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Nanotechnology education

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Precollege nanotechnology education: a different kind of thinking

Abstract: The introduction of nanotechnology education into K-12 education has happened so quickly that there has been little time to evaluate the approaches and knowledge goals that are most effective to teach precollege students. This review of nanotechnology education examines the instructional approaches and types of knowledge that frame nanotechnology precollege education. Methods used to teach different forms of knowledge are examined in light of the goal of creating effective and meaningful instruction. The developmental components needed to understand concepts such as surface area to volume relationships as well as the counterintuitive behavior of nanoscale materials are described. Instructional methods used in precollege nanotechnology education and the levels at which different nanoscale topics are introduced is presented and critiqued. Suggestions are made for the development of new nanotechnology educational programs that are developmental, sequenced, and meaningful.

Keywords: education; instruction; nanotechnology; scale; size.

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1 Introduction

The rapid growth of developments in nanotechnology and nanoscale science has resulted in a need for nanotechnology education at multiple levels to not only train nanoscale scientists and engineers but also to prepare future citizens to engage with the technology [1, 2]. Furthermore, these developments are accompanied by complex questions about the ethical and societal implications of this dramatically different technology. For example, scientists and engineers can build new materials using a bottom-up approach, atom by atom (e.g., [3]), resulting in questions about tinkering with the very nature of matter itself and subsequently “playing God” [4].

It is not just scientists and engineers who will need a greater understanding of nanoscale science developments. Nanotechnology is already having a significant impact on society and revolutionizing manufacturing and health care [5]. For example, advancements in nanotechnology have resulted in new forms of efficient drug delivery [6] and new ways to treat diseases with fewer side effects [7]. There are now engineered materials that are stronger [8] and designed for highly specific purposes [9]. Furthermore, there is a technological revolution taking place in the areas of computing and electronics with new designs that are significantly more energy efficient [10].

In order to prepare the next generation of scientists and engineers as well as engaged citizens, we need new nanotechnology educational programs. This need for nanotechnology education has emerged rapidly in parallel with the quick development of nanotechnology as a field. As a result, schools, universities, and science centers have had to move quickly to create new courses and curricula without the typical time frame to develop and test different approaches. Nanotechnology educational programs have sprung up across grades, subjects, and contexts to meet this growing need with little evidence as to their efficacy. Most of the nanotechnology education efforts have focused on undergraduate and graduate levels with less discussion about developmental progressions for K-12 education. Many of the efforts to create new precollege programs have been driven by university faculty, science educators, and policy makers (e.g., [11]) who recognize the need to prepare the next generation of scientists and engineers but do not have

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the experience to design and implement developmentally appropriate K-12 curricula.

To create a new educational initiative in nanotechnology education requires us to step back, review relevant research about teaching and learning nanotechnology, and build on this body of knowledge to create effective instructional programs. In particular, there is a need to determine what should be taught at different grade levels to scaffold knowledge to produce nanoliterate citizens. Nanoscale phenomena include very challenging concepts such as quantum effects and atomic interactions, topics that are challenging for even the most highly educated individuals. And yet, one nanotechnology engineer stated that he could teach elementary students about nanotechnology (personal communication). Can elementary students learn nanotechnology concepts? What components of this new technology are most easily understood at various developmental levels of K-12 education? Furthermore, what concepts are most important for understanding nanotechnology?

In the sections that follow, we briefly review the instructional approaches and types of knowledge that frame nanotechnology education and consider how different forms of knowledge could be developed to create the most effective and meaningful learning outcomes. We consider the range of skills and perspectives that are needed to prepare people to live in a world with the unique technologies that are emerging from nanoscale science and engineering. Our lens for this discussion is derived from developmental and social constructivist theories [12, 13]. The goal of this paper is to raise questions about the different components of nanotechnology education and to push teachers and curriculum developers to build new programs that are developmental, sequenced, and meaningful.

2 Nanotechnology instructional approaches

An examination of existing precollege nanotechnology educational materials (cf. [14–17]) reveals that many of these focus on tools used in nanotechnology research, applications and products that have resulted from advancements in nanotechnology, behaviors of nanoscale materials that are used in nanotechnology, and macroscale phenomena that are used as analogies for nanoscale interactions. In the sections that follow, these approaches are described, programs that have used these approaches are noted, and then the approaches are critiqued for their strengths and weakness in support of nanotechnology education and nanotechnology literacy.

2.1 Tools approach

Unquestionably, advancements in new forms of microscopy have spurred some of the advances that have taken place in nanoscale science and engineering (e.g., [18]). Scanning tunneling microscopes (STM), atomic force microscopes, and Raman microscopes have been instrumental in pushing nanoscale science and engineering in new directions by allowing for visualization and manipulation of materials at this scale. For the first time in human history, we can move individual atoms [19] and assemble individual molecules one atom at a time [20]. By examining the development of new tools, students can gain a historical view of the advancements that have been made and the role that new tools have played in opening up new research directions at the nanoscale.

There are a number of instructional programs that teach students about scanning probe microscopes and how these microscopes image and manipulate materials (cf. [21–25]). These types of programs are useful in helping students understand non-optical microscopes but are limited in their capacity to teach students about properties and behaviors of nanoscale materials [26]. Furthermore, images of nanoscale objects can lead to misconceptions. For example, the classical image of an atom corral that IBM created with a STM shows a ring of iron atoms on a copper surface [19]. When adults in a museum setting were shown the image and told it was a ring of iron atoms created with a STM, over half (57%) stated incorrect conclusions such as the “copper surface is ‘rough’, ‘soft’ or ‘jelly-like’, or that the iron atoms are ‘sharp’ or ‘rusty,’ or that ‘iron is warmer than ‘copper’ ” [27, p. 84]. The types of misconceptions described here are signals that individuals lack the appropriate developmental framework to meaningfully understand how the new tools function and how to interpret the information gained from these new tools and techniques.

2.2 Applications approach

An applications approach to teaching about nanotechnology allows students to see, at a human scale, the products of nanotechnology and its impact and relevance to them personally (see Figure 1). For example, there are bicycles strengthened with carbon nano tubes [28], wound dressings with silver nano particles [29], and fabrics that repel water and are wrinkle resistant due to their nano structure (i.e., [30]).

Nano electronics
Nano computing
Nano medicine
Nano manufacturing
Nano materials
Nano filters

Figure 1 Nanotechnology applications.

One advantage of an applications approach is that it is relevant to students' experiences, and it can often be experienced at a macroscale. This approach can also mediate student attitudes and alleviate potential fears toward the mass production and distribution of these applications expressed in students [31–35] (see Section 3.7). A disadvantage of an applications approach is that it can be perceived as a "black box" or a "magic trick" resulting in students being introduced to the technology but yet having little understanding of the underlying structures, phenomena, or scales of materials. For example, children can easily observe the hydrophobic stain-resisting effects of nano fabrics but subsequently have no idea as to the underlying mechanism for this action and its connection to nanoscale properties. It may be motivating to watch water bead up and roll off fabric, but without some idea about how this happens the student is left knowing little more about nanoscale science than they did prior to the experience besides its prevalence in modern products. Despite the promise an applications approach has in introducing students to the abundance of nanotechnology products already in use and providing them with relevant examples of these products, little has been done to translate this approach to instructional materials that can promote student conceptual understandings of nanotechnology.

2.3 Nanoscale behavior approach

Using the processes and behaviors of materials at the nanoscale as a strategy to engage students in nanotechnology has the potential to be highly motivating and yet simultaneously confusing. For example, watching memory wire move to a different configuration with the simple addition of heat is amazing and engaging. This commonly used demonstration to teach students about nanoscale structure serves as a discrepant event that hooks students and engages them in exploring the process of nanoscale behaviors [16]. However, understanding the changes in nickel-titanium shape memory alloy crystal configuration from austenite to martensite involves much more than a superficial knowledge of chemistry and materials science (i.e., [36]).

Self-assembly of materials is another important process in nanotechnology [37] that is also found in nature (such as in protein folding or lipid bilayer formation). Educators often use physical models to simulate self-assembly with magnets and plastic blocks [38, 39]. Precollege students find it interesting to see how random motion and collisions can promote self-assembly of specific shapes and materials. Underlying this process are some fundamental ideas that can promote understandings of physics, chemistry, and thermodynamics. For example, the random thermal motion of molecules that influences self-assembly is particularly difficult to understand and is not congruent with our desire to find order in our environment [40, 41]. To understand randomness requires that one have an understanding of probability [42]. Concepts of randomness are complicated by the belief held by many precollege students that there are agents that control and direct random events (such as a coin toss or a lottery) [42, 43]. Even though understanding randomness is difficult, it is important if students are to develop the more sophisticated understandings of important concepts of atomic and molecular motion.

2.4 Analogical approaches

Nanoscale phenomena are not easily experienced at the macroscale, and as a result analogical representations are often used to introduce nanotechnology to K-12 students. Analogies are common in science center displays and lessons on nanotechnology. Using analogies requires students to mentally map a familiar analog to the target [44]. For example, "If an apple was magnified to the size of the earth, then the atoms in the apple would be approximately the size of the original apple" [45, p. 5]; the familiar analog is the size of an apple, and the target is the size of an atom. By definition, analogies are models of reality, and as such every analog breaks down somewhere [46]. Furthermore, while analogies can be beneficial to students in understanding concepts, they can also foster alternative conceptions [47–49]. Piaget et al. [50] argued that analogical reasoning is based on relational similarity that does not develop until early adolescence.

In contrast to Piaget's work, other research has shown that younger children can reason with analogies with relational knowledge [51]. Halford [52] claims that memory limitations can constrain analogical reasoning. Halford suggested that the processing load for analogical reasoning can be reduced if the concepts can be mapped with fewer dimensions or through the use of conceptual chunking. This is particularly salient when multiple size analogies are made to teach about size and scale (relevant to an understanding of nanoscale phenomena). The challenge of multiple analogies is seen in this example that asks students to imagine that a green pea is 1 m wide [53]. If this were the case, then 10 m would be the size of a spoon full of peas. A million meters would be the size of a houseful of peas and so forth continuing on with the pea analogy to compare sizes with descriptions such as New York City covered 1 m deep with peas and on to larger sizes that compare to the world covered in peas. Analogies such as this one are challenging in many ways. First, not everyone eats peas and imagining a spoon full of peas is not a linear image to compare to something a meter long. Then one has to go from one pea to spoons of peas, to a houseful of peas (volume) and then on to conceptualizing how many peas are a meter deep. Many students may never have gone to New York City and as a consequence would not have a clear idea about how large the area of the city cover. This is an analogy that is likely to lead to cognitive load such that students may not be able to follow the chain of reasoning to understand the size of a meter or a kilometer or larger size.

Analogies are also complicated by the fact that students bring an array of different experiences to the learning context, and so all students may not be able to reason with the same analogy [54, 55]. In a study of graphical representations and scale, Ma [56] interviewed museum visitors to see what a scale ladder (a size line with objectives at different sizes) conveyed. Ma reported that in some cases the scale ladder helped visitors understand relative size. However, 27% of visitors found at least one aspect of the ladder confusing.

Utilizing analogies to teach nanoscale properties becomes even more complicated when educators move to teaching about scaling effects (a critical component of work at the nanoscale). The use of analogies breaks down in this context because of the counterintuitive behaviors of materials at the nanoscale as opposed to the macroscale. For example, the color of semiconductor quantum dots changes with the size of the dot [57], magnetic iron particles lose magnetic properties at very small sizes [58], and silicon nanospheres between 40 and 100 nm exhibit much greater hardness than bulk silicon [59]. An understanding of scale requires meaningful cognitive interpretation of size changes at various magnitude scale levels (e.g., molar human scale, microscale, nanoscale, astronomical scale), the associated changes in measurement scales (e.g., meter to nanometer), and the changes in physical behaviors at different scales.

In summary, each of the approaches to precollege nanotechnology education described has advantages and disadvantages. Beginning with a tools approach helps students understand how advancements in tools and techniques opened up new opportunities for innovative science and engineering approaches to working at this small scale. Taking an applications approach provides macroscale relevant examples of how nanotechnology is influencing our world and changing engineering and materials science. Behavioral approaches are very motivating due to the unexpected and unusual ways materials behave at the nanoscale. For example, seeing how color changes when particle size gets smaller challenges and amazes the learner. Finally, analogical approaches can be very useful in helping students bridge the macro to the nanoscale. Analogies provide a framework for understanding size, scale, and behaviors at a scale we cannot directly experience. It is likely that no one approach is ideal to appropriately develop nanoeducation-based curricula, but the strengths and weaknesses of these approaches must be taken into consideration as educators design strategies for students to access the nanoscale world. In the section that follows, we extend this look at nanotechnology education to examine the types of knowledge, levels of development, attitudes, and perspectives that are needed to construct meaningful understandings of nanotechnology.

3 Types of knowledge in nanotechnology education

The array of existing lessons and demonstrations on nanotechnology teach different types of knowledge and different components of the processes of science and engineering. All are important, but some are more focused on nanotechnology than others. Furthermore, teaching students about the counterintuitive properties of nanoscale materials can result in a cognitive confusion that can end up with misconceptions about nanotechnology. In this section, we explore the different types of knowledge and processes that comprise nanotechnology education and explore the developmental underpinnings needed to master these targeted concepts, skills, and processes.

3.1 Declarative knowledge

A common strategy for teaching about nanotechnology begins with teaching students the definitions of terms such as nanometer, quantum, nanotube, and lithography. Students of all ages can memorize declarative terminology, but in order for the new knowledge to be conceptually meaningful it needs to be linked to prior knowledge and experiences [60]. Furthermore, students need to have mastered fundamental science concepts to assimilate this new knowledge into their existing schemas. Early in our work, we taught a middle school class about nanometers and then asked a student if he was the size of a nanometer how would the world be different? The student thought for a minute and then replied that he would be small enough to walk under the door to the next classroom and see what was happening next door. Although it is true that the size of the student would be small enough to pass under the door, the student had no idea how long it would take, how difficult it would be to travel that distance, the degree to which he would likely stick to the floor tiles, and the obstacles that would be encountered in even trying to move at that scale. This student lacked an understanding of the behavior of materials and relevant forces at the nanoscale. It is not enough to have students learn new words and definitions, students also need to have the underlying developmental frameworks and understandings of foundational concepts to meaningfully integrate new ideas into their existing concepts of science and engineering.

3.2 Knowledge of the processes of science

Precollege and informal science center educators have had good success in using nanotechnology education to teach students about the science process skills (observing, predicting, hypothesizing, testing, and drawing conclusions). Many of the demonstrations and investigations designed for museum settings are particularly effective at teaching individuals to observe and predict. Demonstrations with nano fabric and memory wire are particularly good examples [16]. People can make observations, ask questions, and predict what will happen with a different fabric or different type of metal.

When educators attempt to teach elementary students about nanotechnology, one of the best outcomes is when they are able to enhance students' science process skills. An example is the use of black boxes or black bags that contain an unknown object and the learner is asked to make observations, use touch and hearing, and then to use the information they have gathered to make a prediction about the contents of the container (eg., [16]). This investigation models the challenges that nanoscale researchers encounter when trying to study nanoscale materials that are not often directly observable. Furthermore, this investigation is a useful analogy for many types of science research such as space science, microbiology, and physics, where indirect measurements are made and models are created to represent phenomena and objects.

3.3 Conceptual/connected knowledge

Perhaps the greatest challenge is to teach precollege students and the general public about the big ideas that frame nanotechnology and nanoscale science. The ultimate goal is to produce students who have meaningful and connected concepts that they can apply to new knowledge of nanotechnology. The potential for nanoscale science to be a unifying idea [61] for learning biology, chemistry, physics, and earth and space science depends on students being able to relate nanoscience concepts to knowledge they have learned within other science domains. For example, learning about self-assembly at the nanoscale can be even more powerful when students have concepts of molecular bonding, molecular motion, three-dimensional environments, and examples they learned in other contexts such as DNA replication (e.g., [62]).

Many of the recent goals of policy documents [63] stress a need to view science as integrated and not artificially divided into separate disciplines. The *Next Generation Science Standards* has included a new framework for science education on this principle by stressing "cross-cutting themes". Nanotechnology provides an opportunity for these themes to be discussed and the interdisciplinary connections of chemistry, biology, and physics to be highlighted [63].

3.4 Developmental knowledge

It is becoming increasingly clear that developing meaningful and connected knowledge of nanoscale science and engineering is part of a learning progression that has developmental components (e.g., [2, 64]). Concepts (particularly those that are above the level of declarative knowledge) are typically built over time and rest on cognitive development. For example, there is evidence from Piagetian-based research that there are underlying developmental components to understanding objects in space and sizes of objects – part to whole [65]. Concepts of measurement and size are built on fundamental understandings of partitioning as well as conservation of length [65, 66]. Lehrer [67] suggested that learning measurement (a component of understanding size and scale) is built upon a previous understanding of concepts of unit-attribute relations, iteration, tiling, identical units, standardization, proportionality, additivity, and origin of location.

3.5 Development of complex relationships: surface area to volume

As we have discussed, there are different types of knowledge (e.g., declarative, procedural/process, and analogical), but in addition there are complex phenomena that are developed as a result of a synergy of experiences, knowledge, and development. One such phenomenon includes the impact and effect of surface area to volume relationships in a variety of contexts. The relationship of surface area to volume plays a critical role in scientific processes such as rate of diffusion, enzymatic activity, rate of chemical reactions, cell growth, and the physics of building structures of different sizes. Whether the application is medicinal nanoemulsions, environmental nanosensors, or engineered fibers, all are influenced by surface area to volume relationships [68–71].

At the macroscale, intensive properties such as melting point, conductivity, and malleability are considered as being independent of the amount of material that is present, but when materials are at the size of a nanometer, these intensive properties become extensive (size dependent). For example, the smaller the object, the greater the surface area to volume ratio is and surface-dominated properties (such as melting point, adhesion, and capillary action) change with the size of the material.

There is growing evidence that understanding surface area to volume is tied to students' underlying cognitive development. For example, Pinard and Chassé [72] studied students' concepts of conservation of surface area of an object and examined whether or not their concepts of surface area would impact the conservation of the volume of the same object or vice versa. These researchers reported that separating concepts of surface area from volume was not possible until students reached the formal level of thinking.

One component of formal thinking is proportional reasoning, which has been shown to be essential for students to effectively apply understandings of surface area to volume [73]. Proportional reasoning has been called a watershed concept, a cornerstone of higher mathematics, and the capstone of elementary concepts because of its critical role in developing understandings of concepts such as surface area to volume [74]. The ability to apply proportional reasoning emerges as students develop formal reasoning and is correlated with age [75]. According to Lamon [76], students can use proportional reasoning when they are able to conceptualize the invariance of the function ratio between two measure spaces and recognize the equivalence of appropriate scalar ratios. Research has also shown that it is not just age that enables students to develop these kinds of understandings but that there is an important role for instruction to facilitate development [12, 77–80].

In an effort to understand how students learn critical concepts such as surface area to volume, Taylor and Jones [81] examined middle and high school students' understandings of surface area to volume relationships and found that there is a correlation between understanding surface area to volume and having strong reasoning abilities and visual-spatial skills. Even understanding magnified images (an initial stage to understanding size and scale) is associated with good visual-spatial skills [73, 82].

3.6 When concepts collide

As noted above, there are scaling effects at the nanoscale that are counterintuitive [83]. For example, as an object becomes small and size approaches the nanometer scale, extensive properties such as mass, volume, and surface area change disproportionately, and properties normally thought of as intensive such as color, conductivity, magnetization, and hardness change with size in unexpected ways. At this scale, nature has different rules, some of which are quite unexpected. These counterintuitive effects challenge educators to carefully consider the balance of declarative, process, conceptual, and complex knowledge that is needed to educate the next generation of citizens, scientists, and engineers. A more carefully researched educational progression is needed to define how and when nanotechnology should be taught.

3.7 Attitudes and beliefs

In considering instructional approaches and required knowledge for effective nanotechnology education, it is also important to address the complementary attitudes toward and beliefs about nanotechnology that occur when discussion of this technology arises. Attitudes, conceptualized as polarized feelings for or against a particular technology or its application, become particularly exaggerated in the context of emergent technologies for two common reasons. One is the "gee whiz" factor (often perpetuated by sensationalized use of the technology in news and popular media) of the potential of new technologies to change society. This optimism is often balanced by the fears associated with the integration of the technology into the public mainstream [84]. These fears often stem from perceptions of the potential risks to human health and the environment as a result of the technology balanced with the societal benefits [85].

Discussions of attitudes and beliefs as a mediator of student learning in nanotechnology education are important for two primary reasons: (1) literature demonstrates that knowledge of nanotechnology has a complex relationship with attitude polarization [86, 87], and (2) in consideration of citizen science and decision-making processes, attitude-based heuristics are often a more pertinent driver of decision making and informal reasoning than knowledge itself. Each of these issues is discussed briefly below.

There is an assumption made by the knowledge deficit model in science education that an increase in knowledge will naturally lead to individuals having more positive attitudes toward a particular technology. This relationship has been shown to be complex, but rarely does it have direct correlation [88]. Not only is knowledge not a prerequisite of nanotechnology attitudes, but also increasing knowledge does not seem to greatly adjust the polarization of attitudes and beliefs toward the positive end of the spectrum [89]. It appears that worldviews (often tied to moral, ethical, and religious beliefs) and individual experiences are a greater predictor of individual attitudes toward nanotechnology than volume of content knowledge [90]. There does, however, seem to be a threshold value, with experts possessing extensive knowledge exhibiting generally more positive attitudes toward nanotechnology [91].

One of the strongest mediators of attitudes toward nanotechnology appears to be the perceptions of the risks that this technology might have toward human health or the environment. Students are not immune to these fears related to perceptions as our work and others have explored (see [34] for a recent example as well as [2] for a summary of other relevant studies). Our own work has demonstrated that both future scientists/engineers and future science teachers have concerns about the development of nanotechnology for public use [31, 32]. As indicated in the work above regarding the relationship of knowledge and attitudes, perceptions of risk are often dissociated from knowledge levels of nanotechnology and more closely associated with perceptions of the benefits and whether students perceive that the applications will directly contact them internally [31]. In addition, pre-service science teachers rarely rely on knowledge to describe their attitudes and perceptions of risk toward nanotechnology and seem to rely on an inherent value system toward science and technology in general [31].

When engaging in public discourses in which attitudes and beliefs about new technologies are involved, individuals often rely on informal reasoning to make decisions. Informal reasoning is different from formal reasoning as it requires an integration of both evidence-based argumentation from data and a personal reflection of value-based judgments. Sadler and Fowler [33] suggest that in socioscientific reasoning in particular there is a complex relationship of informal reasoning to content knowledge that they call the Threshold Model of Content Knowledge Transfer. This model proposes a step-wise function of content knowledge needed to appropriately address complex socioscientific issues as they arise in the public debate and may be a more realistic model than the typical linear relationship that the knowledge deficit model proposes. For example, Karlsson et al. [34] found that when asked to make a formal argument whether to support the development of certain nanotechnology products, 55% of student arguments were based on values, 20% were based on personal experiences, and only 25% were based on factual knowledge.

It stands to reason that most students will not have the same level of knowledge regarding nanotechnology as expert nanoscale scientists and engineers, so a consideration of attitude formation accompanying knowledge development in nanotechnology is important. Furthermore, there is evidence that studying a new topic such as nanotechnology can be motivating and encourage students to learn more about science and engineering [35]. But unlike knowledge, attitude development is not strictly developmental (i.e., as students develop more knowledge their attitudes toward nanotechnology do not necessarily improve). Providing students with positive experiences with nanotechnology applications, tools that will progress the technology in the future, and careful consideration of the "realities" of nanotechnology divorced from the images of the technology as presented in popular culture are critical to assist students in approaching the public discourse of nanotechnology in a positive light.

4 Discussion

As we have outlined here, there are a number of different approaches to nanotechnology education. But it is not yet clear whether a tools-based, application,

Table 1 Correlation of nanotechnology instructional approaches with knowledge and attitudes.

	Types of knowledge and attitudes			
	Declarative knowledge	**Processes of science and engineering**	**Conceptual knowledge**	**Attitudes**
Tools-based instruction	Yes	Yes	No	Yes
Applications of nanotechnology	Yes	Yes	No	Yes
Behaviors of materials at the nanoscale	No	Yes	Yes	Yes/no
Analogical	No	No	Yes	Yes/no

analogical, or behavior/process based approach is the most effective in engaging students and producing the best learning outcomes. The complexity of concepts that build on different types of knowledge has shown educators that there are essential learning experiences and developmental levels needed to meaningfully master nanoscale science (Table 1). Some approaches are more effective in teaching students about the processes of science and engineering, whereas other approaches are more likely to build positive attitudes toward learning nanotechnology.

The unexpected and counterintuitive behavior of nanoscale materials raises questions about the age to introduce nanotechnology education. It is not efficacious to assume that students can learn nanotechnology concepts at virtually any level of precollege schooling. As described here, many nanotechnology topics require sophisticated understandings of science and engineering. Furthermore, the non-linear relationship of knowledge to attitudes toward nanotechnology is evidence of the need for a more careful and research-based sequencing of nanotechnology education curricula.

The intent in this paper is to provoke discussion about how to develop and test nanotechnology precollege instruction. We argue that the time has come to bring teams of educational psychologists, science and engineering educators, scientists, engineers, and teachers together to produce an effective curriculum for nanotechnology education that is developmentally based and sequenced to result in meaningful learning. We run the risk of teachers rejecting nanotechnology education or teaching it in trivial ways if we are not able to connect this new area of science to the existing instruction within the domains of science.

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