt) etc.

STANDARDS

Next Generation Science Standards

- MS-PS1-1. Develop models to describe the atomic composition of simple molecules and extended structures.

Mathematics Standards | Common Core State Standards

- CCSS.MATH.PRACTICE.MP2 Reason abstractly and quantitatively.
- CCSS.MATH.CONTENT.8.EE.A.3 Use numbers expressed in the form of a single digit times an integer power of 10 to estimate very large or very small quantities, and to express how many times as much one is than the other.

English Language Arts Standards | Common Core State

- CCSS.ELA-LITERACY.RST.6-8.3 Follow precisely a multistep procedure when carrying out experiments, taking measurements, or performing technical tasks.
- CCSS.ELA-LITERACY.RST.6-8.7 Integrate quantitative or technical information expressed in words in a text with a version of that information expressed visually (e.g., in a flowchart, diagram, model, graph, or table).

LESSON OBJECTIVE(S)

Students will be able to:

- Use mathematics and computational thinking to identify the most precise tool of measurement and take accurate measurements
- Investigate the scale of atoms and their subatomic particles (scale, proportion, and quantity)
- Use quantitative thinking and evidence from a model to explain how scientists can know the structure of items that are too small to see or directly measure.
- Plan and Carry out investigation to identify how scientists specifically learned about the subatomic particles that make up the nucleus.
- Analyze and interpret data as they construct explanations and communicate information to others about the models they created and the process of learning measurable information about things we are not able to see.

CAREER CONNECTION(S)

Mentor Background:

Dr. James (Jeff) Carroll brings over three decades of expertise in experimental nuclear physics, marked by his authorship of more than 140 peer-reviewed journal articles, including significant contributions featured in prestigious publications like Nature. Prior to his tenure at the US Army Research Laboratory (ARL), Dr. Carroll spent 15 years as a Professor of Physics. At ARL, he leads the Nuclide Power Team, focusing on expanding scientific knowledge and developing cutting-edge instrumentation for radiation measurements. Dr. Carroll actively promotes inclusivity in research, welcoming participants with diverse backgrounds in nuclear physics to contribute to their ongoing projects, fostering a dynamic learning environment that supports both short-term and long-term research goals.

STEM Careers: Physicists, Electrical Engineer, Energy Research, Mechanical Engineer and Chemical Engineer, Nuclear Engineer, Nuclear Fuel Chemist, Mathematician, Data Scientist, Computer Science, teachers, professors

ENGAGEMENT

Brief Description: In small groups, students will discuss measurements used in daily lives, then as a whole class discuss estimation, accuracy, and precision.

Procedures:

Group students into teams and start with a small group discussion. In groups, ask them to discuss the things that they "measured" today. Give students a few minutes to bring up any examples that they can from the day. Ask each group to share one example.

Record the examples on the board, strategically placing them into clusters based on units of measurement.

Prompt the class for examples they may not have thought about: how did you know it was time to wake up or change classes (Measurement of time)? How much milk was added to cereal (measurement of fluid)? How many steps are needed to cross the street (Measurement of distance)? How fast was the car traveling on the road at various points (Measurement of speed). Add labels to the categories the students generated and the additional examples to the board.

Prompt the students to discuss which of the measurements were "accurate", "precise" or "estimations".

Finally, ask students to discuss in their groups, when can an estimation be an adequate measurement vs. when could a measurement save someone's life? For example, "a surgeon might need a measurement instrument to determine where to make his incision. The accuracy of that measurement instrument could determine the difference between life and death in a surgical setting"[1].

Possible additions to the Engage:

Show this video to lead into the next topic: Measurement and Scale:

Large Numbers

EXPLORATION

Brief Description: Students will categorize tools used for measurement by size, accuracy, need and function. They will then select the correctly scaled tool, in the correct units to conduct a series of measurements to improve their estimation skills, accuracy and precision.

Procedures:

Set up:

Before beginning the lesson, collect various tools that can be used to accurately and inaccurately measure distance, time, temperature, "fluids", etc. If you have tools like a Lumen meter, "kill-o-watt" or other measures not typically taught during a measurement unit, put those into the collection as well to introduce items for the students to measure, and place them into containers and set up stations. The items selected should challenge the students to measure length (small and large), fluids, mass, time, or any other measurements you recognize that your students need to practice. "Students by this age can usually understand how to conserve mass, so double pan balances can now be used in a meaningful way with standardized masses instead of marbles or paper clips. As was the case with length, students should be asked to estimate the mass of objects in grams or kilograms to help them develop a firmer understanding of those common units."[2]

The measurement handout is very vague, but it can be made more specific by including the names of items at the stations the students will visit, made to match your supplies and to challenge your students as needed, then print one copy per group.

Explain the activity:

To engage students in the importance of understanding measurements, students will first explore and figure out what the tools of measurement provided can tell them. Give the groups one example of each tool. It would be best if they were provided an inaccurate ruler, a more precise ruler, and even a caliper to show them the differing levels of accuracy that a tool can provide. Provide them with graduated cylinders of various sizes as well as different units of measurement if available. Provide a wall clock vs a stop watch with more precise measurements of seconds. Now, the students will be challenged to use these tools to gather the most accurate and precise measurements. Provide them with the handout and set them loose to measure, record and draw their results.

Extension to this activity and measurement:

Uncertainty (often referred to as error): One of the biggest take-aways from research inside Army Research Labs, was the level of uncertainty that remains even after the most careful of data is collected and calculations are made. Often the general public does not take into account the uncertainty that is implicit in the data that is provided to them. To help students understand uncertainty, have them choose one measurement from the activity that they think is their most accurate. Then have students calculate the level of uncertainty on that measurement.

"There is a statistical method for calculating random uncertainties in measurements."[3] This requires taking at least 10 measurements of a quantity. This will not be our focus, for now we will consider the

uncertainty associated with one single measurement. The following general rules of thumb are often used to determine the uncertainty in a single measurement when using a scale or digital measuring device.

Uncertainty [σ_x] in a Scale Measuring Device is equal to the smallest increment divided by 2.

$\sigma_x = \frac{\text{smallest increment}}{2}$ Ie: Meter Stick (scale device) $\sigma_x = \frac{1\text{mm}}{2}$ = 0.5mm or = 0.05cm

So in this measurement, the uncertainty (or error) would be 1mm ± 0.5mm, which means that the accurate measurement could have been within the range of .05 mm to 1.5 mm. The concept of uncertainty will carry through each of the following activities, with the intention of bringing more awareness to the level of uncertainty in much of the information offered by science in everyday life.

Resources: Additional Resources for Uncertainty (Created and provided by Coach Linda Crossno)

EXPLANATION

Brief Description: Students will be provided a sealed "black box" model and they will try to map the path of an object through a maze that they are unable to see in a traditional way. They will use their senses, sound movement, reverberation, to draw or build an accurate and to scale map of the path the object follows, even though they can not see it.

Procedures:

Set-up:

Make use of already made, make your own, or purchase a black box maze.

If making, gather supplies:

- Black plastic box (or any opaque box as long as the students can not see inside).
- Cardboard or sponge shapes (rectangle and triangle)
- Tape
- Marble

Create a mini-maze for the marble to travel through by taping the foam or cardboard shapes inside the container, placement should vary so each group has a different maze. Place the marble in the maze then tape the container closed so that students are unable to see inside.



Example of teacher maze set up.

Close and tape the box closed (above)



Optional additional supplies- if you have students build a model rather than just draw it on paper

- Black box (empty and open)
- Tape (masking tape)
- One marble
- Rectangle and triangle cardboard or sponge shapes (cut cardboard or sponge shapes).

Explain the Activity to Students:

Provide each group with a sealed black box maze. Without touching them, ask them what they think a black box is. Have students talk in groups, then share out as a class. Ask the students to pick up the boxes, and share some of the observations they make as they hold them.

Explain to the students that they will be able to "see inside the box", but not through traditional sight using their eyes. Instead, today they are challenged to use their other senses and inference to reconstruct a model of the maze.

Note: Students can construct their model in one of two ways, you can have them use the most appropriate tools of measurement from the previous lesson to measure, draw and show their model on paper. If time and materials allow, students can build a scale matching model using the same supplies as the teacher used to make the models.

Instruct the students to work as a team to develop their model of what is inside the box, reminding them that at no time, are they able or allowed to open the boxes. They should be sealed shut, and they are not permitted to break the seal. All models must be made using their other senses. Provide students time to work through the processes, offering suggestions and support as teams struggle to work

together or become frustrated. Remind them that the science of discovering the unseeable can be frustrating but it requires perseverance. In a sense we are "seeing" what's inside the box, but this requires a broadening of what we mean by "seeing".

You can determine how you will allow students to determine if they solved the problem of a hidden object being in a cardboard box. You can take a picture of each box before it is sealed and let them match their drawing to the image. You can have a drawn map that shows them the layout you used to create the maze. If you have a way to open them, and then reseal them for the next class, you can open the boxes and let them see them. The best lesson of all, may be that they may need to trust that at this time, their model is the best possible version of what is inside that black box that they can know. Like in science, with more testing, more advanced technology or new discoveries, one may be better able to know, map and understand what is inside the box.

Extension to this activity and measurement:

Have the students work on describing the “degree of uncertainty” they have about their model. Ask students to think about the measurements that they took in the previous lesson. Reflect on how accurate a measurement taken with an imprecise tool was versus a tool like a caliper that provides a far more accurate measurement. Now, think about their measurements, inferences and predictions about the black box. Ask them to think about how certain they are that their model is correct. Have them define their model with an estimated accuracy rating (ie: This model has an uncertainty of 10%). Better yet, have them calculate the uncertainty in the measurements that they used.

Resources: Black Box - Video Explanation for teachers

ELABORATE Mini-Rutherford Models

Brief Description: Now that students have an idea about one way to know information about something that they can not see, they will watch a short video or two and this will shift the thinking to questions about atoms and scale. Students will apply their new skills and knowledge of measurement, along with problem solving skills to building a model that will allow them to map the shape of an object in their own “black box” experiment. This experiment will help them discover how scientists can initially “estimate”, then determine more precisely the size and shape of an unknown object (one they can not see). Students deduce the shapes and sizes of unseen objects by tracking visible objects in relation to them, analogous to Rutherford’s alpha scattering experiments.

Procedures:

Set-up:

Before you begin the lesson, you will need to gather the materials for students to construct a mini Rutherford model. For this lesson, you can opt for a full inquiry, partial inquiry or fully guided activity.

For a fully inquiry based format, have all the cut material available, but not assembled for the students. You will need shapes, cut out of multiple layers of cardboard or out of wood (many hardware stores will cut the shapes for you), 1x1 or 2x2 pieces of cardboard or masonite, and legs for the mini-tables (these could be dowels, thread spools or other cylindrical objects of the same height). You will also need an appropriately sized ball for the students to roll (marbles or pingpong).

For a partial inquiry based format, you can construct the tables, with the legs and shapes already attached and fix them to the floor with Earthquake Putty or similar substance. The partial inquiry model in this format would be asking the students to design the experiment to determine the shapes.

The guided model of this experiment is to provide the students with the format for finding the shapes following a set of instructions for the procedures outlined by Rutherford. If you opt for the fully or mostly inquiry based option, here is a student handout that can help guide their planning and experimentation.

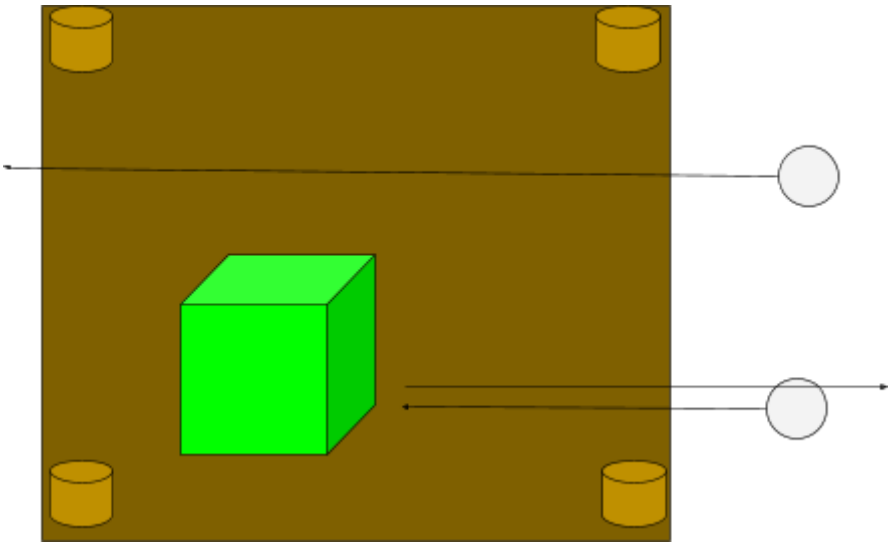
Example Mini- Rutherford Model Setup:

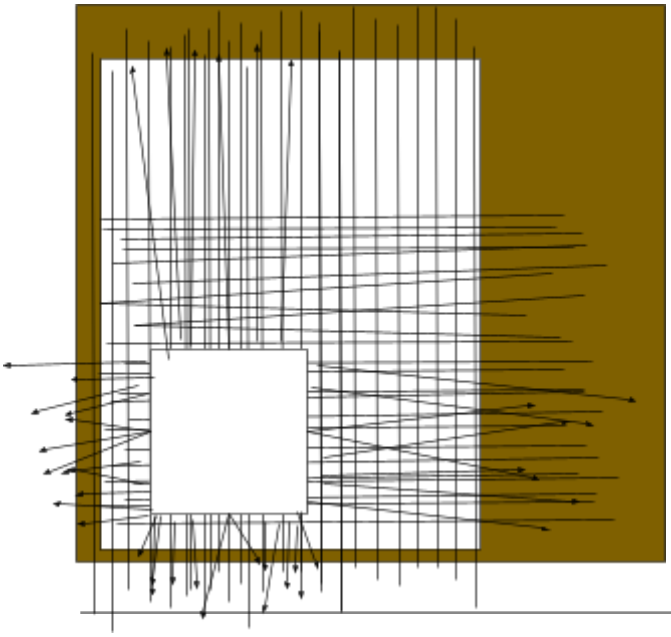
Side view: Cardboard on top of 4 dowel legs, with a square shape glued to the cardboard. (See image below)



Bottom view: (and sample of testing):

Cardboard on top of 4 dowel legs, with a square shape glued to the cardboard). When the ball is rolled in a systematic pattern, the ball will pass through any area where there is not an object, it will be reflected every time it hits an object. If the students map this pattern by repeating the tests from all sides, they should be able to determine the shape, size and position of the object. (see image to the right)





Top view:

Students place a piece of paper on the top of the cardboard and record where the ball passes all the way through, and where it bounces back. Based on reflections, they will be able to determine the shape, size, and location of the object attached to the bottom.

(see image to the left)

Explain the Inquiry Activity to Students:

Show one or both of the video options linked in the lesson below. Ask students to talk in their groups about the ideas they were presented with, the questions they have and their reaction to these scientific ideas. Have them record at least one reaction and one question in science notebooks or on scratch paper. Ask each group to share a reaction with the class. Then have each group share a question, and if needed any other comments they want to express. Probe students to tease out their preconceived notions about how we *know* atoms do not touch. Ask them how scientists can know that if we can not see them.

Explain to the students that much of what we know originally came from (and current research and discoveries are based on) an experiment conducted in the early 1900's by Ernest Rutherford, "the father of nuclear physics". In Rutherford's experiment, alpha particles were directed at a thin gold foil to explore the structure of atoms. Similarly, today you will design your own experiment using rolling marbles or ping pong balls as alpha particles to uncover the shape of a concealed geometric form, akin to a nucleus.

Depending on the format you intend to use, tell the students about the materials they have access to for designing, testing and gathering data from an experiment or explain the format of the investigation as you would like them to conduct it (as explained in the set up). Provide them with the student handout and support students in the process of discovery.

Scaffolding: for students who need support in developing their own experiment, suggest they begin by testing the effect of varying launch angles toward an object on a flat surface to observe how the marbles deflect in different directions.

Resources:
Possible Videos to start off the exploration and drive students to ask questions:

- You Can't Touch Anything
- Atoms Never Touch Each Other

Teacher background information/examples:

Here are resources that can help you build background knowledge on the topic of Rutherford scattering as well as see an example of the model students will use in the explanation.

- Rutherford Scattering
- Detailed teacher background information and additional lessons that help students discover more about atoms and radiation: Detecting Radiation in our Radioactive World

EVALUATION Curation

Brief Description: As the students complete their experimentation and data analysis, they will synthesize their learning through a final product called curation. The process can be applied to all kinds of content: "A person could curate a collection of articles, images, videos, audio clips, essays, or a

mixture of items that all share some common attribute or theme"[4]. In this case, the students will curate a collection of items that help them explain to others the answer to the essential question: "How do scientists study things too small to see?" Their final product as a group will be a poster that they will present to the other teams. Because they will be curating their poster, each team will have something unique and different on the poster so they will not be presenting the same information that everyone else also discovered through the experiment.

Procedures:

Set-up:

Decide what elements your students will need to include in their curation and revise the rubric to match with your expectations. The sample checklist requires students to include the following elements on their poster; it could be converted into a rubric for peer feedback and teacher grading.

- A one paragraph answer to the question: "How do scientists study things too small to see?".
    - Scaffolding: For students who need support with writing tasks, consider offering one or some of the following strategies for writing.[5]
    - Show them mentor texts, examples of excellent writing within the genre students are about to attempt themselves.
    - Devote at least one more class period to having students consider their topic for the essay, drafting a thesis statement, and planning the main points of their essay in a graphic organizer.
    - Encourage students to share their work with peers and give feedback at all stages of the writing process. For those students who need more support, offer this feedback yourself.
- An image of a scientific tool (ie: their mini-rutherford machine, the black box experiment, an image of a device or instrument used by a scientist or a lab that they learned about or discovered during their research of the experiment).
- An image of a scientist that, historically or in the present time, does research similar to what they have discovered. This image needs to have a one paragraph biography of the scientist and their research. It is encouraged that students seek out a scientist that represents underrepresented genders, cultural backgrounds, or has something in common with the members of the team (ie: plays soccer as a hobby). This site, I Am A Scientist, (specifically the Spotlights Library), can be a useful resource to help students with their research.
- One fascinating discovery, fact or idea that the team found as they complete their research and/or experiment.
- Uncertainty: select one area of uncertainty you encountered while conducting your experiments. Create an image (digital or hand drawn) that models why the uncertainty exists, and include a one paragraph description of uncertainty and its impact on scientific study.

When all students have completed their experimentation and curation, conduct a café style, mini-poster presentation. Split the class half, one half of the students will be presenting their posters, the other half will be the audience. Each group will attend two presentations, and present their poster twice. The café style poster presentations will be conducted to showcase the students' efforts and evaluate.

Note: By inviting community partners, administrators, and parents to attend you can encourage a higher level of preparation by students for their presentations. They will have the opportunity to more authentically obtain, evaluate, and communicate information while also receiving a higher level of questioning from the audience members.

Resources:

- I Am A Scientist
- Edutopia- Edutopia's top ten tips for assessing Project Based Learning | PDF

REFERENCES:

Engagement:

1. The Importance of Accuracy in Our Daily Lives | Michelli Weighing & Measurement.
2. Learning & Teaching Scientific Inquiry: Research and Applications

Book by Crystal Bruxvoort and James Jadrich https://my.nsta.org/resource/2084

3. Measurements & Uncertainties

Evaluation:

4. To Boost Higher-Order Thinking, Try Curation | Cult of Pedagogy
5. 7 Easy Ways to Support Student Writing in Any Content Area | Cult of Pedagogy

- This article references several women who were instrumental in nuclear physics research who are often overlooked, Women Have Been Disappearing From Science for As Long As They've Been Allowed to Study Science.
- Doing the assignment yourself first— DOGFOODING—will also help you identify flaws in the assignment that can be tweaked before you hand it over to students.