Integrating Nanoscience into Virginia's *Standards of Learning for Science*

A Draft Document Developed by the MathScience Innovation Center for Use in Advocating Revisions to the Science Standards
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Rationale for Integrating Nanoscience into the Standards

- Nanotechnology promises to have a broad impact on society similar to the shifts from agricultural to industrial to computer-based economies. The United States' economic prosperity is linked to technology and to workers with science and engineering skills. (Stevens, Sutherland, Schank & Krajcik, p. 3)

- Nanoscience is an interdisciplinary field focused on objects which have at least one dimension between 1 and 100 nanometers (10^{-7} to 10^{-9} meters). (Stevens, Sutherland, Schank & Krajcik, p. 4)

- As part of the National Nanotechnology Initiative, scientists and educators have identified major concepts for a nanoscience curriculum. This document is drawn primarily from "The Big Ideas of Nanoscience" written in February 20, 2007 and previously posted on the University of Michigan's website (article in publication); it is based upon a series of national workshops funded by the National Science Foundation for the purpose of "identifying and reaching consensus on the key concepts." (Stevens, Sutherland, Schank & Krajcik, p. 10)

- Virginia's *Standards of Learning* do not address fundamental concepts related to an understanding of the various scales of matter, the impact of scale on the physical and chemical properties of matter, and the forces which dominate at various scales and their interactions. Other areas need to be strengthened including a greater emphasis on the electrical nature of chemical bonding and the various types of bonds, the impact of surface area/volume ratios on properties and reactions (especially as objects become smaller), the properties of materials which can spontaneously self-assemble, and the tools and models which increase understanding and drive the fabrication of new products. Throughout the standards, more modern applications need to be cited.

Revision of Standards & Curriculum Framework

- Examples of current **science standards** which can be modified to provide a strong nanoscience foundation include the following.

  Scientific, Reasoning and Logic Strand (all subjects): development of strong sequence of outcomes related to systems and scale, modeling and simulations, nature of science, and science and technology as defined by the national science standards and the "The Big Ideas of Nanoscience."

  Science 6: 6.1 (investigation, reasoning, logic), 6.4 (matter) and 6.5 (properties and characteristics of water)

  Life Science: LS.1 (investigation, reasoning, logic), LS.2 (cell division)

  Physical Science: PS.1 (investigation, reasoning, logic), PS.2 (chemical and physical properties), PS.4 (periodic table), PS. 5(changes in matter), PS.9 (dual nature of light), PS.11 (electricity and magnetism)

  Earth Science: ES.1 (investigation, reasoning, logic), ES. 5 (rock-forming ores and minerals), ES.10 (history and evolution of Earth), ES.12 (origin and evolution of atmosphere), ES.13 (energy transfer), ES.14 (universe)

  Biology: BIO.2 (biological concepts), BIO.3 (chemical and biochemical principles), BIO.5 (life functions various organisms), BIO.6 (inheritance and protein synthesis)

  Chemistry: CH.1 (investigation, reasoning, logic), CH.2 (periodic table and atomic structure), CH.3 (bonding), CH.5 (phases of matter & forces between particles

  Physics: PH.1 (investigation, reasoning, logic), PH.7 (fluids), PH.10 (electromagnetic spectrum), PH.11 (optical systems), PH.14 (large & small quantities & laws)

- Examples of current **math standards** which can be modified to provide a strong nanoscience foundation include the following.

  Math 6: 6.5 (positive exponents), 6.9 (comparisons between measurements), 6.10 (volume & surface area of prism), 6.13 (properties of quadrilaterals)

  Math 7: 7.1 (negative exponents & scientific notation), 7.4 (proportional reasoning), 7.5 (surface area & volume of rectangular prisms and cylinders; impact of changing one attribute), 7.7 (compare & contrast quadrilaterals)

  Math 8: 8.1 (compare & order numbers in scientific notation), 8.3 (ratios & proportions), 8.7 (practical problems involving volume & surface area of prisms, cylinders, cones, and pyramids; impact of changing one attribute)

  Algebra I: A.10 (laws of exponents & scientific notation)

  Geometry: G.13 (surface area & volume of 3-D objects), G.14 (ratios, impact changing 1 or more dimensions on area and volume)

- The curricular framework and scope and sequence can provide vehicles for incorporating more detail and for increasing teachers' understanding of nanoconcepts.

- The synopsis of major nanoscience concepts and the selected references can serve as a basis for recommending changes to the standards, curriculum framework and scope and sequence and for recommending teacher training.

Synopsis of Major Nanoscience Concepts

1.0 Size & Scale: **Factors related to size and scale (e.g. size, scale, shape, proportionality, dimensionality) help describe matter and shape its behavior).** (Stevens, Sutherland, Schank & Krajcik, p. 20)

Fundamental math concepts: billion, billionth, positive exponents, negative exponents, scientific notation, relationships among length, area and volume, changes in surface area to volume ratios, impact of shape on surface area and volume, ratio and proportional reasoning. In Virginia, these concepts are taught in Math 6 -8, Algebra I and Geometry. (Stevens, Sutherland, Schank & Krajcik, pp. 20-23)

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- Size refers to the amount of something (such as length); a nanometer is one-billionth of a meter. Typically nanotechnology refers to objects which measure between 1 and 100 nanometers on at least 1 dimension. (Stevens, Sutherland, Schank & Krajcik, pp. 4, 20)

- Properties, such as length, can exhibit large differences in size or magnitude; these large changes in magnitude of scale are often defined as "scales" or worlds, e.g. macroworld (10^{0} to 10^{-3}), microworld (10^{-4} to 10^{-6}), nanoworld (10^{-7} to 10^{-9}), atomic world (10^{-15} and below). Scientific notation is a useful tool for communicating very small and large numbers and is helpful in categorizing the size of things by orders of magnitude. Scale ladders, based upon scientific notation, are useful in comparing the size of objects and in making links to common objects. (Stevens, Sutherland, Schank & Krajcik, pp. 20-22)

- Different forces dominate at different scales of the universe and different models are needed to explain interactions between matter. For example, gravity dominates in the macroworld and electrical forces in the nano and atomic worlds. (Stevens, Sutherland, Schank & Krajcik, pp. 20-22)

- Length, area and volume change disproportionately. A small decrease in linear size yields a relative decrease in surface area and an even larger relative decrease in volume. Thus, small objects have a large surface area (SA) in relation to their volume (V). Shape impacts the ratio between surface area (SA) and volume (V) and is more important at the nanoscale. Changes in the surface area to volume ratio (SA/V) impact physical changes such as solubility, absorption, evaporation, and filtration; an increased SA/V ratio speeds these processes. As the SA/V ratio increases so does the chemical reactivity; this relates to the increased number of atoms on the surface relative to those within the bulk material. Many of the unique properties that matter exhibits at the nanoscale result from the large SA/V ratio; properties dependent on volume (bulk) change more rapidly than properties dependent on surface area. (Stevens, Sutherland, Schank & Krajcik, p. 21)

- Predicting the behavior of a system at one scale does not necessarily translate to predicting behavior at another scale. For example, many of the properties of matter on the nanoscale are surprising because they cannot be predicted using our experience at the macroscale and classical mechanics. At the nanoscale, the quantum mechanical model is more accurate at describing and predicting behaviors. (Stevens, Sutherland, Schank & Krajcik, p. 21)

2.0 Structure of Matter. All matter is composed of atoms that are in constant motion. Atoms interact with each other to form molecules. The next higher level of organization involves atoms, molecules, or nanoscale structures interacting with each other to form nanoscale assemblies. The arrangement of the building blocks gives a material its properties. (Stevens, Sutherland, Schank & Krajcik, pp. 23)

- All matter is composed of discrete units called atoms which are in constant motion because of thermal energy. At short distances, atoms interact to form compounds. During the interaction, electrons are rearranged and areas of positive and negative charge created; the electrical force between the opposite charges holds the compound together. Both thermal (heat) motion and electrical forces are necessary for atoms to form compounds. (Stevens, Sutherland, Schank & Krajcik, p. 23)

- The element carbon exists in different forms (allotropes). At the macroscale, the different forms are diamond, graphite, charcoal and graphene. At the nanoscale, allotropes include carbon nanotubes and bucky-balls. These allotropes result from the unique ability of carbon atoms to form many different types of bonding patterns. Each allotrope has a unique structure and set of properties. Nanotechnology exploits the novel properties of these nanostructures to create new materials and devices. (Stevens, Sutherland, Schank & Krajcik, p. 24)

- Nanoscale assemblies (materials) are made of atoms, molecules, or nanoscale structures. Each assembly (material) has a unique structure which determines its properties. Both thermal (heat) motion and electrical forces are necessary for the formation of nanoscale structures and assemblies. These are the same forces that dominate the atomic world. (Stevens, Sutherland, Schank & Krajcik, pp. 23-25)

- At the macroscale, the motion of individual atoms does not impact the properties and behavior of a substance. At the nanoscale, the substance may contain such a small number of atoms that the motion of an individual atom impacts its properties and behavior. (Stevens, Sutherland, Schank & Krajcik, p. 23)

3.0 **<u>Size-Dependent Properties</u>. The properties of matter change with scale. In particular, as the size of a material approaches the nanoscale, it often exhibits unexpected properties that lead to new functionality. (Stevens, Sutherland, Schank & Krajcik, pp. 25)**

- At the macroscale, some properties are not impacted by the amount of material and are useful in describing and predicting behavior, e.g. density, melting point, boiling point, and solubility; other properties are impacted by the amount of material (bulk) and are less useful, e.g. size, shape, color, weight. As the size of an object approaches the nanoscale, the amount of material becomes critical and all properties are impacted by the size and shape of the material. (Stevens, Sutherland, Schank & Krajcik, pp. 25 - 27)

- Some properties and many rates of reaction are related to surface area and are impacted by changes in the SA/V ratio (see 1.0).

- Properties of matter that tend to vary with scale include chemical, magnetic, electrical, optical and mechanical properties. (Stevens, Sutherland, Schank & Krajcik, pp. 25 - 27)

- Electricity and magnetism exist together at all scales. At the nanoscale, electrical and magnetic properties dominate even in materials that do not have these properties at larger scales. Organic materials are made mostly of carbon and do not exhibit good electrical conductor or semiconductor properties at the macroscale. They do so at the nanoscale, making use of them in electronic circuits possible. Even pure carbon is a much better conductor at the nanoscale (carbon nanotubes) than at the macroscale. Living things are driven by electricity which is created at the nanoscale in organic molecules. Solar energy excites electrons in organic molecules during photosynthesis; this is the first stage in producing electricity. Medical researchers have found that they can control living cells by binding 30 nm beads to receptor molecules on a cell surface, then turning on a magnetic field which influences cell functions.

- At the macroscale, interactions between light and matter, such as reflection and refraction, are inexact and often random. Processes whose goal is the manipulation of light are haphazard when nanomaterials are manufactured at the macro level, e.g. fiber optics, photovoltaic cells and dyes. Nano-production techniques allow

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materials to be designed to exactly accommodate specific wavelengths of light. This allows the creation of "photonic band gaps" which permit light to be precisely guided, metered, or otherwise utilized. These band gaps can be engineered to match the energies involved in a particular application. One example of this is the design of photovoltaic cells that use band gap engineering to permit more wavelengths of sunlight to efficiently generate electrons while minimizing the buildup of heat. Quantum dots make use of specific sized nanocrystals to emit specific wavelengths of light when excited by an external source. These can be used for energy-efficient lighting, to tag proteins, or to generate specific wavelengths of laser light.

- Mechanical properties of a material include stiffness and strength. These are governed by many factors including the strength of the bonds holding the material together and the imperfections present in the material. The stiffness of a material is related to the strength of the bonds. Covalent bonds tend to be very strong compared to van der Walls forces. Materials, such as diamond, are very stiff because of the covalent bonds between the individual atoms of the crystal. In contrast, materials relying mostly on van der Walls forces are more easily distorted. The overall strength of a material is limited, however, by the imperfections present in its structure. As the size of a sample decreases, the probability that it contains flaws decreases and the breaking strength increases. Theoretically, carbon nanotubes could be manufactured with no flaws at the molecular level and would therefore be as strong as the covalent bonds between the carbon atoms would allow (some research shows carbon nanotubes to be 12.5 times as strong as steel).

- The properties of minerals influence or fully drive most physical, chemical and biological processes on Earth. The mineral species on Earth, of which about 4500 are currently described, vary in composition and structure and exhibit diverse physical and chemical properties. Nanominerals exist only at the nanoscale, with common examples being certain clays and iron and manganese (oxyhydr)oxides. Most of the known minerals can exist over a range of sizes; at the nanoscale they are referred to as mineral nanoparticles. Although both nanominerals and mineral nanoparticles have a fixed composition, they exhibit a range of physical and chemical properties depending on their size and shape. (Hochella and others, pp. 1631-21)

- Nanominerals and mineral nanoparticles are common and widely distributed throughout the atmosphere, oceans, groundwater and surface water, soils, in and/or on most living organisms. Nanoparticles are produced by mineral growth, weathering, and the grinding associated with earthquake-generating faults. Mineral nanoparticles are distributed globally via atmospheric circulation patterns, with distribution impacted by climate. Nanoparticles are involved in the movement of heavy metals, radionuclides, and human irritants and toxic materials., (Hochella and others, p. 1632-33)

4.0 Forces. All interactions can be described by multiple types of forces, but the relative impact of these forces changes with scale. On the nanoscale, a range of electrical forces with varying strengths tends to dominate the interactions between objects. (Stevens, Sutherland, Schank & Krajcik, pp. 28)

- The behavior of matter can be explained by four forces. At the macroscale, the dominant force is gravity which is the attractive force between masses. At the nano and atomic scales, the electrical forces derived from electrical charges dominate. At the subatomic scale, the nuclear (strong) force, which is responsible for holding the components of atoms together, is dominant. In addition, the weak force is associated with nuclear reactions such as radioactive decay. (Stevens, Sutherland, Schank & Krajcik, p. 28)

- Various electrical interactions occur among atoms, molecules, and nano particles. The forces (bonds) created vary in strength and form a continuum that describes all interactions between matter at the atomic and nanoscale, e.g. Ionic, covalent, hydrogen, permanent dipoles, non-permanent dipoles, van der Walls force (London Dispersion Force). The electrical forces that dominate the atomic and nanoscale exist on a continuum, with none of the forces existing in a "pure" form. (Stevens, Sutherland, Schank & Krajcik, pp. 28-29)

- Hydrogen bonding is a special type of bonding which results from the interaction between a partial negative and positive charge. A common example is the hydrogen bonding which occurs in water; although the bond is weak, it explains many of the special properties of water including its relatively high freezing and boiling point. Hydrogen bonding also exists when hydrogen bonds to nitrogen and fluorine, as well as oxygen. Because hydrogen, nitrogen and oxygen are found in many of the molecules associated with living organisms, hydrogen bonding is a critical component of biological reactions, e.g. DNA and RNA, proteins, carbohydrates, and lipids. (Stevens, Sutherland, Schank & Krajcik, p. 29)

- Metallic bonding involves the attraction between positively charged metal ions and nearby delocalized electrons and is responsible for the physical properties of metals such as conductivity, malleability, heat conduction and luster. (Stevens, Sutherland, Schank & Krajcik, pp.. 28-29)

- Knowledge of electrical forces is necessary to understand the behavior of matter at the nanoscale, to design and build nanoscale structures, and to manage the resulting nanostructure so that it is useful. (Stevens, Sutherland, Schank & Krajcik, p. 29)

- At the nanoscale, Brownian motion (thermal energy), viscosity, and strong electrical forces govern all interactions. Because many living systems evolved at the nanoscale, investigating how they addressed these impacts is critical to understanding effective ways to engineer at the nanolevel. (Jones, *Soft Machines*)

- ATP and other energy-rich biomolecules cause changes in molecular conformations and bond rigidity which bias random processes which are powered by thermal energy. (Jones, *Soft Machines*)

- The rapid self-assembly of mobile biomolecules, such as microtubules, requires that individual intermolecular forces be weak although the combined forces in the whole molecule can be strong enough to do cellular work. (Jones, *Soft Machines*)

5.0 Self-Assembly. Under specific conditions, some materials can spontaneously assemble into organized structures. This process provides a useful means for manipulating matter at the nanoscale. (Stevens, Sutherland, Schank & Krajcik, p. 31)

- Self-assembly involves the spontaneous reorientation of mobile objects, under certain conditions, into a predictable organized structure. Thermal (heat) energy is required for mobility. Both repulsive and attractive forces occur during self-assembly; however, net attractive forces are necessary for stability. These forces are weak bonds such as hydrogen bonds and van der Walls force. The components retain their physical identify throughout the self-assembly process and can be re-separated under certain conditions. On the nanoscale, the mobile components of self-assembly are atoms or aggregates which interact through weak electrical forces. The shape and charge of objects impact the process of self-assembly and the resulting product. (Stevens, Sutherland, Schank & Krajcik, p. 32)

- Self-assembly occurs throughout nature; examples include the formation of snowflakes, cells and viruses. Self-assembly is crucial for living processes including the formation of membranes, the replication of DNA, and protein production. (Stevens, Sutherland, Schank & Krajcik, p. 32)

- Biological self-assembly results from molecular templates that bias random processes in particular directions.

- Nano-addressing is the process by which nano-particles interface or couple with the microscopic and macroscopic environment without losing their intrinsic properties; this is a technological challenge in creating functional nano-applications.

- Self-assembly, which involves combining smaller pieces to make a larger object, is more effective for nanoscale manufacturing. This “bottoms-up” procedure is being used to synthesize new nanoscale structures. Via biopatterning, biological molecules are imprinted on a surface to provide a foundation for bottoms-up assemblies and applications. Many of these techniques result from modifications of living molecules, especially DNA and RNA, to produce specific products. (Stevens, Sutherland, Schank & Krajcik, p. 33)

6.0 Tools & Instrumentation. Development of new tools and instruments helps drive scientific progress. Recent development of specialized tools has led to new levels of understanding of matter by helping scientists detect, manipulate, isolate, measure, fabricate, and investigate nanoscale matter with unprecedented precision and accuracy. (Stevens, Sutherland, Schank & Krajcik, p. 34)

- Scientists have a relatively well developed understanding of how matter behaves at the atomic scale but a limited understanding of the nanoscale where matter transitions from the atomic to the micro (bulk) scale. (Stevens, Sutherland, Schank & Krajcik, p. 24)

- Previously, the small size of the nanoworld made it inaccessible. Now, new tools and instruments, such as scanning probe microscopes, are making the nanoworld accessible and enabling scientists to image nanoscale materials and determine their properties. Computer-based models and simulations of the nanoworld are used to explain behavior, make predictions, and improve general understanding. These new tools and instruments are driving the progress of nanoscience and engineering.

(Stevens, Sutherland, Schank & Krajcik, pp. 34-35)

- Several types of instrumentation are critical to understanding the nanoworld:

  Scanning electron microscope (SEM) – uses a focused beam of electrons to scan a sample and create and image;

  Scanning probe microscopes (SPM) – use a physical probe to scan and create an image; the type of probe determines the information that can be obtained, e.g. interatomic and intermolecular forces, size and strength of magnetic features, heat conductivity and optical properties;

  Atomic Force Microscope, a type of SPM, is a work horse of the nanotech industry; it uses a probe with a point size of less than 10 nm to scan the surface, detect the interatomic and intermolecular forces, and produce images with atomic resolution. (Stevens, Sutherland, Schank & Krajcik, p. 35)

- Scanning probe microscopes are not effective with living materials. For biological materials, various types of spectroscopy including X-ray crystallography and magnetic resonance are used. (Stevens, Sutherland, Schank & Krajcik, p. 35)

- New tools enable scientists to manipulate matter and to design, create, and produce structures on the nanoscale. Under extreme conditions, a scanning probe microscope can be used to move individual atoms. (Stevens, Sutherland, Schank & Krajcik, p. 35)

7.0 Models & Simulations. Because nanoscale objects and phenomena are, by their very nature, too small to see, models are needed to understand, visualize, predict, hypothesize, explain, and interpret data about them. (Stevens, Sutherland, Schank & Krajcik, p. 36)

- Models are simplified representations of objects or systems and are useful for making predictions and working with objects or systems that are otherwise inaccessible. At the nanoworld, size makes the structures and systems inaccessible. (Stevens, Sutherland, Schank & Krajcik, p. 36)

- Models allow scientists to visualize objects and phenomena, to predict behaviors, to design appropriate experiments, and to communicate data and findings. In addition, models are a critical component of the design and build process used by engineers.

(Stevens, Sutherland, Schank & Krajcik, p. 36)

- Many nanoscale structures and systems exist in nature. By studying nature, scientists and engineers are obtaining a better understanding of effective design within the nanoworld and are mimicking nature to create new products and processes. In manufacturing nanoscale products, techniques based upon DNA, RNA and protein synthesis are frequently used. (Stevens, Sutherland, Schank & Krajcik, pp. 36-37)

8.0 Nano & Society. **The field of nanotechnology is driven by the aim to advance broad societal goals. As with other technological advances, the products of nanotechnology may impact our lives in both positive and negative ways.** (Stevens, Sutherland, Schank & Krajcik, p. 38)

- There is a complex interdependent relationship among science, societal goals, governmental policies, and the global economy. Major factors driving the nanotechnology revolution include improved healthcare, increased productivity and sustainable resources. (Stevens, Sutherland, Schank & Krajcik, p. 38)

- In the realm of medicine, nanoparticles are currently being researched for use in tumor destruction, enhanced medical imaging, drug delivery, construction of artificial blood vessels, and scaffolding structures for wound regrowth. In the industrial world they have been proposed for use as a space tether, “gates” for computer messages, delivery of power in electrical grids, storage of hydrogen in fuel cells, and tiny coolant pipes for overheated computers. Water quality and human health are closely linked and can be improved through the use of nanofilters and magnetic particles which seek out toxins like arsenic.

- Nanotechnology promises to have a broad effect on society similar to the shifts from agricultural to industrial to computer-based economies. (Stevens, Sutherland, Schank & Krajcik, p. 38)

- As with any new technology, nanotechnology raises potentially negative consequences and ethical issues. Of great concern is the impact on living organisms because nanoscale structures are small enough to cross biological membranes. (Stevens, Sutherland, Schank & Krajcik, p. 38).

- Simple concepts like the connections between particles, their size, or the distances between them require serious consideration at the nanoscale. Although some investigators warn of the dangers of inhaling nanoparticles, these particles are already in face cream. shoe liners, car wax, and stain-proof slacks.

Selected Resources

Booker, R. & E. Boysen. (2005). Nanotechnology for Dummies. Hoboken, NJ: Wiley Publish

Carolina Center of Cancer Nanotechnology Excellence. http://cancer.med.unc.edu/ccne/

Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems. Urbana-Champaign, IL: University of Illinois. http://www.nano-cemms.uiuc.edu/content/education/online_labs/index.php

Comprehensive and Informative Nanotechnology Portal. www.nanotech-now.com

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Jones, A.L. (2004). Soft Machines: Nanotechnology & Life. Oxford, England: Oxford University Press.

Nano2Earth. http://www.nanowerk.com/nanotechnology/labs/Virginia_Tech_Nano2Earth.html

National Center for Teaching and Learning in Nanoscale Science (NCLT). http://nclt.us

Nanotechnology at NASA. http://www.ipt.arc.nasa.gov/nanotechnology.html

NIH Roadmap for Medical Research in Nanomedicine. http://nihroadmap.nih.gov/nanomedicine/index.asp

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The National Nanotechnology Initiative (NNI). www.nano.gov/html/edu/home_edu.html (NNIN)

University of Virginia. Virtual Lab Homepage. http://virlab.virginia.edu/VL/home.htm

University of Wisconsin-Madison. Materials Research Science & Engineering Center. http://mrsec.wisc.edu/Edetc/

When Things Get Small. University of California Television. http://www.ucsd.tv/getsmall/

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