Chapter 3
Nanotechnology and Education

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Call to the Future

Standing at a wooden podium in a lecture hall at CalTech with a blackboard at his back, Richard Feynman changed the way we see the world. It has been nearly 60 years since he presented his lecture, “There's Plenty of Room at the Bottom” to the American Physical Society. Through a series of “what ifs” and “imagine thats” and even throwing in a wager or two, Feynman sparked the imagination of the scientific community with the prospect of manipulating individual atoms and molecules (Feynman 1960). Could it actually be possible to manipulate matter at the nanoscale, creating functional structures that would revolutionize medicine, computer science, manufacturing, and more? In his vision for what the future might hold, he highlighted the need to engage our youth, suggesting a high school competition that would stimulate interest in the nascent field of nanotechnology.

Feynman speculated that there would be two key challenges facing further exploration at the nanoscale. One would be developing precision tools that could facilitate imaging and manipulating atoms and molecules and the other would be dealing with scaling issues such as relative force dominance and interactions. In the years since that lecture, scientists and engineers around the world have taken on Feynman’s challenges and the field of nanotechnology has rapidly moved to the forefront of global research. Engaging our youth has taken a bit longer to get started, as will be seen further in this discussion.

Advances in imaging tools in the 1980s represented a tremendous breakthrough for nanotechnology. Suddenly, researchers could “see the unseen.” IBM researchers Gerd Binnig and Heinrich Rohrer developed the first electron tunneling microscope in 1981 (which earned them the Nobel Prize in Physics in 1986). Shortly thereafter,

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P. M. Norris, L. E. Friedersdorf (eds.), *Women in Nanotechnology*, Women in Engineering and Science, https://doi.org/10.1007/978-3-030-19951-7_3

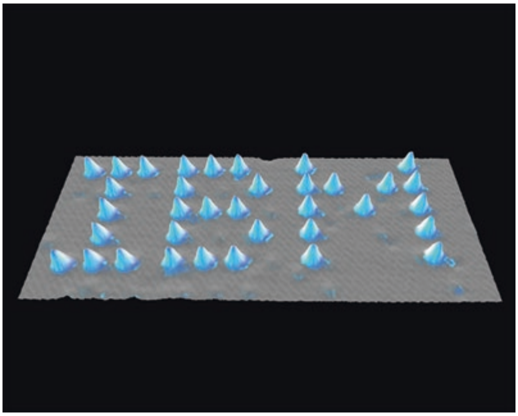

Fig. 3.1. IBM logo courtesy of IBM library

Binnig developed the atomic force microscope, considered a foundational tool for imaging, measuring, and manipulating matter at the nanoscale (Baird et al. 2004). These tools allowed Don Eigler, an IBM researcher, to create one of the most famous images in nanotechnology.

Using a scanning tunneling microscope, he very carefully manipulated 35 xenon atoms to create the IBM logo, a gift to the corporation that gave him a job (Baird et al. 2004) (Fig. 3.1.).

Feynman's vision for the potential of nanotechnology was further expanded as the buckminsterfullerene was discovered by Harry Kroto, Richard Smalley, and Robert Curl in 1985, named for its similarity in appearance to the geodesic dome designed by architect Buckminster Fuller. Additionally, the carbon nanotube, a tubular structure of carbon atom sheets, was discovered by Sumio Iijima in 1991 (Baird et al. 2004). As researchers explored the nanoscale with these new tools, it became quite apparent that nanoscience, by its very nature, lies at the convergence of all scientific disciplines. Both of these carbon allotropes have since served as the basis for a myriad of innovations in materials science, medicine, electronics, and energy storage and manipulation and will no doubt continue to do so in the future.

Richard Feynman stressed the need for our youth to understand the importance of nanotechnology as he recognized that students represent not only the future consumers of technological innovations, but also the future leaders in their research and development. As nanotechnology has advanced over the last 30 years, educators have recognized this call to the future, yet have grappled with how best to engage youth in its often abstract mysteries.

> A key challenge for nanotechnology development is the education and training of a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress of the new technology. The concepts at the nanoscale (atomic, molecular and supermolecular levels) should penetrate the education system in the next decade in a manner similar to the way the microscopic approach made inroads in the last 50 years (Roco 2002).

Student Readiness: Introducing the World of the Very Small

Understanding student readiness and the process by which educators can help students bridge knowledge is key to the successful integration of nanotechnology in both formal and informal educational settings. Learning theories abound discussing the manner in which humans construct knowledge, but most agree that knowledge is built in varying degrees by biology, environment, and experience (Lutz and Huitt 2004).

Jean Piaget linked readiness to learn to clearly define biological constructs (Piaget 2001). He postulated that children move through a series of developmental stages loosely aligned with chronological age. Each stage presents a unique circumscribed process for receiving and processing information. Children in the sensorimotor stage (ages birth–2 years) learn primarily through trial and error, building an understanding of object permanence. They are not able to understand symbols as representing reality. In the preoperational stage (ages 2–7), children are very egocentric, but begin to ascribe meaning to symbols and develop a wicked imagination! The concrete operational stage (ages 7–11) introduces children to cognitive processing of symbols in a logical manner. They begin to problem solve and develop ideas in their heads, but their work is based on an understanding of concrete objects. In the formal operation stage (ages 11–adulthood), children are able to understand abstract concepts through symbols and solve complex problems.

Although very focused on biological constructs, Piaget also described "schemas," building blocks of knowledge that could be added to and changed through environmental interactions and hands-on experiences. These schemas assist children as they encounter new types of information, facilitating processing of that information by guiding how they respond based on their developmental stage and past experiences (Piaget 2001).

In order for successful integration of nanoscience in educational curricula to be achieved, educators should note that children in the early developmental stages will have difficulty working with abstract concepts. Learners will need some type of scaffolding through environmental interactions and experience to slowly build understanding. Educators must understand the schema that their students are using to effectively help them learn and integrate new knowledge. Lutz and Huitt describe this as developing a spiral curriculum with concepts being "addressed at ever increasing levels of abstractness and complexity" (Lutz and Huitt 2004).

Constructivism approaches learning through the lens of mental structures which become more elaborate and sophisticated through interaction and experience (Bruner 1987). Learners construct knowledge based on knowledge that they already possess. This approach highlights the importance of bridging new knowledge with past experiences, noting the power of hands-on activities to make connections and how linking abstract and concrete concepts can help learners bridge the gap. A common application of this in nanoscience education is playing a size and scale card game where students align familiar objects such as a human hair or a fly to their measurement in nanometers. By using a concrete example, students are able to begin imagining the true size and scale of the nanoworld.

Jerome Bruner believes that certain aspects of any content or principle can be successfully taught to any child no matter the complexity of the topic. It may simply be necessary to revisit the topic as the learner gains more knowledge and complex thought processing abilities (Bruner 1987). For instance, according to the Next Generation Science Standards, students in grade 2 should be able to describe and classify materials according to their observable properties such as color. In grade 5, students explore matter and its interactions including the nature of color as the result of light interacting with the matter being observed (NGSS 2013). By the time students are in grades 7–12, they are exploring color through the complexities of wavelengths of light being reflected and absorbed and the size of the matter being observed. Educators can introduce the idea that the size of an object might impact how it interacts with the world at a very early age, weaving it into the conversations about color and revisiting it as the students build knowledge. By doing so, when students begin manipulating matter at the nanoscale in their physics classrooms, it will make perfect sense to them that gold is yellow at the macroscale and turns red at the nanoscale since they understand the relationship between particle size and its interactions with the world around it.

Equally important is the need to ascribe meaning to learning, providing the "so what" to student inquiry. Meaning allows learners to more easily categorize new information so that it can be added to prior knowledge and utilized. It also adds a powerful motivational factor for learning. For instance, a group of seventh and eighth graders demonstrated a high level of interest in a photolithography lab that modeled the process with "Nanosmores." They could relate the new information to fond memories of camping trips, or backyard adventures. The students understood clearly that this was a layering process, with different layers having different properties lending themselves to the proper function of the model. By establishing a comfort zone of understanding, the students were then able to confidently explore "writing with light," a tremendous advance in nanotechnology. And the fact that they could eat the lab at the end certainly didn't hurt!

Meaningful learning requires understanding the big picture as well as the details (Brooks and Brooks 2000). Nanotechnology is a powerful tool for providing meaningful learning experiences because as learners explore matter at the macroscale all the way down to the nanoscale, they become attuned to how and why matter acts as it does. Thinking becomes more flexible and holistic. Learners are able to give meaning to what is observed, or at least construct the questions that will lead them to answers. As mentioned earlier, the conversation can start small, perhaps asking the question, "Why do sugar granules dissolve faster than a sugar cube?" But building on this, older students might be challenged with why the latest Boeing or Airbus jet is being constructed using a composite material embedded with carbon nanotubes (Chu 2016). They may not know the answer immediately, but they can construct the questions. How will these tiny structures impact the strength of a massive jet? Might there be some safety considerations such as conductivity of electrical discharges as jets pass through powerful storms?

Nanotechnology in the Classroom

As the twenty-first century dawned, it became quite evident that efforts to bring nanotechnology to the classroom needed to be stepped up. University students had been working in the lab on this technology with researchers for at least a decade, but very little nanoscience or nanotechnology was being introduced to primary and secondary students. In fact, nearly 50 years after Richard Feynman's famous lecture, not a single state included vocabulary that specifically referenced nanoscience or nanotechnology in their state standards. So in 2006, Dr. Julia Cothron, former Executive Director of the MathScience Innovation Center (MSiC) in Richmond, Virginia, decided to rectify the situation for the students of Virginia. The MathScience Innovation Center is a STEM hub in Central Virginia supporting 12 school divisions with curricula, teacher professional development, and face-to-face and virtual learning experiences with students K-12 in science, technology, engineering, and math (STEM).

Dr. Cothron: "Approaching its fiftieth anniversary, the MathScience Innovation Center (MSiC) asked the question: How should we help prepare school divisions for the 21st century? Already, the Center led Central Virginia's school divisions in the future-oriented areas of space exploration, integrated Earth systems, and robotics. However, the K-12 curriculum did not address mathematical modeling, engineering, or the behavior of matter at very small scales (nanoscience). Of its future-oriented initiatives, nanoscience was the most important because educators did not understand the scientific principles operating at this level or realize the amazing ways that nanotechnology was revolutionizing all pure and applied sciences, including the development of many common products. Nanoscience was an integrating topic that could be woven through all STEM areas and that enabled the MSiC to Imagine, Create, and Lead. Over multiple years, the MSiC imagined ways that nanoscience could be incorporated into Virginia's educational standards, created and taught model lessons and student courses, and led through teacher training and advocacy at the regional and statewide level."

In early 2006, Dr. Cothron and colleagues at the MSiC began an in-depth study of nanoscience and nanotechnology, with the tremendous support of several universities, including the University of Wisconsin, Georgia Tech, and Penn State, who were beginning to conduct teacher outreach workshops. After attending these workshops and building a team of educators intent on bringing nanoscience and nanotechnology to Virginia's students, the MSiC recognized the importance of its inclusion in state standards. Many months were spent developing language that integrated nanoscience in several key standards. Virginia was in the process of revising its 2003 Science Standards for release in 2010. Dr. Cothron et al. submitted their suggestions for nanoscience inclusion to the Virginia Department of Education. While not all of the suggestions were included, enough were integrated in the standards that a pathway was illuminated. In 2010, Virginia became the first state in the nation to include nanoscience and nanotechnology in its state standards.

Successful integration of nanotechnology into curricular structures requires precise, intentional alignment with current curricula so that the content is perceived as "integral to" and not "in addition to" the content that is currently being taught. At the MathScience Innovation Center, a highly structured curriculum framework, closely aligned with Virginia state standards, was developed based on *The Big Ideas of Nanoscale Science & Engineering,* a publication of the National Science Teachers Association (Stevens et al. 2009). These big ideas were identified by a group of experts including scientists and engineers working at the nanoscale in biology, chemistry, and physics, learning scientists, and science education leaders (both formal and informal). Each big idea was carefully defined with a discussion as to why it should be considered a big idea. In addition, each big idea was explicitly related to secondary curricula and current applications in science and industry. This is vitally important as students construct knowledge about futuristic concepts. As noted by Jerome Ernst, "Curricular activities that incorporate real world examples can enhance students' attitudes about science and emerging ideas" (Ernst 2009). Learning goals for each big idea were also identified targeting specific prerequisite knowledge, potential student difficulties and misconceptions, and what could be expected as learning outcomes (Stevens et al. 2009).

The *Big Ideas of Nanoscale Science & Engineering* include:

- Size and scale
- Structure of matter
- Forces and interactions
- Quantum effects
- Size-dependent properties
- Self-assemble
- Tools and instrumentation
- Models and simulations
- Science, technology, and society

Although developed as a guidebook for secondary teachers, grades 7–12, the concepts included in *The Big Ideas of Nanoscale Science & Engineering* are adaptable for younger learners based on previously discussed parameters.

Nanotechnology in the classroom presents educators with a natural vehicle to explore the interdisciplinary nature of STEM (science, technology, engineering, and math) education. As a convergent discipline, nanotechnology helps learners build integrated knowledge structures that enhance scientific literacy and support creative problem-solving. The move towards STEM education was spurred by the recognition that the manner in which our youth experience education should be more closely aligned to how they will work in their careers. Collaboration and the ability to work across and between different disciplines are crucial to innovation and sustainment. Whether students want to pursue a career in health sciences, high-tech manufacturing, the beauty industry, or design, they will need to possess the cognitive flexibility to see the big picture as well as the details of their expertise. In her article, *For Integrating STEM, Experts Recommend Teaching Nanoscience*, Sarah Sparks contends that although it is a challenge to break down the silos of scientific and mathematical disciplines in a STEM classroom, nanoscience and nanotechnology can ease the way by literally “getting down to the basics” and then building everything back up (Sparks 2015). The very act of observing matter in its smallest parts reveals the interconnectedness of STEM fields and how each discipline together can help build understanding.

As educators are exploring nanotechnology with their students, they are experiencing both challenges and affirming student responses to an integrated curricula. It was reported in one physics classroom that the students responded best to topics regarding the behavior of light. They were intrigued by the nature of light and its behavior at the nanoscale, particularly in discussions about iridescence and thin films. Not surprisingly, given our understanding of how students construct knowledge, they thoroughly enjoyed investigations about carbon nanostructures and hydrophilic/hydrophobic molecules because they could build on understandings that they acquired in their chemistry and biology classes. The properties of carbon and its allotropes “made sense” holistically based on prior knowledge.

One point of frustration was the student’s inability to use some of the tools such as AFMs and STMs in their classroom. They were fascinated by how they worked and really wanted to use them in research. Fortunately, universities have now begun to share their resources through such programs as Remote Access Instruments for Nanotechnology (RAIN). Jared Ashcroft of the NACK Network sees RAIN as a vital connection between our future STEM workforce and the research facilities and technologies that will guide their professional development. This program is completely free of charge, bringing advanced technologies to a diverse group of K-12 and college students right in their classrooms. Nineteen universities currently participate in the program (Ashcroft 2018).

Mickey Mouse® gloves were a hit in another classroom exploring the tools and instrumentation that are required to conduct nanotechnological research. Students in pairs were first challenged to build a LEGO® copy of a small model. One student held a timer and the other students assembled the model copy. Then, as if in a magical shrinking machine, students switched roles and the “assembler” was required to do the task again, except this time they must wear a pair of giant Mickey Mouse® gloves. It became very evident how clumsy it felt to work with very small objects without the availability of appropriate tools. This created a great deal of appreciation for the importance of instrument innovation in research and the historical significance of the development of scanning tunneling microscopes in the 1980s. In addition, the experience scaffolded student understanding of size and scale through a hands-on activity that could be used with a broad range of ages.

Most children by middle and high school have been touched in some way by chronic disease, either through family members, friends, or perhaps experiencing it themselves. Nanomedicine has taken the scientific and health community by storm, particularly in health screening and battling cancer. Although chemotherapy has saved many lives by stopping cancer cells in their tracks, it is a systemic treatment, attacking all fast-growing cells in the body including the healthy ones. This can result in terrible side effects, weakening the body's defenses. Recent research has led scientists to find ways to functionalize fullerenes (buckyballs) so that cancer cells are targeted directly, leaving healthy tissue untouched. A group of middle school students were fascinated with an activity using Kool-Aid© cups and gelatin to model a nanoshell, functionalized buckyballs that can selectively target, heat, and destroy cancerous tissues without harming the surrounding tissue. "Researchers are coating gold nanoshells with antibodies and injecting them into the body. The nanoshells circulate in the blood until they attach to antigens on cancer cells. When a laser is shown on the cancerous area, the gold nanoshells heat up—essentially cooking the cancer while the surrounding healthy cells are unharmed" (Jones et al. 2007). The main motivator for the students was how closely this model activity related to what was actually going on in current research. They were also very excited about how soon such technologies would be available on the market for patient therapies. This activity both educated and inspired students to further explore the impact of nanotechnology on society. It also led to some very interesting ethics questions concerning what would happen to the nanoshells once they had destroyed the cancer cells. Would they end up in our rivers and streams? How would that impact wildlife?

In an elementary setting, a fourth-grade educator focused on expanding her students' understanding of size and scale. She shared with them not only how small nanoparticles are, but also how size impacts how matter relates to forces and interactions. The students enjoyed exploring what a nanometer was when they were challenged to cut a paper strip down as small as they could or all the way down to nanoscale, whichever came first. They soon realized that nanosize is VERY small and they did not have the right tools to reach that scale (MRSEC Education Group 2007). Next, the students were introduced to how tiny some very familiar molecules are through an activity that she called "Smellervision." Introduced by the NISE Network, this activity allows students to experience nanoparticles with their senses. Different extracts are placed in balloons and the students try to identify their smell. The students can't see the extract molecules, but they can certainly smell them. What really startled the students was when they realized that the nanoscale scent molecules actually penetrated the membrane of the balloon (NISE Network 2010). And who wouldn't want to explore nanotechnology with rockets! These elementary students were all eyes and ears as they discovered that particle size affects how particles will react in a chemical reaction. Using simple tools such as Alka-Seltzer® tabs and old film canisters, students experienced first hand how size variables impacted the rate that Alka-Seltzer® tabs released gas and "fueled" their rockets. This was then related to surface area, deepening student understanding of chemical reactions.

As every educator knows, education is most impactful on students' lives when they can relate their studies to their own experiences and the world around them. Headlines abound about sunscreens, their proper use, and impact on the environment, particularly coral reefs. Recently, Hawaii passed a bill banning the use of sunscreens containing the chemicals oxybenzone and octinoxate, chemicals that scientists have found to contribute to coral bleaching when washed off in the ocean (The New York Times 2018). We encourage youth to use sunscreen to protect against cancer-causing UV light and the aging effects of the sun, but how can this be accomplished without harming the environment? Students in an exploratory high school course found that sunscreens containing nano-zinc not only seem to be non-harmful to coral reefs, but are also transparent. This appealed to many students who would prefer to avoid the typical "white nose" of lifeguards. By comparing different sunscreens (both macro- and nanomolecule based), and using UV beads as an indicator, students found evidence supporting their hypothesis that nanoparticles in sunscreens are highly effective.

Another group of students were fascinated with what makes matter hydrophobic or hydrophilic. By exploring the structure of matter and hydrogen bonding through a nanotechnology lens, they understood what was going on when they encountered sand that had been nano-engineered to repel water, a product known as Magic Sand®. In a simple water submersion activity, two plastic spoons had sand glued to their surfaces, one coated with regular sand and another coated with Magic Sand® (NISE Network 2011). The educator noted that the Magic Sand® had a nanoscale hydrophobic coating on the grains of sand. Following their experimentation, the students engaged in some collaborative discussions, and were able to imagine numerous creative uses for the nano-engineered sand as well as make predictions about how its use could benefit society. This one experiment had the students experiencing a pure science phenomenon, applying it to current situations, and evaluating its usefulness to society, all through the lens of nanotechnology.

Resources for Educators

There are numerous resources for educators to utilize as they begin to integrate nanotechnology into their classroom curricula. Daniel Herr, working at the Joint School of Nanoscience and Nanoengineering at the University of North Carolina, imagines a transdisciplinary educational ecosystem (Herr 2016). This ecosystem would be made up of a complex community of educators, learners, and community partners sharing the common language of nanoscience. Such an environment would greatly enhance the learning experience, building strong foundations of knowledge, accelerating the synthesis of ideas, and nurturing inquiry into further possibilities. The attached appendix includes just a few of the many online resources available for use in both formal and informal educational settings. Resources include tools to enhance the student learning experience as well as professional development opportunities for educators. Additional invaluable resources are to be found through partnerships with industry and community members. The National Aeronautics and Space Administration (NASA) offers robust support for educators, bringing innovative science right into classrooms through activities and speakers. One lucky group of educators in a Nano Fellows program were mesmerized by Dr. Mia Siochi, a NASA Langley materials scientist, who connected the nanoscience concepts they were exploring with the amazing technologies being used by NASA to build the latest airplanes and rockets. As a consequence of their experience, their students were privy to up-to-the-minute advances in nanotechnology. Making connections with local universities and industry can also lead to resources that will enhance the learning experience. Whether it is a virtual walking tour of a tissue engineering lab, or collaborating to present a hands-on workshop on piezoelectronics in a student conference, these partners are eager to reach out to their communities, building a pipeline of learning.

In Conclusion

Introducing a new way of thinking about education is always challenging and the integration of nanotechnology into current educational models does pose a challenge. But with that challenge comes the thrill of innovation and identifying future possibilities. As more and more states come to recognize the importance of nanotechnology for the future of our students, its concepts will be adopted as an integral part of state standards. Educators and students will have the opportunity to explore matter at the nanoscale in a transdisciplinary educational ecosystem, recognizing nanotechnology's potential to profoundly affect society. Standing at a wooden podium in a lecture hall at CalTech with a blackboard at his back, Richard Feynman changed the way we see the world. As educators, exploring nanotechnology side by side with our students, we can too!

Appendix

Nanotechnology Education Resources
Nanoscale Informal Science Education Network: The NISE Network is a national community of researchers and informal science educators dedicated to fostering public awareness, engagement, and understanding of nanoscale science, engineering, and technology. http://www.nisenet.org/
National Center for Learning and Teaching: NCLT is dedicated to developing and offering nanotechnology-specific instructional modules, professional development, and a network of educator communities related to learning and teaching about the nanoscale. http://www.nclt.us
National Science Digital Library: NSDL is an extensive collection of online resources for science, technology, engineering, and mathematics (STEM) education. Using the search feature provides myriad links related to nanoscience and nanotechnology. http://nsdl.org
National Nanotechnology Infrastructure Network: NNIN provides a wide variety of educational outreach that spans the spectrum of K-12 education. Education and outreach components of the NNIN include an online science magazine for upper elementary and middle school students, Nanooze. http://www.mmm.org/mmim_edu.html and http://www.nanooze.org
National Nanotechnology Initiative: NNI provides resources for students and teachers including information about nanotechnology programs from community colleges to PhDs; a description of the growing Nano and Emerging Technologies Student Network; and links to multimedia contests, videos, and animations. Additionally, a searchable database of nanotechnology education resources can be found at nanoHUB.org. https://www.nano.gov/education-training/teacher-resources
Materials World Modules: An NSF-funded program produced a series of interdisciplinary modules based on topics in material science, including composites, ceramics, concrete, biosensors, biodegradable materials, smart sensors, polymers, food packaging, and sports materials. Modules are designed for middle and high school STEM classes. http://www.materialsworldmodules.org
Exploring the Nanoworld: The University of Wisconsin-Madison materials Research Science and Engineering Center (UW MRSEC) uses examples of nanotechnology and advanced materials to explore fundamental science and engineering concepts at the college level and to share the “wow” and potential of these fields with public audiences. The website includes movies, kits, references, and teaching modules for K-12 teachers. http://mrsec.wisc.edu/Edetc/index2.html
Center for Nanotechnology Education and Utilization: CNEU at Penn State’s College of Engineering offers resources such as webcasts, video modules, workshops for educators, and resources related to careers in nanotechnology from both the educator’s and industry’s point of view. http://www.cneu.psu.edu
NanoWerk: Explore one of the world’s most comprehensive lists of nanoscience and nanotechnology resources. This site includes the latest news makers in nanotechnology. Http://www.nanowerk.com

Nanotechnology Education Resources
Nanotechnology Applications and Career Knowledge (NACK) Network: Nano4Me.org provides webinar and workshop information for educators, educational resources for students, and guides for developing integrated nanotechnology curricula. http://www.nano4me.org
Understanding Nano: This website is dedicated to providing clear and concise explanations of nanotechnology applications along with information on companies working in each area. www.understandingnano.com
Nanozone: A fun website for students and the general public interested in learning about nanotechnology. http://www.nanozone.org
NanoHUB: An online community of researchers and educators hosting a rapidly growing collection of simulation programs for nanoscale phenomena that run in the cloud and are accessible through a web browser. Also offers workshops, virtual tools, and databases. https://nanoHUB.org
National Science Foundation: The Nanoscience Classroom Resources page provides a diverse collection of lessons and web resources for classroom teachers, their students, and students' families. https://www.nsf.gov/news/classroom/nano.jsp

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