Chapter 1
Introduction to Nanotechnology

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Introduction

Nanotechnology is the study, manipulation, and application of matter at the nanoscale, where the nanoscale refers to lengths of less than a hundred nanometers (nm). To put this into perspective, a typical sheet of paper is 100,000 nm thick and a human hair is on the order of 80,000 nm in diameter, so this is almost unbelievably small. Scientists, engineers, and developers are interested in working at these size scales because materials at the nanoscale can behave differently than the same material at the bulk or macroscale. Depending on the material, at very small size scales, they may become stronger, more ductile, damage resistant, conductive, or chemically reactive. Even properties like color depend on size at the nanoscale. While nanotechnology remains an active area of research in almost all areas of science, engineering, and medicine, a vast array of applications and products have emerged that take advantage of the novel properties of nanomaterials.

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Why Size Matters

Some of the observed changes in material behavior at the nanoscale are due in part to the increased role of surface atoms. In bulk materials, the number of surface atoms is a small fraction of the total number of atoms and average material properties are based on the atoms in the interior of the material. For very small materials, however, the properties of the surface atoms dominate and can change the chemical behavior of the material. For example, while bulk gold is considered inert, it becomes reactive or even catalytic at the nanoscale. Figure 1.1 uses two-dimensional arrays to illustrate this point. In this figure, the array on the left is made up of nine “atoms,” of which eight are on the outside or are “surface” atoms. The array or “particle” on the right is made up of 81 “atoms,” of which 33 are on the outside. Therefore, in this simple illustration, 89% of the atoms of the small “particle” reside on the surface, while only 41% of the atoms that make up the slightly larger “particle” on the right reside on the surface.

In addition to its reactivity, size also impacts the color of gold. At the macroscale, gold is, of course, gold or yellowish, but below a certain size gold can appear red or blue. This effect illustrates the importance of quantum effects at the nanoscale. In noble metal nanoparticles, free electrons can collectively resonate in response to incident light. As a result, smaller metal nanoparticles absorb shorter wavelengths, the blues, and reflect back the longer wavelengths, giving them a reddish color. As the gold nanoparticles get bigger, the wavelength absorption shifts resulting in more red light being absorbed while wavelengths at the blue/purple end of the visible light spectrum are reflected. When small nanoparticles are made from semiconducting materials, they are typically called quantum dots. Quantum dots illustrate quantum confinement where either the electrons or the holes are confined resulting in

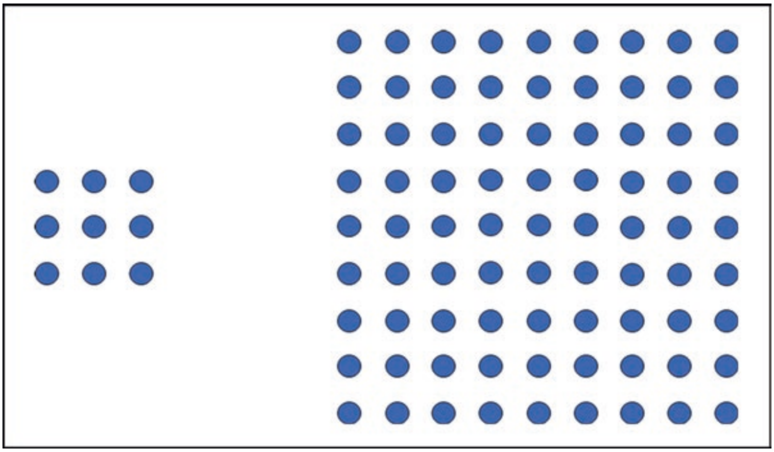

Fig. 1.1 Size matters. Two-dimensional arrays illustrating influence of size on number of surface atoms

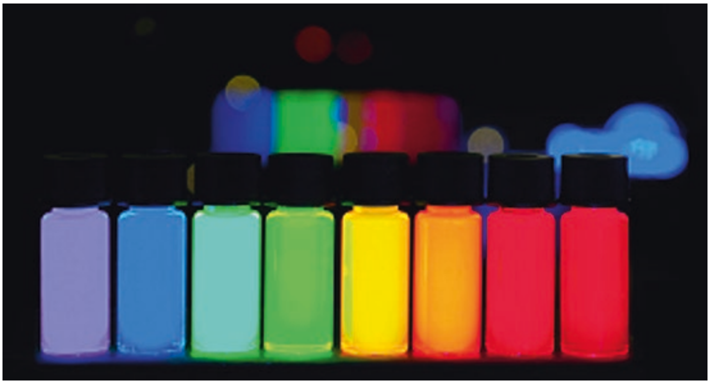

Fig. 1.2 Quantum dots. The image shows ZnCdSeS alloyed quantum dots from PlasmaChem. The emission wavelength of a quantum dot can be tuned by changing its diameter. This image is used under the Creative Commons Attribution-Share Alike 3.0 Unported license

discrete energy states for the overall particle. This is sometimes referred to as an artificial atom. As Fig. 1.2 shows, larger quantum dots emit longer wavelengths of light when excited, giving off red or orange colors. Smaller dots emit shorter wavelengths which results in blue and green colors. Working at the nanoscale allows scientists and engineers to tune the optical properties of nanoparticles by adjusting their size and shape (Kreibig and Vollmer 1995; Woggon 1997).

Reactivity and color are just two examples of how material properties are influenced by size. Atomic arrangement and bonding also influence material properties. To illustrate this point, consider two well-known bulk materials, graphite and diamond. Graphite and diamond are two of the allotropes of carbon. Allotropes are different physical forms of material made from the same element, in this case carbon. In graphite, the carbon atoms are arranged hexagonally in sheets, and the resulting material is black and slippery. Within the sheets, each carbon atom is bound to three others and these bonds are very strong. The bonds between sheets are weak, however, which is why material is left behind when a pencil is traced across a sheet of paper. In diamond, the carbon atoms are arranged tetrahedrally; it is transparent and very hard and strong. The carbon atoms in diamond are each bound to four others in a three-dimensional arrangement called the diamond cubic structure. While both graphite and diamond are made entirely of carbon, their properties are very different because of how their atoms are arranged and the bonding between them.

There are several other allotropes of carbon that have extraordinary properties and the discovery of these carbonaceous nanomaterials fueled much of the early enthusiasm about nanotechnology. Hollow molecules of carbon called fullerenes were discovered in 1985, the most famous of which is C_{60}, the Buckminsterfullerene, after Richard Buckminster Fuller, the architect renowned for geodesic domes (Kroto et al. 1985). Nicknamed buckyball, this molecule has a truncated icosahedron structure, like a soccer ball, with 60 carbon atoms. The identification of another form, carbon nanotubes (CNTs), was published in 1991 (Iijima 1991). CNTs are like a single layer of graphite with the carbon atoms arranged hexagonally, rolled in a tube with a diameter on the order of nanometers. Single-walled CNTs refer to a single tube, where multi-walled CNTs refer to a tube, in a tube, in a tube, depending on the number of walls. When CNTs were characterized, it was discovered that they were the strongest (100 times stronger than steel) and stiffest materials known to exist (Yu et al. 2000). Since CNTs are also low in density, excitement grew about applications, such as an elevator to space, that could be made possible with these strong, lightweight materials. Depending on their chirality, carbon nanotubes can exhibit very high electrical conductivity (metallic behavior) or can behave more like a semiconductor, leading to applications in electronics. The optical properties of carbon nanotubes, including tunable absorption, have application in areas of optics and photonics. Carbon nanotubes are also excellent thermal conductors leading to applications for thermal management. Although there remains much work to be done to fully understand and produce CNTs with the desired properties, they are already being used in a wide variety of applications from strong lightweight composites in automobiles and sporting goods, light-filtering window films, enhanced gas sensors, and radiation-hardened electronics in space.

Allotropes of carbon continue to be discovered and developed, including graphene, a single layer of graphite, referred to as the wonder material and leading to a Nobel Prize in 2010 (Novoselov et al. 2004; Royal Swedish Academy of Sciences 2010). The discovery of graphene was important to nanotechnology not only because of its exceptional properties (strong, flexible, electrically and thermally conductive, impermeable, etc.) but also because it opened up an entire new field of two-dimensional (2D) materials.

One of the most influential scientists in the area of carbonaceous nanomaterials was Mildred Dresselhaus (American Physical Society 2018). Known as the "Queen of Carbon Science," Dresselhaus was a solid-state physicist who made critical advances in the understanding of the thermal and electrical properties of buckyballs, carbon nanotubes, and graphene, often developing the methods to characterize and measure these properties. She is also credited with introducing the field of low-dimensional thermoelectricity for the conversion of a temperature gradient into electrical energy.

Materials by Design

Building at the nanoscale is often broken into two categories, top-down or bottom-up. An example of top-down approaches is lithography techniques that allow engineers to carve away thin layers of material to create nanoscale features. This is common in the fabrication of nanoelectronics. Bottom-up methods include self-assembly in which scientists rely on understanding molecular interactions to design a construct that will form when they combine the pieces. DNA origami is a classic example of self-assembly in which scientists mix together strands of synthesized

DNA which will hydrogen bond into predicted shapes. At the nanoscale different forces become dominant. Gravity strongly influences how objects behave at the macroscale. Shrink a material down to the nanoscale and the intermolecular interactions or van der Waals forces play a much greater role in how something behaves. These differences can be exploited to make materials by design. The new tools available to manipulate and build at the nanoscale have led engineers to create smart materials that can both sense and respond to their environments with applications in everything from bridge maintenance to dental braces.

There are certain expectations when dealing with materials. One assumes that strong materials will be heavy, and light materials will be weak. Julia Greer, however, disagrees. Greer is proving that engineers no longer need to be bound by these traditional material properties (Greer 2018). By harnessing the novel properties that exist at the nanoscale, entirely new classes of materials can be made with never before obtained characteristics. She focuses on using nanoscale building blocks, nano-pillars, -pipes, and -tubes, for example, to construct larger materials. She has developed a method to combine nanomaterials with their size-dependent properties and hierarchical architectural elements to create entirely new combinations of properties, such as materials that are strong as steel and light as a feather. To illustrate the effect in a ceramic material, for example, she has demonstrated that a highly porous ceramic material with wall thickness of 50 nm fails and crumbles under compression, just as a brittle ceramic would be expected to do. By reducing the wall thickness to 10 nm, however, the structure does not fail under the compressive stress, and actually springs back when the load is removed exhibiting elastic behavior that would be expected in a metal (Meza et al. 2014). The reduction in wall thickness in this example puts the ceramic material into the regime where novel behavior begins, and the ceramic becomes tougher. Using the two-photon lithography method her group developed, they create structures with unique properties, such as exceptionally strong but very lightweight. There are many applications that can take advantage of the unique attributes of these structures. Examples include battery cathodes, photonic crystals, and three-dimensional scaffolds for bone regrowth. The most significant roadblock to large-scale application of this technique is scale-up.

One challenge of nanotechnology is understanding interactions at the nanoscale in order to purposefully take advantage of these interactions to design new nanomaterials. Sharon Glotzer is identifying the rules of interaction and developing the computational tools needed to achieve materials by design (Glotzer 2018). Her work is not limited to naturally occurring structures or arrangements of atoms. These future smart materials will likely possess coupled properties not typically seen together in a single material and ideally will be programmable, reconfigurable, and adaptable to environmental cues. Glotzer has shown that computational materials science is becoming a reality. Her models examine how hard nanoscale particles spontaneously organize in the absence of interparticle forces, solely due to the entropy in the system. By understanding the behavior of nanoparticles, her modeling work has opened up the design of completely new materials. Using this approach, in over less than a decade, her lab was able to go from predicting the assembly for a specific type of nanoparticle to predicting phase diagrams for entire families of nanoparticles. With increased understanding, improved models, and expanding computational power, the Glotzer team identified trends and are now able to design optimized nanoparticles for targeted assemblies.

Inspired by Nature

The nanoscale is where much of nature works. For example, the diameter of double-stranded DNA is 2.5 nm and ribosomes, which translate mRNA into proteins, also fall within the nanoscale. Plants and animals use nanoscale structures to fight infection, repel water, cut down on reflected light, and create vibrant colors. Scientists, motivated by what they see in nature, are mimicking these structures for use on medical implants, solar cells, and adjustable camouflage. For example, the hierarchical nanostructures observed on lotus and hosta leaves are being replicated to impart superhydrophobicity on surfaces to make self-cleaning windows and wind turbine blades that not only stay clean, but do not ice up in harsh environments. This technology has been commercialized in coatings that can be sprayed on everything from concrete to work boots and gloves, or even mobile devices that can be rinsed under a faucet. Nanostructures can even increase water availability. The structure on the back of the Namib beetle has been replicated by a company to harvest water from fog (NBD Nano 2018).

Structural color, such as the vibrant blue of the Morpho butterfly, has inspired the use of texture not only for color, but also to improve performance of photovoltaics. Entrepreneur Marcie Black's first company, Bandgap Engineering, developed nano-engineered solar cells, also known as black silicon solar cells. By reducing energy loss through reflection, the nanotexture increases the efficiency of the solar cells and enables more power to be produced from the same exposed area. Using a low-cost process called metal-assisted chemical etching reduces the cost to produce the silicon solar cells. This technology is now used to make most of the multicrystalline silicon solar cells on the market. Black's current company, Advanced Silicon Group (ASG), is using the same technology to develop nanotextures for biosensing (Advanced Silicon Group 2018). ASG's silicon nanowire biosensors can measure the distinct concentrations of many different proteins in a solution. One target application of this low-cost and quantitative sensor platform is for the tracking of progress of lung cancer treatment to improve patient outcome and lower health costs.

Inspired by the way abalone builds its shell, Angela Belcher engineers custom materials using biology as her factory with a technique to manipulate viruses to build nanostructures (Belcher 2012). Nature produces impressive materials through processes enabled by proteins coded at the genetic level. Naturally occurring biologically formed structures include complex SiO_2 nanostructures formed by diatoms and small single-domain Fe_2O_3 magnets used for navigation by magnetotactic bacterium. These microorganisms have a DNA sequence that codes the protein sequence providing the instructions or the "blueprint" to build the nanostructure. Belcher wondered if simple organisms such as bacteria and viruses could be convinced to work with the rest of the periodic table and if a DNA sequence could be determined to code the protein sequence corresponding to a desired structure. Using this technique, she engineered viruses to express the ability to grow nanowires and self-assemble through a process of directed evolution (Nam et al. 2006). She has also engineered viruses to pick up carbon nanotubes and grow TiO_2 around them for solar cells. Belcher's exquisite structures are built under ambient conditions in a process using nontoxic chemicals with the release of no toxic chemicals into the environment. This research has led to the formation of two companies. Cambrios Advanced Materials uses Belcher's technique to synthesize inorganic materials from soluble precursors and assemble these materials into functional nanostructures. Siluria Technology focuses on the conversion of natural gas into transportation fuels and commodity chemicals enabled by chemical catalysts that eliminate the need for high-temperature and -pressure processes. Looking to nature, scientists and engineers like Belcher are now able to purposefully build and manipulate at the nanoscale.

Small Science Solving Big Problems

The potential to one day detect and treat cancer at the cellular level created a compelling vision for nanotechnology in medicine. Paula Hammond has made significant advances in the fight against cancer (Hammond 2015). Using molecular engineering, she has developed a way to treat even the most aggressive forms of cancer. She has likened cancer to a supervillain that is "clever, adaptable, and very good at staying alive." The villain's superpower stems from genetic mutations that enable new modes of survival allowing it to live through even the best available chemotherapy treatments. Using molecular engineering, there are ways, however, to turn off a gene. Molecules that are short sequences of genetic code, known as small interfering ribonucleic acid (siRNA), can interfere with gene expression, effectively directing a cell to block a specific gene. Therefore, by treating a cancer cell with the gene-blocking siRNA to prevent the survival genes from being expressed, and then dosing it with a chemotherapy drug, it could be destroyed. There are challenges, however. While siRNA works well within a cell, it degrades within seconds when exposed to enzymes that exist in the bloodstream or other tissues. Hammond's super weapon against cancer is a nanoparticle with a core that contains the chemotherapy drug. A very thin layer of siRNA is wrapped around this core. To protect the negatively charged siRNA, a positively charged polymer is used to cover and protect it in the bloodstream. To successfully reach the tumor the particle needs to get past the body's immune defense system which identifies and destroys foreign objects in the bloodstream. So, one more negatively charged layer is added to the particle that serves two purposes. The layer is a highly hydrated polysaccharide (that naturally resides in the body) surrounded by a cloud of water molecules that acts as an invisibility cloak. This layer enables the particle to travel through the bloodstream long and far enough to reach the tumor without being eliminated by the immune system. The molecules in the outer layer also allow the particle to bind to the tumor cell.

Once bound, the nanoparticle is taken up by the cancer cell and can deploy its payload. By modifying the layers, this technique can be personalized. As doctors and researchers identify new mutations, additional layers of siRNA can be added to silence these genes. Also, the type of drug at the core can be varied depending on the type of cancer or developments in more effective chemotherapy treatments.

Using nanotechnology to combat cancer is also the focus of Michelle Bradbury. The goal of her work with translational silica nanomaterials is to help doctors detect, diagnose, and treat cancer (Bradbury 2018). The ability to make cancer, in particular diseased lymph nodes, glow by shining light on silica nanoparticles will revolutionize surgery. Doctors will be able to map diseased sites in the body and surgeons will be able to actually see which cells are cancerous and remove them while leaving behind healthy tissue. The nanoparticles accumulate on the cancer cells because of peptides on the outside of the particle which selectively bind with tumor cells. The nanoscale size of the particles allows patients to eliminate nanomaterial that does not bind to the targeted cancer.

While considerable progress has been made toward the goal of early cancer treatment, the areas impacted by nanomedicine are much broader than cancer alone. The large surface area-to-volume ratio of nanomaterials along with the ability to functionalize them is ideal for sensors. Nanomaterials have been used in sensing applications, such as over-the-counter pregnancy tests, for many years. Perena Gouma develops nanostructured sensing elements that detect specific biomarkers (Gouma 2018). Her “electronic nose” can be used to detect markers of disease in people’s breath and monitor infection or diabetes, for example. Gouma is also the first person to receive National Science Foundation (NSF) I-Corps funding. She earned the support for a functionalized solar-powered “nanogrid” which breaks down hydrocarbons in polluted water (Cordova 2015). In addition to sensing applications, nanotechnology is enabling cheap, quick, and on-site DNA sequencing via nanopores. Lab-on-a-chip technology is bringing diagnostics to the field and, as microfluidics make way for nano-sized channels, increased sensitivity and detection will allow for even higher throughput screening of disease with less sample. Nanomaterials are also used in dental applications, tissue scaffolds for wound healing, antimicrobial bandages, imaging agents, and many other areas of medicine.

The work of Naomi Halas exemplifies the way nanotechnology spans multiple disciplines and applications (Halas 2018). She specializes in creating nanoparticles which have surface resonances across visible and infrared wavelengths. Her research in plasmonics and the ability to carefully control nanoparticles led her to develop the idea of the “tunable plasmon.” The Halas lab has developed techniques to chemically manipulate the shape of nanoparticles which affect the collective electronic resonance, or plasmon, of the particle. Tuning the nanoscale geometry can change more than the color with applications in the broad area of metamaterials. Halas is driven by a desire that her work have “unique applications of societal and technological impact.” This has led her to commercialize her responsive nanoparticles, starting companies specializing in cancer treatment and novel forms of energy generation. She is also part of a team, along with Qilin Li, commercializing technology with a light-harvesting membrane to heat and desalinate water in a single step (Rice University 2018; Li 2019).

In addition to desalination and collecting water from fog as noted in two of the examples above, the use of nanotechnology has the potential to help in other ways to improve access to clean, cheap water. Theresa Dankovich developed paper-based water filters infused with silver nanoparticles to allow for local water purification (Folia Water 2018). She started Folia Water with the goal of large-scale, low-cost production of the filters to enable people in developing countries to clean their own water. She also developed a method to produce the filters using nontoxic and renewable materials. In addition to providing energy for desalination and other methods of purification, nano-enabled sensors provide low-cost, low-energy methods to monitor water quality. The use of nanotechnology extends beyond the sustainable production and monitoring of clean water to the reclamation of polluted water. Scientists have developed nanoscale spongelike materials that soak up oil from water after a spill (Hashim et al. 2012; Barry et al. 2017). Additionally, nanocatalysts are being used to break down pollutants in water and soil.

Working to Ensure the Safe Development and Adoption of Nanotechnology

Along with research and development focused on applications, considerable attention has been devoted to the potential implications of nanotechnology. Two early voices in the area of ethics and societal perception were Rosalyn Berne and Barbara Herr Harthorn (Berne 2019; Harthorn 2019). Berne, who developed courses on nanoethics for engineers, used a 5-year CAREER grant from NSF to initiate a conversation on societal issues by interviewing 35 nanotechnology scientists and engineers. Her discussions are the basis for the book “NanoTalk” (Berne 2005). Harthorn, former Director of the NSF Center for Nanotechnology in Society, studied the perception of nanotechnological risk among experts and the general public in the USA and the UK. She also coedited the book “The Social Life of Nanotechnology” (Harthorn and Mohr 2012).

Responsible development of nanotechnology also includes the consideration of potential environmental, health, and safety (nanoEHS) implications. The body of knowledge gained in this area is immense and numerous women have contributed to the advancement of nanoEHS research including the development of tools and methods to evaluate nanomaterials and measure exposure. Several technical journals have been established which focus on these research areas, including NanoImpact where Socorro Vázquez-Campos serves as an associate editor (NanoImpact 2019). The US Government alone has invested over a billion dollars in this area of research; “Highlights of Recent Research on the Environmental, Health, and Safety Implications of Engineered Nanomaterials” includes more information (National Nanotechnology Initiative 2016). Worldwide collaborative efforts have been established, including the US-EU Communities of Research (US EU Nanotechnology Communities of Research 2018). In the EU, Eva Valsami-Jones and Iseult Lynch serve on the

Coordination team of the NanoSafety Cluster and recently published a reflection on the tools that have been developed for the risk assessment of nanomaterials (Fadeel et al. 2018; Lynch 2018; Valsami-Jones 2018). Jo Ann Shatkin has written extensively on the health and environmental risks of nanotechnology and recently identified key advancements in nanoEHS over the past 15 years (Shatkin 2012, 2018).

One important area that has advanced significantly is the safe handling of nanomaterials in a laboratory or industrial setting. Resources for laboratory safety developed by universities, government agencies, and organizations and professional societies have been assembled and promoted by the National Nanotechnology Coordination Office (National Nanotechnology Initiative 2019). The National Institute for Occupational Safety and Health (NIOSH) conducts research and field studies to help industry protect their workers (The National Institute for Occupational Safety and Health 2018). NIOSH Current Intelligence Bulletins that summarize state of the science and publications that provide approaches for safe handling of nanomaterials and workplace design suggestions are valuable resources for nanotechnology researchers and developers alike.

Preparing Students, Workers, and the General Public

New nanotechnology discoveries and the development of innovative applications enabled by nanotechnology require scientists and engineers knowledgeable about the novel properties and behaviors at the nanoscale. Furthermore, public acceptance of nanotechnology is important for these new applications to be broadly adopted. To address these needs, educational programs for K-12, 2- and 4-year colleges, graduate schools, and the general public have been developed in many regions of the world. The goal is to help build the workforce for future nanotechnology research and development, and to ensure an informed citizenry (National Nanotechnology Initiative n.d.; Malsch 2014; Asia Nano Forum 2018; Focus Nanotechnology Africa Inc. 2018). In an effort to benchmark efforts in nanoscale science and engineering education (NSEE), a workshop was held in 2010, followed by workshops in 2014 and 2017 (Murday 2010, 2014; Akbar et al. 2017). These workshops provided opportunities to assess current efforts, share best practices, and identify resources. One of the outcomes of these workshops was the assembly of hundreds of NSEE resources, from lesson plans and demonstrations to videos and hands-on experiments in a searchable database (Spadola and Friedersdorf 2017). A few of the many notable efforts in the area of NSEE are highlighted here.

The Nanoscale Informal Science Education Network (NISE Net) reached over 30 million people during its 10-year funding by the NSF (Bell 2015). This project, led by the Boston Museum of Science, established a national network of nearly 600 organizations including museums, universities, industry, and others. The NISE Network had three focus areas: educational deliverables (activities and programs, exhibits, media, and professional development), network infrastructure (project teams, regional hubs, and partners), and expanding the knowledge base of nanoscale science education.

The program established NanoDays, an annual event held at sites across the country, and the world, that highlighted nanoscale science and engineering with a focus on the current and future impacts of these areas on society (National Informal STEM Education Network 2018). A variety of demonstrations and other resources were developed during the active years of this program. Kits with instructions and materials for demonstrations were sent to educators at no cost to use during NanoDays. Although new kits are not being developed under this program, digital versions are available for download and many participants continue to use these resources during NanoDays and throughout the year in their educational and outreach efforts.

NanoDays helped to provide a focus on nanotechnology, but there are many other efforts in K-12 NSEE. Nancy Healy spent more than a decade teaching nanotechnology through outreach efforts into classrooms, summer camps, and, perhaps most importantly, K-12 teachers with Research Experience for Teachers programs, workshops, and boot camps (National Nanotechnology Coordinated Infrastructure 2018). Beyond reaching hundreds of teachers and thousands of students in her local community, Healy coordinated education and outreach efforts across the National Nanotechnology Coordinated Infrastructure, a nationwide network of nanotechnology user facilities based at 16 university sites across the country, and its predecessor the National Nanotechnology Infrastructure Network. The efforts of Julia Cothron, Mary Frances Hobbs, Daphne Schmidt, and Yvonne Pfluger at the MathScience Innovation Center in Richmond, Virginia, to develop and deliver nanotechnology to students and teachers were critical as the Commonwealth of Virginia was the first state in the USA to include nanotechnology in its K-12 science standards (MathScience Innovation Center 2018; Virginia Department of Education 2019).

Technicians are a critical piece of the nanotechnology workforce. Training occurs in a variety of ways including certificate programs and associate degrees through community or technical colleges. Deb Newberry established an Advanced Technology Center in Nanotechnology Education through an NSF grant called Nano-Link (Nano-Link Center for Nanotechnology Education 2018). Nano-Link has developed resources for educators and students and has worked closely with industry to assess their needs for trained technicians. Newberry also developed collaborations across the country to leverage resources and have a greater impact. The Nanotechnology Applications and Career Knowledge (NACK) Network, supported in part by NSF, also assists in technician training (Nanotechnology Applications and Career Knowledge Network 2019). One focus area of the NACK Network has been to provide students (and teachers) with access to cutting-edge equipment and cleanrooms through collaborations between colleges and universities. The Remotely Accessible Instruments for Nanotechnology (RAIN) partnership enables remote access to equipment like electron microscopes where students can control the instrument from their classroom (NACK Network 2019).

At the university level, nanotechnology classes are now commonplace in engineering and science departments and many certificate, minor, and degree programs have been established (National Nanotechnology Initiative n.d.). Students interested in any area of science, technology, engineering, and mathematics (STEM) will likely encounter nanotechnology. To encourage K-12 students on this path, the novel properties at the nanoscale can be used to inspire them to pursue a STEM education. One way to excite students is to tie current and future applications to superpowers. For example, the nanoscale structure of gecko feet that enables them to scamper up walls has been inspirational for students and developers alike. Along with metamaterials enabling invisibility cloaks, bulletproof CNT textiles, and ultra-strong lightweight cables for swinging, gecko-inspired gloves can round out the gear for any burgeoning superhero!

Summary

Nanotechnology is already impacting nearly every aspect of daily life. Stain-resistant pants; the powerful computer in mobile devices; touch screens; water-resistant electronics; brighter yet more energy-efficient displays; sunscreens and cosmetics; sports equipment; paints and protective coatings; antimicrobial bandages; lightweight yet stronger materials to protect warfighters; electromagnetic shielding for electronics in space; more efficient food packaging; and sensors with uses in medicine, food, and air quality are just a few examples of applications enabled through nanotechnology.

The women highlighted in this chapter and throughout this book are just a few of the many who have made significant contributions across a wide variety of science and engineering fields through their work in nanotechnology. As progress and understanding grow, improvements to existing products will give way to whole new applications and methods enabled by nanotechnology. The talented girls and young women that follow in this exciting field will bring this promise to fruition.

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