Nanotechnology: Nano Measures with Giga Implications for Education

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Introduction

Nanotechnology, or nanoscience, is an emerging field of study that is interrelated with science, engineering and mathematics. Nanotechnology presents a number of useful applications for everyday use and applications as we bridge the twenty-first century with the twenty-second. In this chapter, the authors postulate not only a number of everyday uses and applications for nanotechnology, but also provide historical contexts and future possibilities for elementary education, secondary education, and higher education.

The prefix “nano” derives from the Greek language, meaning *very small*. Nano is defined as one-billionth of a meter and is akin to the ratio of a tennis ball to the size of Earth (Rafique et al., 2020; Taha et al., 2022). The nanoscale and nanoparticles are considered as anything measured at, or less than, 100 nanometers (nm) (Bayda et al., 2019). For reference, there are 1 million nanometers in a single millimeter (Figure 1).

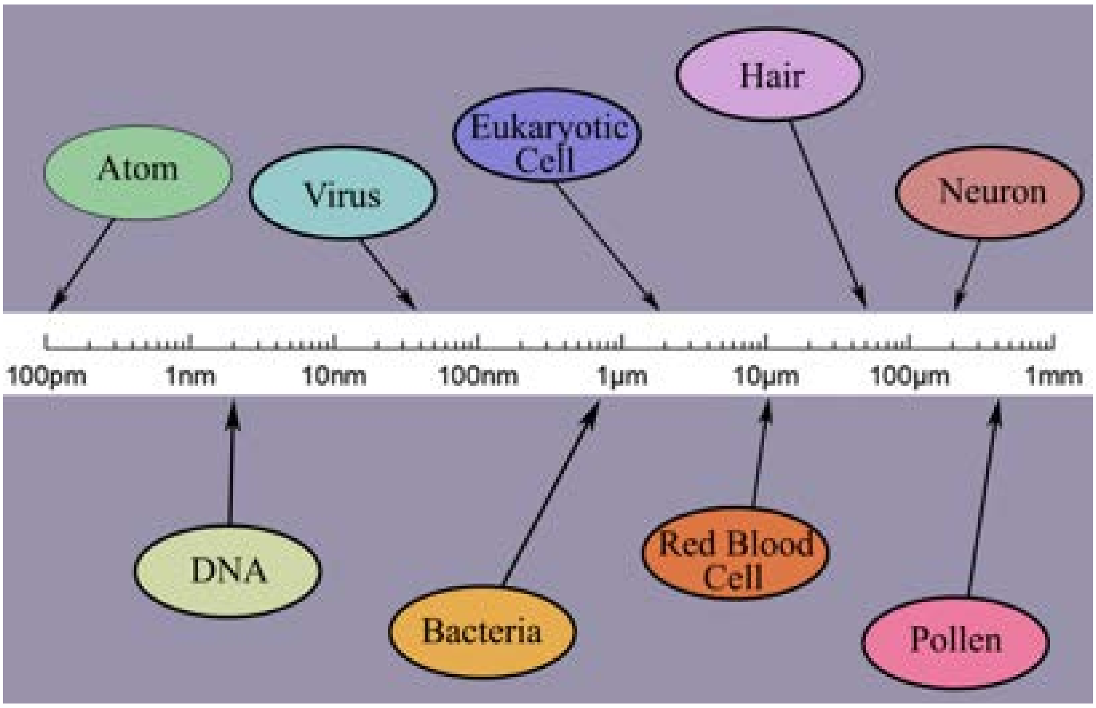

Figure 1. A comparison of the nanoscale

The field of nanoscience and nanotechnology combines the fields of biology, chemistry and materials sciences (Mitin et al., 2008; Rafique et al., 2020). Interestingly, engineered nanoparticles can have different compositions and effects in comparison to the same exact materials at a larger scale. There are potential unseen risks for humans and other living things dependent on the manner in which nanotechnology is employed (Rafique et al., 2020). The structure and function of nanoparticles is dependent on their shape, size, inner characteristics and surface characteristics (Mitin et al., 2008). Nanoparticles can either remain free or grouped together based on their chemical properties (Rafique et al., 2020; Taha et al., 2022). Nanoparticles can also be formed though industrial means or by breaking down larger particles. Despite its name, nanotechnology does not only refer to working in smaller dimensions; it involves altering the molecular properties of materials to alter its structure and function to the best desired properties of the respective material.

Just as with all scientific disciplines, there are a variety of different classifications of nanomaterials; the first being natural vs. artificial nanomaterials. Natural nanomaterials, as the name implies, are naturally occurring in nature; examples of such being particles in smoke or the particles that make up our cells (Griffin et al., 2017). Viruses are another commonly, naturally occurring nanoparticle that goes unknown to most (Taha et al., 2022). Lozano (2022) defines artificial nanomaterials as those that are man made, such as particles from vehicle exhaust or particles from medicines created by scientists. In the 1920s, tire companies used the nanoparticle, Carbon Black, to improve the performance of their tires without knowing of the existence of nanoparticles (Taha et al., 2022). Another dichotomy of nanomaterial classification comes in the form of Fullerenes and Nanoparticles. Fullerenes are allotropes, or different forms of the same element, of carbon. Some examples of Fullerenes that are familiar to most would be diamond or graphite. Nanoparticles can include Fullerenes but also include the nanoscale version of other elements such as gold or silicon (Lozano, 2022).

Perspectives in Progress

The origins of nanotechnology are widely debated amongst the scientific community. Richard Feynman is considered to be the pioneer scientist in the field of nanoscience when he introduced the concept in 1959 (Bayda et al., 2019; Rafique et al., 2020). Looking back throughout history, it was found that other scientists had worked with nanoparticles. Sixteenth century Swiss physician, Theophrastus von Hoenheim, had used gold nanoparticles to treat his patients and John Utynam had patented a gold nanoparticle-based glass in 1449 (Bayda et al., 2019; Rafique et al., 2020).

The concept of the nanometer was introduced in 1925 by Richard Zsigmondy, who would go on to win a Nobel Prize in the field of Chemistry. The term “nanotechnology” was coined in 1974 by Norio Taniguchi to describe nano-sized materials (Rafique et al., 2020). It is fair to say, even with nanoparticle uses and recent advances, the field of nanotechnology and nanoscience is not a new field of study. Although it is not a new field, it is still leading to and making great strides in the fields of science, technology, engineering, and industry (Mitin et al., 2008).

Nanotechnological Applications

Unbeknownst to many, nanotechnology has a variety of uses. In the field of material sciences, nanotechnology is applied to improve material properties, such as friction, wear, or adhesion. According to Rafique et al. (2020), nanoparticle materials illustrate different and superior qualities, in comparison to traditional materials, such as, but not limited to, enhanced ductility, flexibility, wear resistance, and magnetic properties. The use of nanotechnology to engineer different atomic sizes, structures, and surface areas also allows for the alteration of melting points for different materials. An increase in atomic surface area can lead to an increase in the melting point of a material while decreasing the surface area will have an inverse effect. The surface area of nanoparticles also has an effect on the electrical conductivity, as smaller surface areas lead to greater electrical conductivity. Materials manufactured using nanoparticles were shown to have 10 times the thermal conductivity than that of metal (Ikumapayi et al., 2021).

Mechanical properties of material can be defined on the basis of different factors such as strength, hardness, the ability to penetrate other materials, resistance to deformation when affected by outside forces, and how much weight a material can bear (Rafique et al., 2020). Smaller nanoparticles have been found to possess greater levels of mechanical properties; strength in particular. Ikumapayi et al. (2021) also noted in their research that materials manufactured with nanoparticles could withstand extreme strain and were very strong. Nanoparticles of sizes less than 15 nm were found to be superparamagnetic. For reference, paramagnetism is defined as being attracted by a magnetic field but not retaining magnetic properties when removed from the magnetic field. In terms of elasticity, the strength of the bonds between nanoparticles directly correlates with the elasticity of the respective material.

In the biomedical field, nanotechnology, called nanomedicines, have been employed to improve drug design and targeting along with uses such as the artificial development of human tissue. Nanotechnologies have been found to be useful in treating pulmonary patients (Doroudian et al., 2021). The researchers found that nanomedicines were able to better target specific areas of treatment for patients, which led to lessened recovery times than traditional medicines. The nanomedicines were engineered to respond to internal or external stimuli, such as temperature or pH, to allow for a controlled, precise release of the therapeutic treatment to the specific targeted sites. These nanomedicines are not limited to respiratory ailments. Nanomedicines have also been found useful in the treatment of cancer. Additionally, Grodzinski et al. (2019) also found that the precise targeting of the medicines to the areas of ailment had led to increased rates of recovery and more efficient treatment. Nanomedicine has also been utilized for bone regeneration and appetite control (Ikumapayi et al., 2021). These are a few examples and highlights of its uses and successes. Nanomedicine likely possesses an immense upside and may lead to much improved recovery and treatment of patients for a variety of medical conditions.

Contemporary Uses

Nanotechnology is currently in use in consumer products and the industrial sector in items such as sunblock, paints, dyes, and cosmetics. The nanoparticles used in cosmetics and sunblock allows manufacturers to alter product designs to the specification and preferences of their respective clientele. The nanoparticles used in sunscreen, titanium dioxide and zinc oxide, provide a higher degree of consistent protection from harmful UV radiation (Lozano, 2022). These nanomaterials offer better light reflection for a longer time period.

A study by Ikumapayi et al. (2021) notes that nanotechnologies can be employed in food packaging to determine whether or not the products have been contaminated. Nanotechnologies can also be employed to alter the flavor of foods, as nanoparticles can be applied to target cells on taste buds to enhance or block specific flavor profiles. Another example of how nanotechnology has affected food is in the “spreadability” of condiments. The increased surface area of the nanoparticles has allowed for mayonnaise to be easier spread on bread (Lozano, 2022).

One of the biggest fields that nanotechnology has made an impact in is the field of electronics. Whereas in the past semiconductors were utilized, nanotechnologies have advanced the features of currently existing technologies in features such as image resolutions. In the aspect of computing, the sheer size of nanotechnology has allowed for advances in features such as memory and processing speeds. Interestingly enough, the industry of creating microtechnologies and microfabrication began in the electronics industry (Ikumapayi et al., 2021). Microfabrication devices typically refer to items such as integrated circuit technologies and micromachining and are typically silicon wafers. These microtechnologies also include products such as smart phones, integrated circuits, solar panels, semiconductors, and flat panel displays. The sizes of these products are measured in micrometers, which is even smaller than a nanometer. In today’s world, microfabrication is being combined with nanotechnology to produce new and higher quality products (Ikumapayi et al., 2021).

Economic Implications

Provided the aforementioned development and uses of nanotechnologies, it is paramount to address its economic implications. The innovations of nanotechnology allows for the creation of more job opportunities. The nanotechnology sector allows for jobs that move away from demanding physical labor, to tasks requiring a more technologically literate skill set. Today's society is moving more towards the mastery of a technological-based skill set and away from traditional manual labor and manufacturing jobs of the past. The current trend in which our society, workforce, and educational focus is currently working towards benefits future jobs that will arise from the nanotechnology industry. Recent projections of the nanotechnology industry suggest that the total worldwide market will exceed 40 billion dollars by the end of this decade (Adam & Youseff, 2019). As of 2018, the nanotechnology industry in Europe and the United States were able to generate $941 million and $903 million in gross revenue, respectively (Talebian et al., 2021). Given the immense revenue generated from this industry, it is reasonable to predict the growth, creation, and future needs for technological skill-sets required for nanotechnological positions.

Building the Foundation: Elementary Education

Introducing nanoscience in primary school provides young learners with opportunities to conceptualize and make connections to nano measures. Teacher facilitated guidance and the utilization of interactive activities supports students in developing basic nanoscience terminology and basic nanometer measures related to how matter acts in minute scales (Mandrikas et al., 2020). While many nanoscience concepts are rather abstract, there are a variety of approaches teachers can employ to help students conceptualize and connect for understanding. Modeling nano surfaces and water interactions provided hands-on, experiential learning for students of all backgrounds (Kolb et al., 1984; Mandrikas et al., 2020; Vygotsky, 1978). Providing young learners with real world connections and assisting students with social avenues for learning in context are additional strategies teachers can employ for bridging connections via discovery learning (Dewey, 1916; Piaget, 1933). Most importantly, providing exposure to young learners paves pathways and provides background knowledge students can employ towards more complex learning as they progress in grade levels from high school through higher education courses (Mandrikas et al., 2020).

The use of real-world connections concerning size, shape, and scale of visible, concrete objects at the primary level undergirds later nanoscience concepts that can be introduced in lower and upper secondary school. Additionally, inquiry-driven, hands-on learning experiences introduce and train students on a classroom structure and framework that is essential for further scientific discovery (Jesionkowska et al., 2020; Lati et al., 2019). The similarity in classroom structure can provide a consistent background as students move from concrete objects and interactions in elementary school to more abstract concepts introduced in middle and high school. Good design will embed these learning progressions within both elementary and secondary school curriculum in a systematic and developmentally appropriate manner.

Building the Structure: Secondary Education

As with primary school settings, hands-on activities with manipulatives, analogies, and models enables secondary school students to grasp abstract nanoscale phenomena not accessible through direct observation (Stavrou et al., 2015). Additionally, relating nanotechnology applications to everyday applications through group interactions and experiential learning settings makes the learning relevant and meaningful (Kolb, 1984; Vygotsky, 1978). Employing cooperative group settings and beginning with macroscale observations about the world first leading into nanoscale phenomenon provides connections for knowledge. These pro-social interactions forge supportive social networks, forming linkages for cognition (Stavrou, et al., 2015; Vygotsky, 1978). Students can learn about the interconnections between science, technology, engineering, and society through discussing real-world applications and societal impacts of scientific discoveries and emerging technologies. Discussing the applications and societal impacts of nanotechnology enables students to appreciate and construct meaning with respect to the interconnections between science, technology and society (Stavrou, et al., 2015). The combination of understanding societal impacts, increasing scientific literacy, and expanding potential career opportunities are all justifications for expanding nanoscience education in secondary schools (Figure 2).

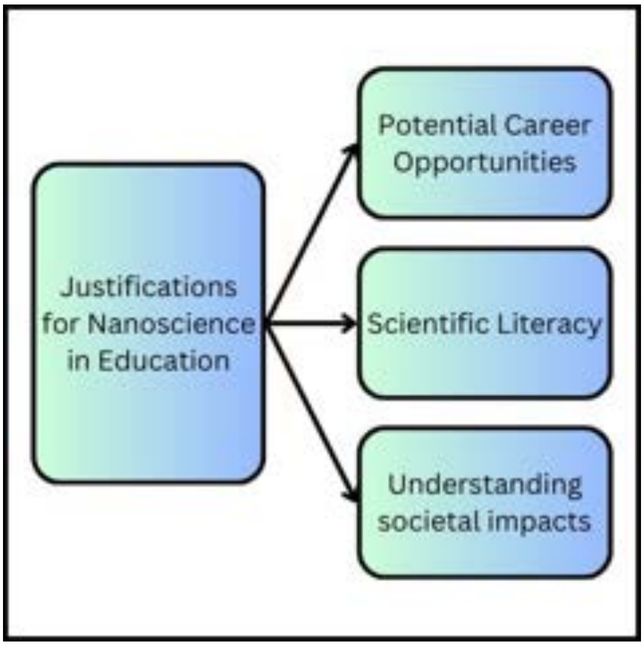

Figure 2. Justifications for nanoscience education

Nanotechnology is a sector which holds value in many different types of industries. High school is the bridge between primary school and higher education that prepares students for future workforce qualifications. School-aged students typically begin to consider future careers when they enter secondary school during ninth grade. The progression of science classes in secondary schools in the United States typically begins with general science or biology in the first year of high school, followed by chemistry and then physics or another science elective (DeBoer, 2019). The current section will explore the potential preparations that secondary science educators can take to provoke interests in students for considering a future career in the nanotechnology sector.

Biology and chemistry are typically taught to students in their ninth or tenth grade years, respectively, and are usually the initial scientific classes offered to secondary education students (DeBoer, 2019). Typically, introductory biological and chemistry coursework does not cover nanoparticles and nanotechnology. Nanotechnology may be covered in physics curricula but is not a component of biology and chemistry units (Ipek et al., 2020). This may also be due to the fact that the field of nanotechnology is relatively new and has not made its way into mainstream scientific curriculum. Another challenged faced by secondary educators in integrating nanotechnology into the curricula is the interdisciplinary nature and the unique functionality of matter at the nanoscale (Feldman-Maggor et al., 2022). Along with the topic of nanotechnology not making its way into mainstream scientific curricula, it has been found that most secondary education teachers of all disciplines, biology, chemistry and physics, have not developed proficiency in the topic of nanotechnology (Ipek et al., 2020).

The lack of exposure can be attested to a number of reasons. The first challenge faced is deficiency of knowledge on the topic by scientific instructors and the lack of exposure to nanotechnology in mainstream secondary scientific curricula. According to Ipek et al. (2020), teachers who undertook in-service training or courses in nanotechnology had significantly higher awareness in that area than teachers who did not. It is also important to note that the topic of nanotechnology is not usually taught to preservice science teacher candidates in university teacher preparatory programs (Feldman-Maggor et al., 2022). Including nanotechnology would significantly improve the understanding of the topic for instructors, which would lead to greater comprehension and understanding for students taught by future instructors.

Along with proper science teacher preparation in the topic of nanotechnology, an adjustment in scientific curricula must be made accordingly in order to properly accommodate the future demand of jobs in the nanotechnology field. Literary research by Peters-Burton et al. (2014) fielded a set of ten critical components that may work together to form new opportunities for students. The first component is a STEM-focused (Science, Technology, Engineering, Mathematics) curriculum that includes strong courses in all four STEM areas, intentionally integrated into STEM and non-STEM subjects. The second component is that STEM-course instructional practices and strategies, grounded in research, focuses on project based learning. The third component requires the school's structure to have the chance to change the students' relationship between one another, teachers, and the acquisition of knowledge. The next component involves threaded into areas considered informal, such as clubs or apprenticeships. The remaining sequence by Peters-Burton et al. (2014) involves real world STEM partnerships, early college-level coursework, well-prepared professional growth, and supports for underrepresented students.

Conceptual Learning

The United States National Science Foundation, through a series of workshops, identified nine "Big Ideas" to be addressed when it comes to teaching about nanotechnology and nanoscience. These nine ideas include: size and scale, structure of matter, forces and interactions, quantum effects, size-dependent properties, self-assembly, tools and instrumentation, models and simulations, and science, technology, and society (Stavrou et al., 2015; Hingant & Albe, 2010). Aspects of these ideas can be introduced in early secondary education and expanded upon throughout middle school and high school in a systematic progression. Many proposed frameworks for nanoscience education have a framework based on a constructivist theory of education (Laszcz & Dalvi, 2023; Khamhaengpol et al., 2021; Vygotsky, 1978). Embedding the "Big Ideas" into middle school and early high school science and math courses helps prepare students for more specific nanotech and nanoscience concepts in later high school and college coursework.

Conceptually, one of the biggest challenges facing teachers and students with regards to nanotech education is simply the size and scale of the topic itself. Concepts of very large and very small objects are not easily understood by students (Hingant and Albe, 2010). Students have been shown to struggle with understanding the size and scale of objects without conceptual comparisons. Tretter et al. (2006b) demonstrated understanding regarding the size and scale of objects at the nano-level was highly inaccurate. Struggling to conceptualize extreme scales is a barrier to accessing nanotechnol concepts. Tretter et al. (2006a) found that twelfth-grade and doctoral students had a more refined size and scale knowledge than younger aged students and linked that knowledge to both direct and indirect experiences. It is essential for the future study of objects on the nanoscale to develop a learning progression within secondary math and science courses that enhance students' abilities to conceptualize minute objects by providing experiential learning. The use of tools and technology can further help with creating these indirect experiences since objects and interactions on a nanoscale cannot be directly observed (Hingant & Albe, 2010). Furthermore, students' understanding of size and scale has been shown to positively correlate with math and science abilities across these grade levels (Chesnutt et al., 2018).

With this understanding, Delgado et al. (2008) studied students in grades seven through eleven to determine a developmentally consistent learning progression for students. The authors studied four aspects of size and scale: ordering, grouping, relative size, and absolute size. These four aspects are logically connected so the consistency of the students were studied across these four aspects. The researchers found that, "these findings strongly suggest and are consistent with a developmental trajectory in which a learner first acquires consistency between ordering and grouping, followed by ordering and relative size, then ordering and absolute size, and finally absolute and relative size." (Delgado et al., 2008, p. 9). The study's results illustrated that in order to prepare students for education in nanotechnology, embedding size and scale concepts gradually throughout math and science courses in middle school and early high school would be beneficial. Taylor and Jones (as cited in Hingant & Albe, 2010) argued that students must have a critical level of proportional reasoning ability to understand the relationship between surface area and the volume of objects. This understanding reinforces the "Big Idea" of size-dependent properties. One of the important concepts in nanoscience is this very ratio that changes with the size of the object and is maximized at the nanolevel.

Proportional reasoning is an important mathematical concept introduced typically in early middle school grades. Ensuring students' understanding of ratios and proportions, while already an important part of math curricula, facilitates students making connections to these specific shapes and sizes.

Curricular Relations

Nanotechnology is related to and can be interwoven within several disciplines. Beginning in primary school, students can be afforded opportunities for exposure to nanosciences within courses provided throughout their educational experience. Nanotechnology and nanosciences are not limited to solely STEM disciplines and provide learning experiences beyond traditional STEM course offerings. (Figure 3).

Chemistry

Chemistry education primarily focuses on the properties and relationships of elements, molecules and compounds. The aforementioned aspects of chemistry fall into the realm of nanoscience, given the size of molecules and particles. Nanoscience involves altering the properties of molecules which affect the structure's bonding relationship between compounds (Lozano, 2022; Rafique et al., 2020; Taha et al., 2022).

Biology

Biology education focuses on the relationship between organisms and the natural world. Nanomolecules can provide certain organisms abilities to better their chances of survival and reproduction. Along with aiding the survival of species in the wild, nanotechnologies are also used in the field of medicine to better treat diseases and ailments (Cullinane et al., 2013; Doroudian et al., 2021; Ikumapayi et al., 2021).

Physics

Primary and secondary physics education deals in the structure of matter and its interactions in the universe. Topics of focus within this discipline involve structures on a nano or molecular level. Nanotechnology and nanosciences are utilized to alter the properties of materials through the alteration of a material's molecular structure (Rafique et al., 2020; Taha et al., 2022).

Engineering

Engineering is the practical employment of science in areas such as, but not limited to, design, architecture, machinery and infrastructure. Engineers are generally responsible for manipulating nanomaterials for industrial purposes. These materials can be utilized in sectors such as computer hardware, pharmaceutical materials, clothing. and food production (Hornyak et al., 2018; Mitman et al., 2008).

Computer Science

Computer science deals with computers, their hardware, programs, and algorithmic processes. Nanotechnology is utilized to advance computing speeds, processing power, and increasing computer memory storage (Ikumapayi et al., 2021). The creation of new computer technologies falls into the realms of both computer science and engineering.

Non-STEM

Nanotechnology is not only limited to the industries of science and engineering. Instances of non-STEM utilizations of nanotechnologies include clothing, food and cosmetics. Nanoparticles are harnessed to improve the quality of clothing or cosmetics by altering their original molecular structures, which in turn affects its external properties. In the food-production industry, nanotechnology can be applied to alter the taste of foods or its adhesion to surfaces (Lozano, 2022).

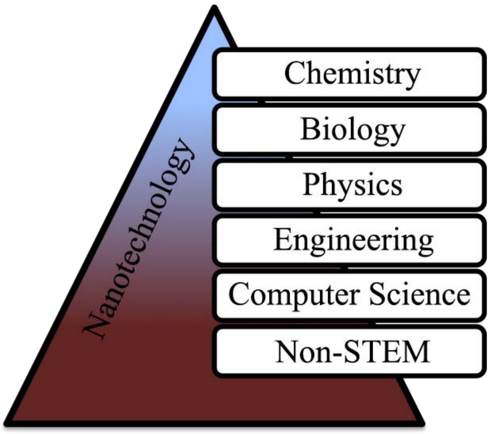

Figure 3. Relationships among nanotechnology and areas of study

Curricular Units and Connotations

It would be reasonable to assume there may be pushback from educators or administrators for nanotechnology implementation due to the perception of having to rearrange entire scientific curricula to include nanotech units. Fortunately, that may not be the case, as there are ways to add nanotechnology to already existing coursework. Nanotechnology possesses potential for inclusion in a number of course offerings, such as biology, chemistry and physics, as well as courses for non-science majors (Park, 2019; Quirola et al., 2018). For biology classes, nanotechnology can be interwoven into a unit covering the human immune system (Quirola et al., 2018). In the human immune system unit, topics concerning nanoparticle use in vaccines and medicines may be included.

Incorporating opportunities for student projects to include social interactions, debate, and teacher facilitation develops content knowledge as well as social skills development (Mandrikas et al., 2020; Quirola et al., 2018; Stavrou, et al., 2015; Vygotsky, 1978). A relatively simple experiment or demonstration includes providing biology students with an activity involving pouring water and then honey on a cabbage leaf. Students then observe how both substances form a ball on the surface of the cabbage leaf before rolling off (Cullinane et al., 2015). Students would then pour the water and honey on another leaf, to which they would compare and contrast their observations. This experiment can be used to introduce and interweave the concept of nanoparticles and their occurrence in the natural world (Cullinane et al., 2013; Quirola et al., 2018).

In chemistry it was suggested to include nanotechnology in a unit dedicated to polymers where the use of nanoparticles in manufacturing would be discussed. Quirola et al. (2018) recommended that students create models of nanoparticles and their bonds to better visualize their functionality. Blonder and Sakhnini (2017) also conducted a study in Israel where they were able to use their already existing high school chemistry curriculum and insert nanotechnology topics. The Israeli chemistry curriculum covered the following topics: basic concepts, atomic structure, structure and bonding, oxidation-reduction, acids and bases, the chemistry of foods, and kinetics. The curriculum also had optional units on polymers, physical chemistry, and biochemistry. Blonder and Sakhnini (2017) also noted that the curriculum generally follows worldwide chemistry progressions and thus, their study could be applied and replicated in other countries. Ha and Lajium (2022) had also found that teaching nanotechnologies in secondary chemistry classes and making real-world connections increased student motivation for learning.

Physics would seem to be the most ideal content area to interweave nanoparticles given the topic's focus on molecular structures and intermolecular interactions. Quirola et al. (2018) recommended using physics to introduce the concept of the nanoscale and nanotechnologies. An activity that was utilized in the Quirola et al. study was the classification of items on the micro, macro, nano and subatomic scales. From there, the concept of surface-volume ratios would be taught, where the concept of nanoparticle manipulation could be made with real-world connections.

Extracurricular Opportunities

Nanoscience and nanotechnology concepts can be easily embedded within existing middle and high school STEM curricula. Exposure to these concepts, at the very least, helps to provide a baseline scientific literacy concerning nanotechnology and its implications in science and society (Hingant & Albe, 2010; Spyrtou et al., 2021). The goal is that nanotechnological concepts will inspire a number of students to strive to engage in deeper learning regarding nanoscience and nanotechnology. One potential avenue for middle and high school aged students, short of specific nanotechnology courses, would be through extracurricular opportunities. Peters-Burton et al. (2014) lists blended formal/informal learning beyond the school day and real-world STEM partnerships as two of their ten critical components of Inclusive STEM High Schools (ISHSs). Providing extracurricular opportunities such as clubs, camps, or short after school courses would be relatively easier than creating a whole new curriculum, adding instructors, or changing school schedules to address the potential needs of students wanting to expand their knowledge of nanotechnology prior to higher education.

Teacher Professional Growth

Nanotechnology is not a topic that is typically taught in teacher preparation programs. For schools to remedy this issue, in the short term, the implementation of nanotechnology into curricula requires professional growth opportunities for teachers. Teachers typically partake in professional growth for reasons such as advancing their careers, mandated requirements, or staying up-to-date with respect to pedagogy (Feldman-Maggor et al., 2022). In order for the successful implementation of nanotechnology in existing curricula, teachers must commit to engaging in professional growth. Effective professional growth garners higher success rates when growth is school-based, engaging, and able to be sustained for long periods of time to allow for cycles of reflection (Borko et al., 2010). Another option that may entice more STEM educators, which has become increasingly popular since the COVID-19 pandemic, is the ability to partake in professional growth opportunities in an online, virtual setting.

Building the Future: Higher Education

As students progress from primary education to secondary education, and finally higher education, courses and the course content itself becomes more and more compartmentalized. Students transition from elementary grade level content to precise, categorical department and course content in college. Given the more rigidly structured, categorized course assignments in education, promoting nanotech coursework or courses outside of science creates challenges for recruiting student nanotechnology course enrollment.

A strategy that has been employed for soliciting student enrollment in nanoscience aside from student science majors, is nanotechnology for non-science undergraduate majors (Park, 2019). Facilitating a non-science major enrollment option exposes a greater number of students to principles of basic chemistry, nanotechnology applications, and utilization of nanotech concepts for generating conceptualization. Employing a non-science major course offering provides yet another bridge for transitions from primary education to secondary education and finally higher education. The course included lab exercises, exams, and an applied project to assess students' understanding. The goal was to utilize chemistry for introducing relatable, conceptual nanotech applications for promoting critical thinking and integrative learning (Park, 2019).

Nanoscience Connections and Applications

Biological and Medical Science

Nanotechnology has aided in the role of creating significant strides in the field of medicine and pharmaceuticals. Nanotechnology has been shown to have a greater efficacy for treating patients, as the nanoparticles have been shown to specifically target areas of ailments (Doroudian et al., 2021; Ikumapayi et al., 2021; Lozano, 2022). With the success and continuous development of nanoparticles in the biological and biomedical fields, it is reasonable to predict a growing industry and job market (Figure 4).

Environmental Science

Climate change is an issue that is not new to many. The issue of climate change stems from human activities such as releasing carbon emissions into the atmosphere, through means of automobile emissions or pollutants released from factories. As a result, environmental scientists have been working to reverse and minimize the negative changes to our planet. Nanotechnologies are being employed in the field of environmental sciences to improve the areas of waste management, air pollution, and water scarcity (Taran et al., 2021).

Chemistry

University level chemistry is positioned to delve much deeper into the relationships of elements with respect to the real-world. Resources at the university level provide college students with a more hands-on, guided-inquiry approach to chemistry in comparison to what is available at the secondary educational level (Jesionkowska et al., 2020; Lati et al., 2019). Along with a deeper understanding of the scientific discipline, universities are better equipped to impart students with the necessary skills to find employment in their respective field as a result of required laboratory classes. Nanotechnologies are also applicable in the field of chemistry as a result of potential alterations to the bonds of chemicals and molecules, which in turn can improve the properties of the elements in comparison to their natural forms (Rafique et al., 2020).

Forensics

Forensics is a relatively newer field of science in comparison to its counterparts of biology, chemistry, and physics. The field of forensic science focuses on criminalistics and is relevant for matters pertaining to examining evidence concerning criminal law. The addition of nanotechnologies to forensic science has allowed for improved detection, recognition, and analysis of crime scene evidence (Tambo & Ablateye, 2020). Advancements in nanoscience may lead to an overall improvement of the legal system.

Physics

The study of physics typically delves into the interactions of all matter in the universe on an intermolecular level. As such, it can be considered the basic framework for all science and engineering disciplines. Given those intermolecular relationships and measures, nanoscience possesses the closest relationship with the field of physics. The close relationship of concepts, coupled with nanoscience’s interdisciplinary nature, has led to the pioneering of concepts that have advanced technologies such as cancer treatment and microscopy (Bayda et al., 2019).

Engineering

To describe the field of engineering as vast and diverse would be an understatement. Just as there are a plethora of topics that fall under the umbrella of science, the same can be said for the discipline of engineering. Nanotechnology has allowed for substantial progress in a variety of engineering fields. For instance, nanotechnologies have been wielded by biomedical engineers to improve already existing CRISPR technologies to genetically engineer plants to better the production of therapeutics, biomaterials, and bioenergy (Demirer et al., 2021). Another stride made by nanoengineering is the improvement of transportation. Through the employment of nanoparticles, the strength, durability, and longevity of concrete and cement on highways has improved (Mobasser & Firoozi, 2016). The previously mentioned examples are just a few of the variety of uses of nanoparticles by engineers.

Material Sciences and Manufacturing

In addition to the use of nanomaterials for identifying solutions to some of the world’s most basic needs, nanomaterials are being employed to improve everyday life. According to Talebian et al. (2021) nanomaterials are used in cosmetics, sports and fitness, textiles, and home appliances as well as in many other industries. Considerable investments in nanotechnology has led to the increased production of nanoproducts, particularly in the United States (Talebian et al., 2021). These consumer products are manufactured in a diverse array of industries. Additionally, investment in nanotechnology does not appear to be slowing and the authors note that “A strong global economic growth and job creation is expected to emerge and strengthen in the coming decades” (Talebian et al., 2021, p. 59).

Computer Science and Electronics

Ever since the advent of computers in the mid-twentieth century, technology has allowed for ever smaller processors and storage devices. In 1965, Gordon Moore coined “Moore’s Law” that stated that the number of transistors on a computer chip doubles every two years allowing computer devices to shrink exponentially. However, this law is running into physical limitations (Taha et al., 2022). Transitioning to the use of nanomaterials helps to overcome the physical limitations of traditional silicon transistors. Although still in the early stages of development, advances in quantum computing are increasing the calculating speed and storage capacity of computers tremendously (Taha et al., 2022). Computer science is a growing and high demand career path, and the future of computing requires understanding of nanotechnology. Coincidentally, the advances of computer science, machine learning, and ever growing data sets, allow for even greater research into nanotechnology and nanoscience (Taha et al., 2022; Talebian et al., 2021).

Food and Agriculture

Nanoparticles have an ever increasing role in the livestock and agricultural industries. The use of nanoparticles in modern farming practices have helped the industry respond to global population growth by reducing crop and animal loss. Nanotechnology is starting to be employed in formulations, pesticides, fertilizers, and even sensors (Mittal et al., 2020). These innovative uses are being employed to make the industry more resilient and increase food security. However, these uses are relatively new and growth in this area of nanoscience is essential. Additionally, further study is needed to examine risks and long term effects on soil, water, and the natural environment as a result of additional use of nanoparticles.

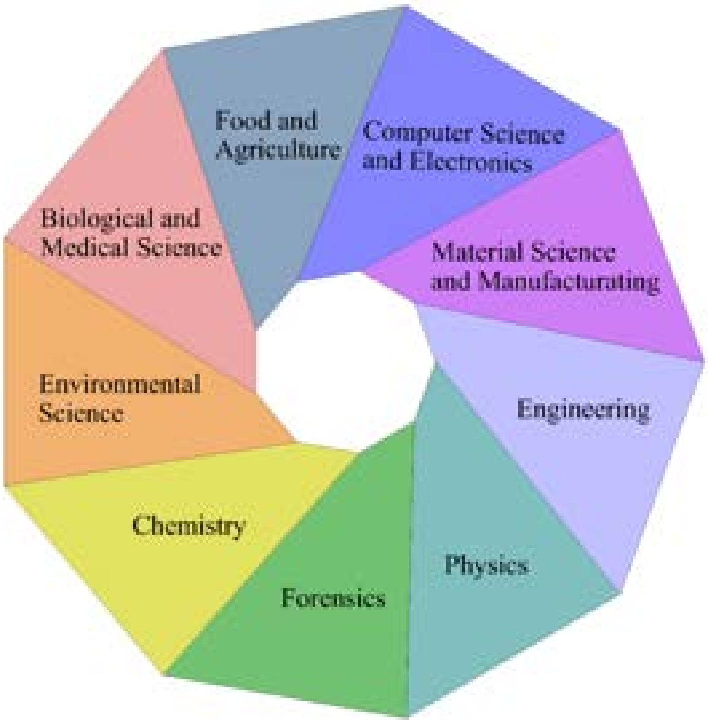

Figure 4. Nanoscience connections and applications

Conclusion

The field of nanotechnology, while dealing with incredibly small objects, looms large over the future of STEM education. As tools and technology increase our understanding of the very small, ironically, knowledge continues to grow. Interestingly, the properties of materials on a human level can change at the nanolevel with the changes in size, shape, inner, and outer geometric characteristics. Whether these nanoparticles occur naturally, or if they are artificially made, they afford a whole new world of possibilities across many different disciplines and industries.

Opportunities exist in medicine, environmental science, forensics, engineering, manufacturing, computer science, agriculture, biology, chemistry, and physics. Given the enormity of the financial, political, and societal potential, it is easy to identify how large investments in research and development are being made in nanotech by national governments, universities, non-profit organizations, and private companies. It is also easy to discern why addressing nanotechnology as a component of a STEM curriculum in education is relevant.

Students as early as primary school can begin learning to conceptualize and understand nano-measures using real-world examples and hands-on activities. Students in the middle and high school grades can begin to dive into the more abstract nanoscale objects and interactions not accessible to direct observation as they continue to develop abstract reasoning ability. Experiential, hands-on, inquiry-based activities can provide for a better conceptual understanding while also promoting social group interactions (Dignam, 2023; Kolb et al., 1984; Vygotsky, 1978).

Students at the primary school level can also begin to identify connections between science, technology, engineering, and society. Effective curricular design embeds and intertwines necessary learning progressions within current science and math courses from primary school through secondary school. To facilitate this process, high-quality and impactful teacher professional growth must be incorporated to close the gap between teacher knowledge and the curriculum. In addition, teacher pre-service programs afford knowledge for developing teachers to impart with future students. Finally, secondary schools can provide extracurricular programs for students to inspire learning more about nanotechnology in the forms of clubs, camps, and curricular offerings.

Students in higher education institutions are enrolled in courses that become more specialized and rigidly structured. Recruitment of students into nanotech fields is critical, as the need for this type of expertise is rapidly developing. Aside from science students, an introductory course in nanotechnology would help promote critical thinking as well as provide a background for those entering industries that will inevitably be influenced by nanotechnology. Nanotechnology is a rapidly expanding field with many applications across a great diverse set of industries. Educational institutions are tasked with preparing students with learning for jobs that do not yet exist. Possessing an awareness of current trends in areas of STEM and the labor market requires current academic studies in technology and education to be relevant for student preparedness.

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