The power of nanoscale

BY SHOIEB SHAIK, DAWEN LI, MARION J. GOLDSTON, AND SCOTT WEHBY

Two decades after basic research into nanoscience began, nanotechnology is finally delivering on its promised benefits to society. Because nanosized particles (*nanoparticles*) can exhibit unique properties, such as luminescence or catalytic behaviors, under specific conditions, students often want to know more about them. To prepare students for the nano era, it is important to include nanoscience and nanotechnology concepts in the middle school curriculum. This article describes activities in which students examine how the ratio of surface area to volume is related to the size of an object, a concept that allows nanoparticles to react quickly with other matter and exhibit unusual properties. Following the 5E model, students explore the characteristics of matter at the nanoscale.

Engage: Evoking students' ideas

Although most of the world uses the International System of Measurement, commonly referred to as the *metric system*, many students in the United States are not familiar with it. So, as part of the Engage phase of the lesson, we administer a presurvey to find out what students know about metric units. (Pre-survey is available with this article's online supplemental materials; see Resources.) Students are asked to make a list of various metric units associated with length. Additionally, we give students metric units for length, which they sort from largest to smallest (see online supplemental materials in Resources). We also encourage students to give examples of unit size, such as, "A centimeter is about the size of my pinky nail" and "A meter is about the distance between outstretched arms."

After discussing students' ideas about metric measurement, we found that our students had some familiarity with centimeters and meters but lacked a solid grasp of kilometers, millimeters, micrometers, and nanometers. Our students said they had heard of the units but struggled to give examples. One student asked if a nanometer was related to an iPod Nano, which "comes in a small size." This student was heading in the right direction. After listening to their brief discussion on these units, we knew that we needed to give students referents to assist them in conceptualizing nanoscale objects.

Explore and Explain

To help students understand length (distance) in metric measurements, we ask them to measure a variety of everyday items using millimeter, centimeter, and meter units. Through these activities, students are also asked to find the number of centimeters in a meter, the number of millimeters in a meter, and the number of millimeters in a centimeter. Armed with these experiences, students then explore materials whose sizes are measured in units too small for the human eye, shifting the exploration into a study of the power of nano.

Safety note: We recommend that the following hands-on activities be conducted in class-

FIGURE 1: Increase of surface area–to-volume ratio as an object is downscaled

Cube size (length × width × height)	Surface area	Total volume	S/V ratio	Conclusion
4 × 4 × 4 subcubes	96	64	1.5	By decreasing the length of a cube's side, the overall surface area decreases, but the surface area–to-volume ratio increases.
3 × 3 × 3 subcubes	54	27	2	
2 × 2 × 2 subcubes	24	8	3	
1 × 1 × 1 subcubes	6	1	6	

Note: A subcube has a dimension of 1 × 1 × 1 in a universal unit.

rooms where eating is permissible, because eating and drinking is prohibited in labs in which hazardous chemicals are used. Remind students that this is a lab, and they should only taste when instructed to do so. Goggles are recommended throughout the activities. A soda can may be used as an example to further demonstrate finding surface area and volume. Be sure to wash and bleach all cans prior to use and tell students not to attempt to drink from, puncture, or squeeze the cans. Alternatively, pictures of soda cans may be used instead. Also, check with students to determine whether they have any medical conditions (e.g., food allergies, diabetes). If so, they should not do the taste test.

Part 1: Sugar tasting

Teams of three or four students are provided with two small Styrofoam cups labeled A and B. Each student measures and adds 50 mL of room-temperature water to each cup. Students are given a sugar cube and asked to find its mass (about 3 g). They then measure an equal mass of granular sugar. Students are encouraged to view the cube and granules with magnifying glasses or microscopes on small pieces of black construction paper. Next, we ask students, "What will happen to the sugar cube when placed in a cup of water?" and "What will happen to the same amount of sugar granules placed in a cup of water?" Students record and explain their predictions (see Resources to download a table for students to use, available with this artcle's supplemental materials) before simultaneously adding 3 g of granulated sugar to cup A and the sugar cube to cup B. After placing both the granulated sugar and the sugar cube in their cups, students stir both cups five times. One student in each group then tastes the liquid from each of the cups. (If you would like to have all students taste-test, have

CONTENT AREA

Math and science

GRADE LEVEL

6-8

BIG IDEA/UNIT

Nanoscale

ESSENTIAL PRE-EXISTING KNOWLEDGE

Basic knowledge about measurements, conversions, and metic units

TIME REQUIRED

60-90 minutes

COST

Under $50 for each kit

them pour small amounts of the sweetened water into small, individual cups.)

Students are asked to discuss and explain what they think accounts for their "sweet" observations. Student ideas are reflected in the following comments from our students:

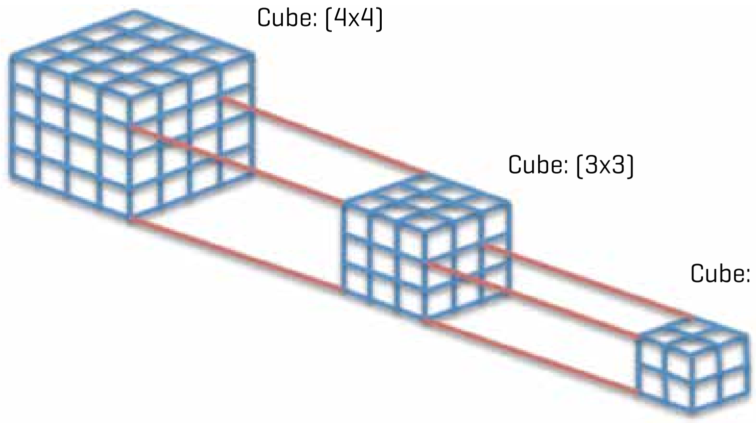
- Demonea said, "I can't really tell the difference. They both taste the same."
- Latisha said, "Cup A is really sweet and B is kind of sweet too. I think the sugar in cup A dissolved faster."
- Jon also said, "To me it looks like more sugar dissolved in cup A—it was sweeter."

Students are asked what they think could cause cup A to taste sweeter. Most of our students said the sugar grains were smaller, so they dissolved faster than the cube. What they didn't mention was the fact that the sugar granules had greater surface area exposed to the water.

The intent of the previous activity is to assist students in making the connection between the size of the sugar granules and the effect it has on sweetness, at least upon the sugar's immediate addition to the water. At this point, the teacher discusses with the class surface area in terms of the activity, using the following questions:

1. How would you describe the difference between the appearance of the cube and the granules?
2. Compare and contrast the granules to the large cube using multiple criteria, such as surface area and volume.
3. What did you notice when you placed the two types of sugar in the cups of water and stirred? How might your observations help explain the difference in sweetness?
4. Use your observations to formulate an argument about why the same mass of sugar granules was sweeter than the sugar cube.

FIGURE 2: Scaling down in size: Surface area–to-volume ratio



Follow-up discussion led to the idea that individual granules of sugar have all sides exposed to water, whereas only the outside of the single cube was exposed to water. Thus, the surface area is larger for the granulated sugar and it dissolves faster. The impact of surface area on the physical change of the sugar is associated with the level of sweetness and paves the way for looking at even smaller particles and their interactions with other matter.

Part 2: Surface area

Students are challenged to consider the surface area–to-volume ratio more specifically. They are asked, "If we cut a tiny, single sugar granule into 1 million smaller units, what might happen to the rate of dissolving?" Students record three or four ideas on sticky notes, which are collected, displayed, and shared with the class. They are then asked how many sides of a sugar cube are exposed, and in their groups, students define the surface area of a cube. Several of our students explained their ideas, but Sam's was closest: "It must be the area of the surfaces of the cube." As a class, we developed a definition of *surface area* as "the sum of all the areas that cover the surface of the object."

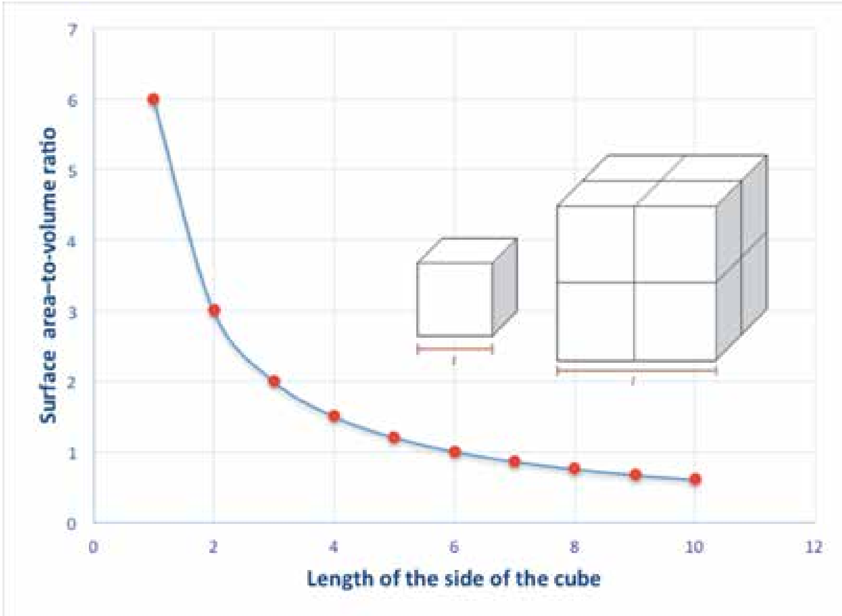
To illustrate surface area visually, students are given a premade paper cube, which they unfold to draw a diagram of what it would look like (see Resources). Note: A cube is covered by six equal-sized squares. The area of each square is "side × side" = $a \times a = a^2$. Joining all the side squares will form a cube. Therefore, students find that the surface area of a cube is 6 (number of side squares) × area of each side square (a^2) = $6a^2$. Students are then challenged to find the surface area of a soda can using images of cans (see Resources).

The next step is to have students make a connection between surface area and *volume*. They are asked to generate a definition for volume. Students are often quick to say that volume relates to the loudness of sound, which is technically correct, but the wrong definition for our purpose. So, in think-pair-share groups, students come up with a definition for *volume* related to matter: "the space that something takes up." Students are asked, "What dimensions of a cereal box are needed to determine its volume?" Through discussion, students explore the three dimensions of volume (length × width × height) and then practice finding the volume of differently shaped boxes using a range of cubic units.

After students explore volume and surface area, they are ready to look at the surface area-to-volume ratio. Students are first asked, "For a cube with sides *a*, what is the surface area?" Next, they are asked, "What is the volume of a cube with the side measurement *a*?" Lastly, students are asked to set up surface area and volume as a fraction, with surface area as the numerator and volume as the denominator. Now they can calculate the surface area–to-volume ratio: surface area/volume = $6\ a^2/a^3 = 6/a$. When considering the size of a cube in nanoscale, the ratio could reach the order of magnitude of a billion, because as a cube is scaled down in size, the surface area–to-volume ratio dramatically increases.

Students are given interlocking cubes with a side length of 1 cm to explore surface area–to-volume ratio. (Note: Math teachers might have interlocking cubes that you could borrow for this activity.) Students build a series of cubes and tabulate their results in terms of surface area, volume, and surface area–to-volume ratio as the cube sizes are systematically scaled

FIGURE 3: Increase of surface area–to-volume ratio when an object is downscaled



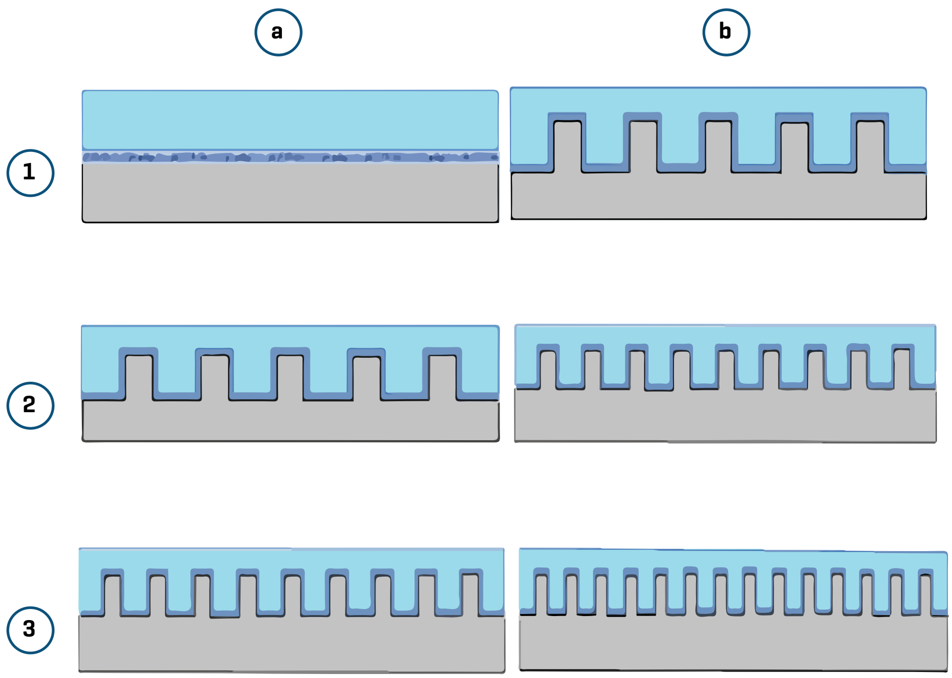
down (see Figures 1 and 2). Next, students search for a pattern and write a rule about the *size effect*, or what happens to the surface area–to-volume ratio as the length of a cube's side decreases. Then, using the graph in Figure 3, students are asked to identify the relationship between the length of a cube's side and the surface area–to-volume ratio. They quickly find that as the length of the side decreases, the surface area–to-volume ratio increases.

The last challenge posed was, "Considering the pattern and rule you found, what do you predict, will occur if the cube were scaled down to the size of a nanoparticle (a billionth of a meter)? Be prepared to defend your prediction." Taking the conceptualization into the realm of nanoparticles, students are challenged to find the percentage of estimated surface nanoparticles for different sizes of cubes (see Basic Math Formulas in Resources).

Elaborate

After examining size effect on the surface area-to-volume ratio, students apply their understanding to a different context: gecko feet. We chose this interesting phenomenon because gecko feet have a large number of tiny, structured patterns that increase surface area and allow the animals to grip even glass surfaces. Each gecko foot has projections that are about hundred of nanometers wide. Although the force per unit area between gecko feet and surface is weak, the dramatic increase of contact area with a glass surface provides an overall strong surface adherence that can hold up a gecko's body. As a gecko moves forward, the foot projections bend, reducing the contact area and interface adhesion.

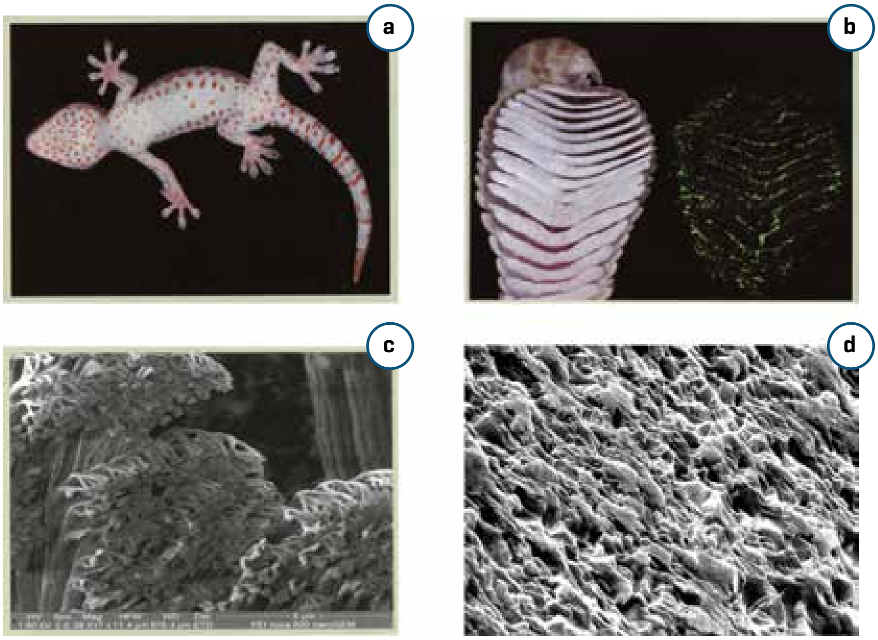
FIGURE 4: Interfacial area between two structures



Students first examine three pairs of diagrams (see Figure 4) and answer the following: "Which one of the pair would hold together better when glued? How do you know whether a *planar* (flat) interface (Figure 4-1a) or *interdigitated* (interlocking) interface (Figure 4-1b) has the greater interface area? Explain or illustrate your choice for each pair. Which one of all the examples would hold together best? Support your answer."

Students then examine images of a gecko's foot (see Figure 5) and answer the following: "Using what you have learned, construct an argument about why gecko lizards have the ability to cling upside down to a glass surface as shown in Figure 5a without having sticky secretions on the pads of their feet." After students think of some ideas, have them share with each other before linking the answer to the surface–area-to-volume concept. Gecko feet must adhere well to surfaces but also easily release so the animals can move rapidly over any surface. Figure 5b shows the underside of the gecko foot on low magnification. The image reveals rippled structures that, on contact, create a grip (*adherence*). Image 5c is a scanning electron microscope (SEM) image of gecko feet at about 26,000 magnification. Although gecko feet are small, the extremely high surface area–to-volume ratio of tiny "hairs" on the rough surface of the gecko's feet creates an enormous surface area for a firm grip on objects. Figure 5d is a magnified SEM micrograph of a glass surface. Even though a glass surface looks smooth to the naked eye, under powerful magnification, it turns out to be rough. The rough glass surface increases surface area and assists the gecko in forming a firm grip.

FIGURE 5: Application of surface area–to-volume ratio: Gecko feet



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(a) A gecko clings to glass upside-down; (b) low-magnification image of the backside of a gecko foot; (c) SEM image (high magnification) of a gecko foot with countless tiny projections; and (d) SEM image (high magnification) of a glass surface, showing the roughness of a "smooth" surface.

Evaluate: Tube challenge

The following can be used as an individual evaluation or as an embedded team assessment. Students are given the cardboard center of a paper towel roll to hold materials. Challenge students to choose appropriate materials that will increase the surface area–to-volume ratio inside the tube. The roll cannot be cut, and students cannot make any changes to the outside of the roll or the ends. Provide students with a variety of materials such as small stones, beans, fine sand. Check with students to see whether they have any allergies or medical conditions before using these materials.

Then ask students to draw and describe how the filling items change the surface area–to-volume ratio. They should explain the ranking of these ratios. Students must measure the items used in the modifications and share their final conclusions with the class. Evaluate the tube challenge experiment using the following criteria:

- Clearly explained how the items selected for the modifications increased the surface area–to-volume ratio

Extension

The following can be an individual assessment or an embedded assessment with teams. Give students or student teams the names of nanoparticles (NP) used in STEM fields and have them use digital technology and the internet to create an NP profile on paper (see Different Types of Nano Particles in Resources). The profile should include the NP's name (formula), approximate size, unique properties, and three uses in society or research. Examples assigned to teams may include:

- titanium dioxide NPs used in cosmetics, sunscreens, hydrogen fuel production, solar cell fabrication, and self-cleaning glass;
- copper tungsten oxide NPs used in oil spill cleanup;
- carbon nanotubes used in medicine; and
- silver NPs used in filters for catching harmful bacteria in polluted water.

Conclusion

The engaging activities described in this article explore topics of contemporary research, exposing students to and enhacing their understanding of the type of work being undertaken in STEM fields. These activities provide students with the opportunity to explore the fundamental size effect at nanoscale and apply mathematics to illustrate the power of nano with respect to surface area–to-volume ratio. ●

REFERENCES

National Governors Association Center for Best Practices and Council of Chief State School Officers (NGAC and CCSSO). 2010. *Common core state standards*. Washington, DC: NGAC and CCSSO.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

RESOURCES

Area of plane shapes—*www.mathsisfun.com/area.html*

Basic math formulas—*www.basic-mathematics.com/basic-math-formulas.html*

Calculate the area of an object—*http://bit.ly/29gYLJD*

Nanoparticle lesson plans—*http://bit.ly/298AtP7*

Power of Nano video—*http://bit.ly/29h1IPC*

Online supplemental materials for this article—*www.nsta.org/middleschool/connections.aspx*

Different types of nano particles—*http://bit.ly/29gxqZg; http://bit.ly/298DSgT; http://bit.ly/29b0EHV*

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Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013)

- The chart below makes one set of connections between the instruction outlined in this article and the *NGSS*. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities.
- The materials, lessons, and activities outlined in the article are just one step toward reaching the performance expectations listed below.

Standard

MS-PS1: Matter and its Interactions
http://nextgenscience.org/dci-arrangement/ms-ps1-matter-and-its-interactions

Performance Expectation

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

DIMENSIONS	CLASSROOM CONNECTIONS
Science and Engineering Practice	
Using Mathematics and Computational Thinking	Students calculate the surface area–to-volume ratio for a cube made smaller and smaller. They then use this information to predict (from their data) what would continue to occur if the cube were to reach nanoparticle size.
Disciplinary Core Idea	
PS1.A. Structure and Properties of Matter • Atoms form molecules that range in size from two to thousands of atoms.	Students answer the following prompts: What will happen when a sugar cube is placed in the cup of water? What will happen with the same amount of sugar granules are added to the cup of water?
Crosscutting Concept	
Modeling	Students answer the following prompts: What will happen when surface area increases or decreases? What are the advantages and disadvantages associated with changes in surface area–to-volume ratio? Does it affect the properties of the material?

Connections to the *Common Core State Standards* (NGAC and CCSSO 2010)

Mathematics

MP.4. Model with mathematics.

6.RP.A.1. Understand the concept of a ratio and use ratio language to describe a ratio relationship between two quantities.

7.RP.A.2. Recognize and represent proportional relationships between quantities.