2006-2672: LAYING THE FOUNDATION FOR NANOSCIENCE AND NANOTECHNOLOGY WITH AN INTRODUCTORY MODULE FOR HIGH SCHOOL STUDENTS

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Laying The Foundation For Nanoscience And Nanotechnology With An Introductory Module For High School Students

Abstract

In response to the need to create a skilled workforce in nanotechnology and to excite young students with the wonders and potentials of science, the National Center for Learning and Teaching in Nanoscale Science and Engineering, is developing educational materials for grades 7 – 16. Learning theory and cutting-edge research are used in the development of modules on nanoscience and nanotechnology. This paper describes the rationale for such materials and describes an introductory module in which students are lead through a series of inquiry-based and hands-on activities, which lead to a design project. Its goal is to teach an underlying principle in nanoscience and nanotechnology—the significance of the surface-area-to-volume ratio as objects get very small. The first section of the module investigates how the physical form of a material can influence the degree to which an object interacts with its environment. Different forms of different materials (steel, superabsorbent polymer, and sugar) are investigated as a function of dimensionality and size. The second section is centered on math tools needed to express very small quantities, viz., powers of 10 and scaling, and we intend that students get a feel for how small "nano" is. Shape and size effects on surface areas and volumes are explored in the third section. Graphs illustrate how the surface area to volume ratio changes with size. Consequences of such a trend are discussed in readings about nature and new technologies. The culminating event is an open-ended design project that incorporates the concepts from the previous activities and facilitates engineering design skills. Preliminary field testing has yielded both qualitative and statistical results.

Introduction To the Science & Technology

A seed was planted in 1959 by Richard Feynman when he postulated that it was possible to write "the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin." [1] The idea lay dormant until the early 1980s, when technology made it practical to visualize and even manipulate individual atoms on surfaces. The result was a new realm of science and technology—the nano-realm. The nanoscale is between the microscale and the atomic scale. With respect to lengths, the nanoscale ranges between about 1 and 100 nanometers; it may extend into the hundreds of nanometers.

Being able to understand and manipulate objects and functions at this scale has extraordinary potential for two general reasons. The first may be obvious. Feynman's proposal is an example. Just being small—very small—is sometimes a big advantage, as in information storage, and as in interacting with other small things. For example, the building blocks of life are nanoscale objects. The medical area is expected to be especially impacted by nanotechnology.

The second reason is not so obvious. It may seem surprising that a scale *larger* than the atomic scale is a new area of science and technology. Nevertheless, it is true that scientists understand the atomic scale much better than the nanoscale. This is because the nanoscale does not "play by the rules". The "rules" that are relevant for the microscale (and larger), Newtonian mechanics, and those for the atomic scale, quantum mechanics, are well understood. It is somewhere in the nanoscale—in the transition from the dominance of one set of rules to the other—where surprising behaviors are opening doors to possibilities where we did not know that doors even existed, such as a piece of tape 1 cm^2 that can hold up 20 kg—and then be removed as easily as a sticky note, or particles much smaller than a light wavelength that change their color just by changing size, or the power of a supercomputer on your desktop. And this is not even the tip of the iceberg. Because nanotechnology holds the promise of building things as nature does, atom by atom, "it holds the potential to change *everything.*"[2]

From Scientific Research To the Classroom

Thus nanoscience and the technology that it motivates may be among the most significant science/technology revolutions to date. The National Science Foundation had this in mind when it launched a comprehensive effort to enhance nanoscale science and engineering education. The effort began in stages over the range of years 2000 – 2005, beginning with graduate education, then undergraduate, high school, and K – 8.

There are several reasons that argue for the study of the nanoscale in pre-college education. Nanotechnology is an *enabling* technology; it is not a technology category, but will make possible advances in many areas. Thus many policy decisions will arise for which citizens should have achieved a level of scientific literacy to make informed decisions. The number of such decisions will also grow because with great potential comes great hype. Citizens should have a knowledge base to help them separate the bad propaganda from the good.

A second reason for pre-college nanoscale education is the need to stimulate a desire in more students to pursue science or engineering in college, and for a subset of them to pursue nanoscience and technology. Student enrollment in college courses for science, technology, engineering, or math careers has been roughly constant for 10 years, while the need, even without the ensuing growth in nano, is not being met. "As nanotechnology moves into the mainstream, companies ... will face a serious shortage of talent—far worse than what is already occurring."[3] Yet, "[a]t the secondary level, teachers, counselors, and administrators, for the most part, do not recognize the coming impact of nanotechnology... ."[4] An introduction to nanoscience and technology may be especially motivating both because of the extraordinary potential of the technology and because students will see here, more than with other areas of science, that it is a very unfinished business; science is a very dynamic enterprise.

Yet another reason is the possibility of a synergistic effect upon learning traditional science topics, most probably, the structures and functions of atoms and molecules. Misconceptions about the atomic scale are common and are due in part to the lack of direct experience at that scale. They are greatly compounded when the experiences that scientists tell us about are so qualitatively different from our macroscale familiarity. Thus we rely on models, which often are macroscale analogs (e.g., the "solar system" model of the atom). If, however, we offer to students a continuous journey of learning from the macroscale through the micro- *and nanoscales* to the atomic, students can "see" the manifestation of the electron cloud behavior as they "get close" to an atom. The difference in the curriculum is analogous to the following. The typical curriculum progression of macroscale—microscale—atomic scale (skipping the nanoscale) is like first learning about an airport and its environs, and then taking off in a seaplane, flying above the clouds, and landing in an ocean, with no idea of the relationship between land and sea. But if the nanoscale is inserted, the analogous journey is traveling on land to the shore and then stepping onto a boat. The traveler has seen everything along the way and knows exactly where he/she is.

Finally, nanoscience and technology are inherently interdisciplinary because nanoscale phenomena are functions of size, not of some other delineating factor that defines disciplines, such as living vs. nonliving. This word *interdisciplinary* is almost ubiquitous when nanoscale research groups are described. Often more than one physical science area is represented (e.g., physics, chemistry, materials science), and if a biological system is the research interest, molecular biologist will be on board. The collaboration between biologists and chemists, especially will increase as biological applications increasingly involve surface chemistry. When the science interacts with technology, a corresponding range of engineers will contribute. Such collaboration often occurs in other areas of research (although it is generally most germane to nanoscale research), and scientists and engineers concerned with high school education have long advocated interdisciplinary lessons.

For practical reasons, lessons about the nanoscale usually will be a good fit in a physics or chemistry class, but a strong argument can be made for biology. Nanotechnology is expected to have a huge impact on biotechnology, and more fundamentally, a biological cell is a highly evolved nanomanufacturing facility.

Having justified the task, its difficulty should be acknowledged. The scale of the phenomena makes direct observation in a pre-college school difficult to accomplish for most examples. One must try to find or invent meaningful macroscale phenomena that have a clear relationship to the nanoscale, and that can take place in a classroom; or one must create models *that do not mislead*. Upon examination, this has not been easy for some molecular and atomic content in chemistry and physics education. Almost always, cost or hardware requirements preclude promising ideas.

A Module To Introduce the Nanoscale

We are creating a module to introduce the nanoscale to students, targeting high school juniors/seniors and their teachers. We mention teachers explicitly because in almost all cases, we suspect that these materials must be educative for them. This is the responsibility of any materials that introduce new content.

Our primary mission is to engage all students in the classroom with materials consisting of a sound selection of content and best-practices. Reflecting the reasons stated above for introducing nanoscale learning, we want to motivate interest in science, and we want to contribute to the achievement of several learning goals.

The module is designed to take about 2 weeks. This is a significant chunk of curriculum time, but the learning goals and tasks are not add-on content; they are standards-based content and skills and, as such, can supplant other lessons. The module consists of four major parts: three sections have well-defined learning goals; the fourth is a design project.

The module is delivered in two components: pdf files and kits. A pdf file is downloaded by the teacher, printed, and copied for students. This is the Student Edition.

Another file is the Teacher Edition. It contains a page-long statement of the module's mission. For each section, it contains information about materials and materials preparation, purpose, summary, objectives, content background information, connections to the curriculum, estimated times, suggested items for students to ponder before they open their Student Edition, comments on each activity, and answers to prompts that students are to respond to.

A kit of hands-on materials is shipped to the teacher.

The Module Topic

When first considering the content for this introductory module, the question at hand was: what is *most* fundamental to understanding the nanoscale? The potential nanoscale topics are far ranging, as one would expect. The combinations of atoms that can form nanoscale objects are huge. Nevertheless, there are categories of properties that are being studied. The three examples given above—the super-strong "sticky note" (an example of scientists trying to catch up with nature as exhibited by a gecko's feet), the particles that change color just by growing or shrinking, and the personal supercomputer—are examples of surface, light, and electrical nanoscale properties, respectively. Others include mechanical (such as strength and plasticity), chemical reactivity, magnetic, and thermal.

All of these properties are types of behavior whose description qualitatively changes during some range of nanoscale size change. The mention of size change is the key to the choice of the major topic of this module, viz., the geometry of getting small. This is the property upon which all of the behavior properties depend. More specifically, they all depend on the surface area, the volume, or the ratio of surface area to volume. As the linear dimensions of an object decrease, this ratio increases—and at the nanoscale, this ratio becomes huge. This is the "*big idea*" for this module; i.e., it is the "coherent foundation for the concepts, theories, principles, and explanatory schemes for phenomena" in nanoscience.[5] A big idea from a scientist's perspective is a foundational explanation that functions both within and across disciplines. From a science educator's viewpoint, a big idea is a "building block for future learning ... [and] is key for future development of other concepts and helps lay the foundation for continual learning."[6] Thus this module can function as the first in a series of nanoscale learning experiences, or as a unit that introduces a new area of science and technology as an interesting context for its learning goals (such as the geometry mentioned above).

The Whole Module

With the module's big idea set, we turned to *learning goals*. These were chosen with a consideration of science and mathematics standards (National Science Education Standards[7], AAAS's Project 2061[8], and National Council of Teachers of Mathematics[9]), prerequisite knowledge, common curricula currently in schools, and learning performances. Later in this document, these factors will be linked to examples. The learning goals are listed here following the big idea:

<u>big idea</u>

As object size decreases, the surface area to volume ratio increases—at the nanoscale, this ratio is huge.

learning goals

1 - The physical form of a solid influences the degree to which it interacts with its environment: the smaller it is in three, two, or one dimension(s), the more readily it interacts.
2 - The magnitudes involved with the nanoscale can be represented with powers of 10 and scaling.
3 - The surface area to volume ratio changes with the shape or size of an object. This ratio changes dramatically in the nanoscale.

There is a section for each learning goal. Each of the three sections begins with an introductory article about something familiar, yet describing an aspect that students may not have thought about (such as a relationship between environmental temperature and animal size and shape).

Then come hands-on activities, which are designed for groups of three or four students. The activities range in time from a few minutes to 1 – 2 class periods. These are mentioned below.

Each section ends with text that expounds the concepts in the hands-on activities.

The Sections

In Section 1, an extra effort is made to engage students. There are three hands-on parts—each with the same theme but with very different materials:

- A: applying a flame to steel in two forms: a nail and steel wool
- B: adding water to a superabsorbent polymer in two forms: pellets and powder
- C: dissolving in the mouth five forms of sugar: approximately spherical (3-dimensional [3-D], thin (approaching 2-D), fibrous (approaching 1-D), smaller 3-D, and even smaller 3-D.

Section 2 deals with two mathematical tools that are necessary for relating to nanoscale quantities: powers of 10 and scaling. The section has four hands-on parts:

- A: Length and volume scale differently: These are measured for a "grow animal" made of a superabsorbent polymer before and after water absorption.
- B: how to represent a wide range of lengths: Macroscale lengths spanning four powers of 10 are determined and must be illustrated on a single sheet of paper. The range is too large for a simple scaled drawing. We would think of using a logarithmic scale. What might students invent?
- C: expressing scaled heights: first at the human scale; then at the nanoscale
- D: Bring it all together: A poster is constructed. Its theme must relate an object at the macro-, micro-, and nanoscales, and the representation from Part B is used.

Section 2 features some nature-of-science processes that are practiced too rarely in many classrooms. Part A sneaks in a science process message: scientific investigations do not always fit into one class period. The animal may still be expanding slightly at the end of a week. The teacher may also use this as another process lesson by letting students decide when to stop taking data. Parts B, C, and D have different types of open-ended prompts. The relative representation in Part B is an obvious instance. In Part C1, students infer estimated heights. In Part C2, students are asked to imagine what they would see if they were nanometer-sized.

Of the three sections, Section 3 is most directly connected to the big idea. Section 3 is mainly about geometry with some qualitative graphing at the end. It begins with the more familiar two-dimensional geometry and then advances to three dimensions.

- A: first, two dimensions: Using a specific number of identical sticks, students create polygons that minimize or maximize perimeter / area. Students are asked to mentally take two of the ratios beyond what the sticks can show, and reach a conclusion about the limiting shape.
- B: now three dimensions: Using a specific number of linking cubes, students create shapes that minimize or maximize surface area / volume. Analogies with Part A are considered, as is the suitability of using the linking cubes to model a one-dimensional object.
- C: For B, volume was constant, and shape was varied. Here, shape is constant (cubic), and volume is varied. Students record length (L), volume (V), and surface area (SA). A Flash computer file has been created to extend this cube-building exercise.

  From these data, students create two graphs, V vs. L and SA vs. L, and analyze them qualitatively.

  Finally, the ratio SA/V is plotted vs. L. Students consider whether this ratio reaches a maximum.

At the end of Section 3, students make connections between Sections 3 and 1 by considering how the linking cubes be used as models of the forms of materials in Section 1 and where the particle forms in Section 1 would be plotted on the SA/V vs. L graph created in Part C?

co-teaching ?

The content of Sections 2 and 3 is mainly mathematical—tools for expression, analysis, and understanding the nanoscale. Thus the module lends itself well to be co-taught by a science and a math teacher. Such collaboration would not only match the more qualified teacher to the respective content. It could shake up students' misguided attitudes about compartmentalized learning. Math teachers, especially, often look for ways to give math more meaning to students.

Unfortunately, in our initial testing of the module, we have encountered numerous roadblocks to such collaboration, even when teachers appreciate the benefits. All that we can do is encourage such teamwork.

Design

The Sections are guided activities; as such, there are a number of features of inquiry that may not occur. They include posing questions, examining information sources, planning investigations, identifying assumptions, thinking critically, and considering alternative explanations.

Engineering design projects provide opportunities to develop these thinking skills. But don't tell the students. They are often motivated by the goal to produce the product via a process that cedes many choices to them. Such motivation, if experienced often enough, could spur a larger subset of students to pursue science, engineering, and technology in college. Major manufacturing organizations in the U.S. are advocating for such changes in curricula because they predict dire consequences if current projections of inadequately skilled workers, including engineers, are realized. A projected nanotechnology revolution will make these consequences even more acute.

For all of these reasons, a culminating design project is considered a critical part of the module. The Design project starts with an article that describes the problem in need of an engineering design solution and gives some background information. It begins thusly:

> "You and your design team work for a company that is a leader in high-quality water treatment systems. The company has just signed a contract with NASA to create a better water treatment system for the International Space Station (ISS)."

The current state-of-the-art and its undesirable features are given. A solution requires a different approach. Photocatalytic nanoparticles that degrade the major contaminants are available, as is a simple recipe for their adhesion to plastic. Plastic objects of different shapes and sizes are available, although students are free to try anything. Students do not simply optimize surface area; for the plastic substrates made available, prices are given, and for any other objects that students choose, price must be considered. A dye models the contaminated water. The photocatalyzed breakdown of the dye molecules is monitored by color strength or pH.

The students are given a generic eight-step Design Process [based on Dieter[10] pp 3-11]:

> 1) *Write*: need, shortcomings of other solutions, goals... 2) *Brainstorm*... 3) *Plan*... 4) Make a *prototype*... 5) *Evaluate* prototype... 6) *Improve* the design... 7) *Present* this prototype to your colleagues in other groups... 8) Prepare a final *report*...

The situation and the process steps outlined for the students satisfy the following characteristics, which are intended to increase the effectiveness of a design project. (The characteristics are paired with their effects.) real-world connection → motivation; lack of specific constraints → student choices; testable product → data for evidence-based reasoning; and iterative → evaluation → re-design.[11]

The teacher has the following assessment rubric:

(For brevity's sake, only the OUTSTANDING column is completed here.)

ASSESSMENT OF DESIGN PROJECTS

CRITERIA	OUTSTANDING 10 points each	GOOD 9 points	ADEQUATE 8 points	POOR 7 points	NOT ACCEPTABLE 0 points
problem	o Students presented very convincing				

	evidence of a need. o Students crafted a strongly convincing problem statement.				
prototype	o Prototype is completed ahead of schedule. o Prototype works beyond what was intended.				
feasibility	o Prototype is highly successful in addressing the problem. o Prototype is accompanied by an impressive set of test data.				
presentation (oral or written)	o Presentation is very well organized. o Presentation includes very complete remarks that are well supported by graphics: data displays, drawings, pictures, video, etc.				
aesthetics	o Prototype has strong eye appeal. o Prototype appears to have been very carefully crafted.				

Testing the Module

We have done some preliminary field testing of the module. It has been used in eight classrooms located in all parts of the U.S. and in five different NCES locales. For such a small sample, the ranges of demographic data are large. All classes have been either chemistry or physics, and have ranged in level of difficulty from introductory to advanced. The grade level range was 10 – 12. The maximum class size was 28. The teachers were half and half: male and female. Their level of academic preparation ranged through the Ph.D. The one category without a large range was years experience teaching high school science. The minimum was 11 years.

statistical analysis

A Design project rubric (see above) was used to score five criteria. The points are totaled, and a class average is obtained: 90%.

Identical pre- and post-tests are given. They are analyzed three ways. The *simple percent gain* was 80%.

The *mean normalized gain* was a moderate 0.38, which may be interpreted as equivalent to the class as a whole having progressed 38% beyond the mean pre-test score toward a perfect score of 100%. Said another way, it is equivalent to 38% of the class having achieved a perfect score of 100%. This compares favorably with a typical science classroom. Normally when presented with new material, only about 2% of the class score 100%.

The *standardized mean gain effect size* is an impressive 2.33. In other words, students gained 2.33 standard deviations between their pre- and post-test scores. This effect size was considerably greater than the highest effect size of 0.73 reported by Lipsey & Wilson[12] for various types of social-science research including 22 effect sizes for K-12 math and science instruction.

qualitative analysis

The teachers responded to a lengthy on-line survey. With such a small sample, there was little clear consensus, but there was some. The consensus for one survey item was negative, viz., the clarity of the Student Edition. We recognize that and have also solicited feedback from others (both teachers and editors) who simply read the module. (They did not use it with students.) The constructive criticism led to the following changes:

Section 1: In the explanatory article at the end, we tried to describe, using words and diagrams, the structure and function of a superabsorbent polymer. More diagrams were requested, so we collaborated with learning technology experts (Braatz group at the University of Illinois – Urbana), and now students (and teachers) will be able to link to a computer-animated explanation.

Section 2: Half of the activities were simplified. The biggest change was the elimination of an activity that directed students to create a semi-log graph.

Section 3: The beginning and ending articles were overhauled due to a lack of relevance to the hands-on parts.

Section 4 and Design: Because the procedure for Section 4 must be changed, new versions will be offered for feedback.

There was a positive consensus for two items. These teachers would encourage others to order the module. The second was in the “student outcomes” category. The module helped students function better as a team member.

Teachers went beyond the requisite numerical response ratings during the on-line survey to add the following comments:

> “Every day as they come into class, they ask me what to do next regarding the Nanoscale module.”

> “This [formulate explanations and models] is the best feature of the module.”

Phone interviews with some of the teachers gave us many specific suggestions plus the following information about the module’s fit into existing curricula. The module fills a hole that often exists in chemistry curricula, viz., the relationship between surface area and reaction amount. In physics curricula, the module is a good fit between classical and quantum physics.

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Student is amazed, or amused, by how fast a superabsorbent polymer absorbs water when the polymer particles are small.

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