National Nanotechnology Initiative 2020 Request for Information Compiled Responses

The National Nanotechnology Initiative (NNI) released a Request for Information (RFI) and supporting information on October 13, 2020, to inform the development of the 2021 NNI Strategic Plan. This document is a compilation of responses received.

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Hi,

My Name is Dan Vilenski, Entrepreneur who started and managed three Israeli subsidiary of US companies (Applied Materials. KLA and Kulicke & Soffa). These three companies had sales volume in 2019 over 1 billion dollars out of Israel.

For 10 years I headed the Israeli National Nanotechnology Initiative (INNI) as a volunteer, this program is considered to be a very successful operation with great tangible Academic and industrial results.

Regarding your request to identify effective mechanisms, strategies for communication, and priority topics to shape the future directions for the initiative - I suggest to initiate a cooperation between NNI and INNI that will leverage the expertise, Innovation and success of the two organisations, I will ready to lead such a cooperation program from the Israeli side at no charge.

I am in advance discussion stage of such a cooperation program with Dr. Lisa Freidersdorf, heading the NNI. The idea is to start slow "walk and upon success start to run".

I am available for additional discussion.

Regards
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RFI Response: NNI Strategic Planning

28 October 2020

There are three areas of nanotechnology research pending that have significant national interest. They are ultra-high efficient Solar Cells made from quantum dots with an Intermediate band (IB), electrical conductivity of carbon nanotubes (CNTs) for electrical (Alternating and direct current (AC/DC) for power distribution, semiconducting Single Wall CNTs (sSWCNTs) for microelectronics.

Quantum Dot (QD) Solar Cells

GASb or III-Sb Quantum dot Intermediate band solar cells (QD-IBSC) for high efficiency with a design goal of 47% for Air Mass 0 (Space) and great than 50% for Air Mass 1.5 (Terrestrial) with concentration. Modeling shows that a maximum of 63% or 630 Watts per square meter is possible under concentration.

However, there are several important parameters that need to be considered for an efficient QD-IBSC device:

- The energy gaps between the valence band (VB) and the QD levels, and between the intermediate band and the conduction band (CB), need to lie within certain ranges to achieve a high efficiency. Using detailed balance theory to solve for the best bandgap values gives a maximum efficiency of 60.8% with ECI=0.7 eV and EIV= 1.2 eV [16]. The contour plot in Figure 1b shows that there is a wide range of high efficiency values that can be achieved using EIV and ECI.

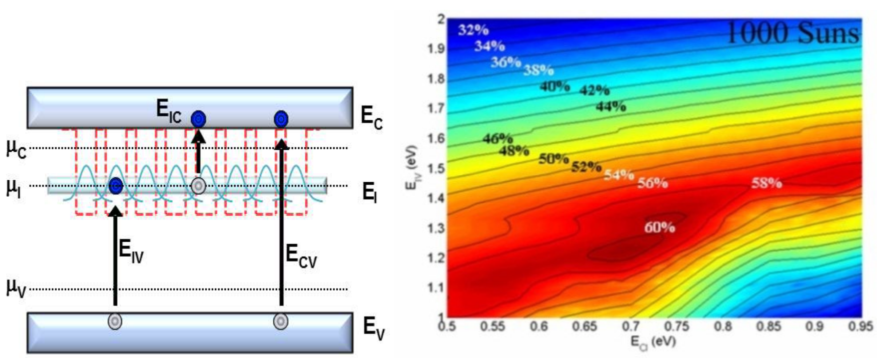


Figure 1.0 a) Energy band diagram showing the operation of the intermediate band solar cell. b) 1000 sun efficiency contour for the IBSC design calculated using an AM1.5 spectrum.

- For a QD-IB solar cell it is also important to minimize (ideally, zero) the valence band offset - ΔEv in Figure 1(a) - as any significant valence band offset will result in a reduction of the open-circuit voltage *V*oc of the device due to extremely fast hole relaxation from the valance band of the barrier to the lowest QD hole level associated with the very closely spaced hole levels.

- For the epitaxial QDs to be formed spontaneously by the strain-induced Stranski-Krastanov process, a certain minimum value of lattice mismatch between the QD material and the barrier material is required.
- A closely spaced array of QDs is needed, so that the discrete energy levels normally observed for an isolated QD broaden to form mini-bands. A high density of QDs is also required for adequate absorption. In order to achieve the required high density of strained QDs some sort of strain-balanced QD superlattice structure is almost certainly required to prevent the formation of lattice mismatch induced threading dislocations. These defects result in a high degree of non-radiative recombination that will degrade the device performance.
- A long carrier lifetime in the QD and the barrier material for efficient carrier extraction is also required.

InAs quantum dots were funded by the National Reconnaissance Office in Chantilly, VA and demonstrated by Rochester Institute of Technology (RIT). Recommend research be pursued using GaSb and III-Sb quantum dots be conducted. Estimate cost is less than $2m over 24-30 months at a university. There are several U.S. companies capable of mass producing these types of solar cells.

Electrical Conductivity of CNT based cables and wires

There is an ever-growing demand for electrical energy transmission to support microelectronics, portable power devices, grid applications, and space systems technology (see Figure 1 for examples). The need for advanced wiring concepts that can minimize ohmic losses and signal noise is paramount. The aerospace industry is constantly interested in reducing inactive spacecraft mass as a way to save payload costs and increase hardware efficiency. In general, *the wire harness mass is approximately 10-15% of that of the total spacecraft.* The harness mass includes the power distribution cables (~25%), data transfer cables (~55%), and the mechanical fasteners and shielding (20%). If wire mass associated with spacecraft function, solar panel interconnects, and data transmission were decreased, there could be significant savings in spacecraft mass. In addition, if electronic failure mechanisms could be lessened from advanced wires, with less arcing and shorting, there would be considerable benefit to enhance mission safety and lifetime.

In high power transmission lines, resistive losses account for about 7% of the energy produced. Reducing these losses to 6% would result in a national annual energy savings of $4x10^{10}$ kilowatt-hours (an annual energy savings roughly equivalent to 24 million barrels of oil annually or at $40/barrel, $960 million annually). Advanced data transfer and low voltage cables are another technology area that can reduce U.S. energy consumption - given that data centers consume annually 3% of the electricity and the portion is growing at 12% a year (DOE).

Underlying all of these technologies is the need for advanced materials to improve electrical conductivity and mechanical stability. Historically, this has been limited to the selection of a few common materials like steel, copper, and aluminum with sufficient, but not completely ideal, properties. Recently, the discovery of nanomaterials, like carbon nanotubes (CNTs), opens up the possibility to push the frontier of materials development such that advanced wiring concepts can be realized to begin addressing many of these present-day challenges. Power cables, manufactured from CNTs, could be used to rewire the electrical transmission grid, and enable continental—and even worldwide—electrical energy transport.

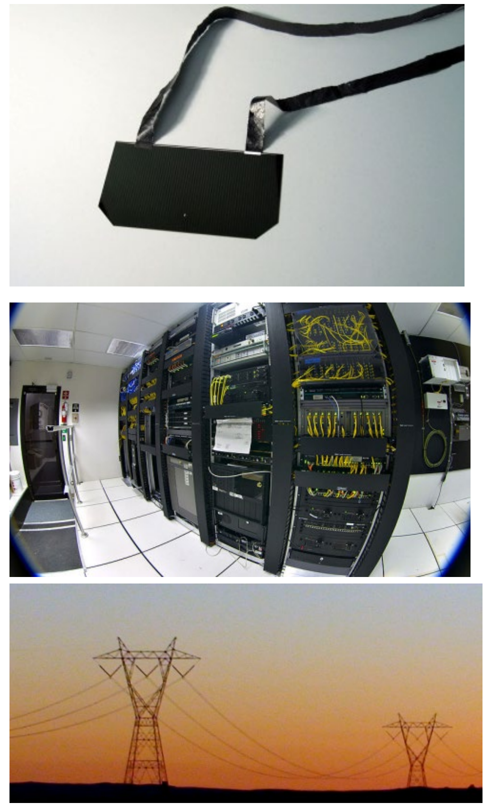


Figure 1. (Top) Use of single wall carbon nanotube (SWCNT) ribbon photovoltaic interconnect; (middle) Image of a Data center; and (bottom) high tension power lines.

Depending on the chirality and physical bundling, carbon nanotubes can have outstanding electrical and thermal conductivities, both properties are essential to wire and cable applications. An order of magnitude increase in conductivity exists for SWCNTs compared to copper when considering the theoretical internal resistance of 4.2 k□□□m for a 1 nm SWCNT diameter, corresponding to a SWCNT resistivity (□) of 1.3×10^{-6} □cm or a conductivity of 7.7×10^{5} S/cm. The bulk resistivity (□□□for copper at room temperature is 1.7×10^{-6} □ cm or a conductivity of 5.9×10^{5} S/cm. This yields a specific conductivity for Cu (density is 8.92 g/cm^3) of 6.6×10^{4} (S cm^2/g). Assuming a density of 0.8 g/cm^3 for SWCNTs, yields a specific conductivity for the SWCNTs of 9.6×10^{5} (S cm^2/g). *Thus, there exists a nearly 15 X improvement of the specific conductivity when comparing SWCNT wires to copper.*

Another important attribute of SWCNTs is their current carrying capacity. SWCNTs have been shown to be ballistic conductors at room temperature, with mean free paths up to hundreds of microns. Current densities have been measured as high as 10^{7} A/cm^2 and have been predicted to be as high as 10^{13} A/cm^2. A lightweight material which can carry extremely high currents with superior strength and flexibility should be ideal for conventional wire applications. In addition, the extraordinary mechanical properties of these materials may ultimately improve spacecraft robustness and mission life as well as the lifetime and reliability of high-tension AC/DC power transmission.

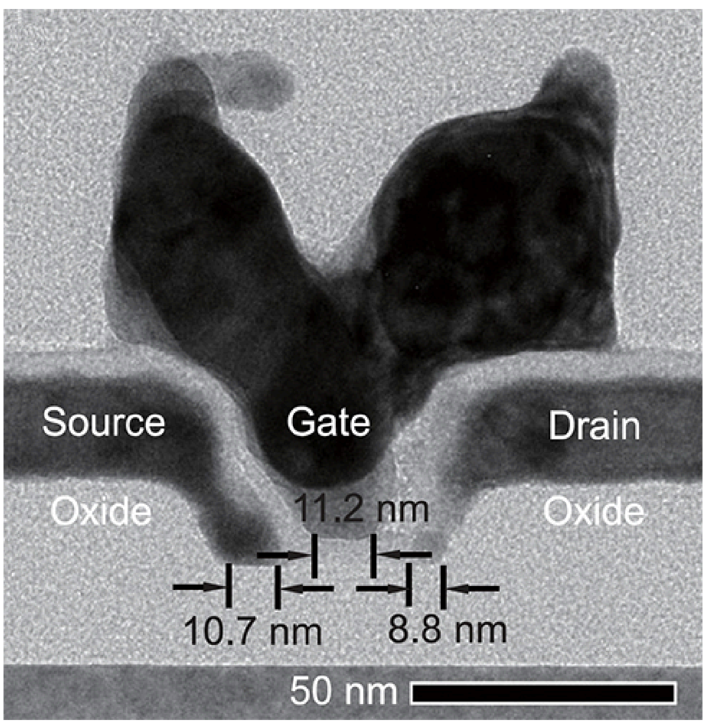
Semiconducting Single Wall CNTs for Microelectronics

CNT microelectronics covers analog Field Effect Transistors (FETs) for radio frequency microelectronics, mixed signal, CNT non-volatile universal memory and digital FETs for logic.

Carbon nanotubes (CNT) appeal to the semiconductor industry because they're superior electrical conductors compared to silicon with a mere 1 nanometer body thickness. So why don't we have CNT chips in everything from mainframes to mobile devices, yet? Scalability of the transistor and large-scale integration are still big challenges. But two papers my colleagues and I recently published in *Science* and *Nature Nanotechnology* show promising breakthroughs in these two areas critical to CNT chip reality.

Footprint achievement tips the nanoscale

First: scaling. We know 3D FinFET silicon chips could hit their power and performance limit at 7 nanometers. And while the recent announcement of 5nm silicon nanosheet transistors boost scale, power, and performance at the next node, we know its limits, too.



A transistor is more than its gate. The Source, Drain, and spacers all add up for a total footprint. Pictured: a CNT transistor with a 40nm footprint. (Figure 1B in "Carbon nanotube transistors scaled to a 40-nanometer footprint", published in Science.)

In our *Science* paper "Carbon nanotube transistors scaled to a 40-nanometer footprint," we scaled an entire CNT transistor to The International Technology Roadmap for Semiconductors' (ITRS) goal of transistors reaching a 40nm footprint – a goal they set and haven't changed since 2015. For reference, today's top-of-the-line 14nm transistors actually take up about 90nm of chip real estate.

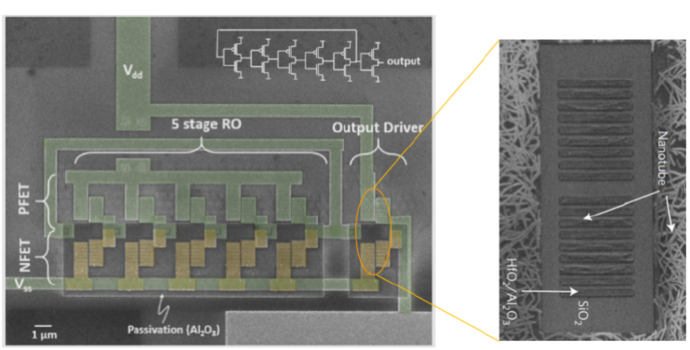
We can potentially scale a CNT transistor further than silicon for the primary reason that they're intrinsically only 1.2 nm thick. This *thinness* has the domino effect of reducing gate length to 10 nm because it provides a better electrostatic control of the gate, and helps minimize current leakage. Plus, electrons travel faster in CNTs than silicon, enhancing device performance.

But we needed a new way to connect CNTs to their source and drain (pictured). We had to find the perfect mix of materials that could "bake" these 10nm elements together at a manufacturable temperature. Our previous working end-bonded contacts between source-and-CNT, and drain-and-CNT required processing temperatures so high, at around 850°C, that the channel could not be any shorter than 60–100 nm. Switching to a cobalt-molybdenum alloy for the wiring between the elements effectively lowered the temperature to an acceptable 650°C – shrinking the distances down to 10nm.

Dr. Qing Cao, the lead author of the paper, and other colleagues on the team demonstrated that – at this newly achieved footprint – the CNT transistor can achieve performance at a level comparable to today's transistor standards.

CNT elements come together on ring oscillator

Demonstrating such an extremely scaled single transistor, even with a less manufacturable process flow, gave us the motivation to solve the integration challenges for practical CNT technologies. And for the last five years, my team has been developing individual elements of CNT technology. We know how to separate semiconducting CNTs, make CNTs "self-assemble" on a wafer, and fabricate reliable n-channel CNT Field Effect Transistors, or "FETs" (which usually degrade quickly due to contact metal oxidation) using various techniques.



All elements have to work simultaneously in a functional ring oscillator. Pictured: Top-view scanning electron microscopy image of a 5-stage CNT ring oscillator and CNTs placed trenches. (Figure 1B in "High-speed logic integrated circuits with solution processed self-assembled carbon nanotubes", published in Nature Nanotechnology.)

The challenge in developing a disruptive, early-stage technology is that some techniques used to solve one issue can end up destroying other elements of the device and the circuit. This is the fundamental reason why all nanotechnology-based demonstrations, like those using CNTs, were limited to a very low integration level. And it casts doubt on the feasibility of using them in a practical way.

But we took a major step forward in solving this integration challenge in our *Nature Nanotechnology* paper, "High-speed logic integrated circuits with solution processed self-assembled carbon nanotubes," where we show how to put all the pieces together to make a standard benchmark circuit in any logic technology – a CMOS ring oscillator.

Dr. Jianshi Tang and my other team members combined our previously developed methods to purify and place CNTs together (individually, they look like penne pasta floating in solution), but made one key adjustment by adding a sidewall oxide to protect the n-FET channel from degrading during the manufacturing process (the sidewall resulted in a three times higher yield, further ensuring that the requirement of all elements on the ring oscillator work simultaneously is met).

The functional 5-stage CMOS ring oscillators described in the paper (and pictured, above) can already work at 1 V (an industry standard). Despite low CNT density in the channel (you can see the six CNTs in the same picture) and relaxed parameters, the stage switching frequency reaches 2.8 GHz (355 picosecond) – the first example of breaking the GHz barrier for any nanotech based demonstrations. It is projected that, with a density of more than 100 CNTs per micrometer, and properly scaled device dimensions, we can achieve sub-picosecond stage delay, significantly faster than today's silicon chips.

As we write in the paper:

Since CMOS ring oscillators directly reflect the maturity of the technology, it is long-awaited proof that the important issues of transitioning this promising material into a real technology are being vigorously resolved.

From "Carbon nanotubes ready to take the torch from silicon by IBM Research Editorial Staff, July 5, 2017.

CNT Analog FETS

Carbon nanotubes (CNTs) are tantalizing candidates for semiconductor electronics because of their exceptional charge transport properties and one-dimensional electrostatics. Ballistic transport approaching the quantum conductance limit of 2G0 = 4e2/h has been achieved in field-effect transistors (FETs) containing one CNT. However, constraints in CNT sorting, processing, alignment, and contacts give rise to nonidealities when CNTs are implemented in densely packed parallel arrays such as those needed for technology, resulting in a conductance per CNT far from 2G0. The consequence has been that, whereas CNTs are ultimately expected to yield FETs that are more conductive than conventional semiconductors, CNTs, instead, have underperformed channel materials, such as Si, by sixfold or more. We report quasi-ballistic CNT array FETs at a density of 47 CNTs mm−1, fabricated through a combination of CNT purification, solution-based assembly, and CNT treatment. The conductance is as high as 0.46 G0 per CNT. In parallel, the conductance of the arrays reaches 1.7 mS mm−1, which is seven times higher than the previous state-of-the-art CNT array FETs made by other methods. The saturated on-state current density is as high as 900 mA mm−1 and is similar to or exceeds that of Si FETs when compared at an equivalent gate oxide thickness and at the same off-state current density. The on-state current density exceeds that of GaAs FETs as well. This breakthrough in CNT array performance is a critical advance toward the exploitation of CNTs in logic, high-speed communications, and other semiconductor electronics technologies.

From Brady et al. Sci. Adv. 2016; 2: e1601240 2 September 2016, PHYSICAL SCIENCE
“Quasi-ballistic carbon nanotube array transistors with current density exceeding Si and GaAs”

CNT Non-volatile Universal Memory

The increasing difficulty for improved performance with further miniaturization of established memory devices is an opportunity for the emerging memory technology based on carbon nanotubes (CNTs) (NRAM®). Regarding scalability and device footprints for the current status quo; static random-access memory (SRAM) (is fast but takes up a lot of area) uses six FETs to store a bit of information, dynamic random-access memory (DRAM) (is slower but higher density so less area) uses one FET and one capacitor to store a bit, and NAND flash memory (with very dense and slow memory that stores data when the power is off) uses one FET. In contrast, an NRAM storage element is integrated in the back of the line (BEOL) and depending on applications can be in a 1 transistor-1 resistor (1T1R) or a cross-point configuration with optional 3D scalability through multiple NRAM layers with the minimum dimension for the CNT element or ‘puck’ (see figure 1) determined by the width of the underlying via (bottom electrode) defined by the process node photolithographic/alignment tolerances.
Beyond competitive scaling, NRAM has demonstrated performance advantages against the incumbents, as well as with its peers in the emerging memory technology space, by showing remarkable device characteristics including low 20 µA program current at low voltage, trillion+ (>1012) program endurance, fast <5 ns program time, excellent retention (10 yrs @85C), and multilevel cell potential. As the physical operation understanding of the CNT resistance switching continues to improve, NRAM device performance advantages are expected increase even further.

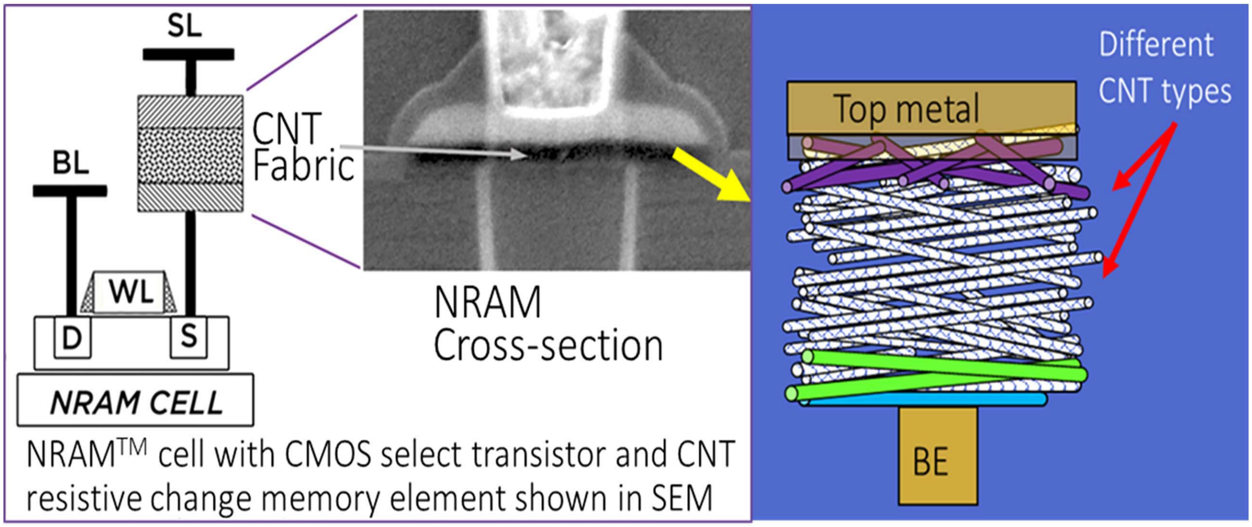


Figure 1. Schematic (and SEM) of an NRAM cell

From NRAM: a disruptive carbon-nanotube resistance-change memory D C Gilmer, T Rueckes and L Cleveland, Published 13 February 2018 • © 2018 IOP Publishing Ltd Nanotechnology, Volume 29, Number 13

Dear NSET Subcommittee,

As the concern and threat of plastic pollution in the environment, our food, air and water grow, I believe the National Nanotechnology Initiative (NNI) should continue to focus efforts on nanoplastics. The NNI has been instrumental at forming an inter-governmental special interest group on this topic. The group is very active and growing with at least 16 agencies represented on the calls and at our first in-person meeting in Jan 2020. The threat of nanoplastics is concerning because they likely can cross the gut-blood barrier and be transported throughout the body to other organs of concern, like the brain. Nanoplastics can be formed intentionally or from breakdown of larger plastic items. They may constitute a large portion of the "missing plastics" in the environment. We know 8 million tons of plastic are dumped into the ocean annually (Geyer et al 2017), but only a small portion of that can be accounted for in plastic pollution monitoring studies. Since nanoplastics cannot be seen with a regular microscope, their detection, quantification, characterization and toxicological risks cannot be easily determined. The field of measuring these particles in environmental or tissue samples has only just been conceived, and NNI can help bring the research community together to overcome the measurement challenges. I encourage the subcommittee to place emphasis on this topic for the NNI strategic plan.

Thank you,

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The Institute for Soldier Nanotechnologies (ISN) is a team — the Massachusetts Institute of Technology (MIT), the U.S. Army, and industry — working together to discover and field technologies that dramatically advance Soldier protection and survivability capabilities. It is one of the most substantial concentrated efforts in fundamental research focused on nanotechnology for both the Army and MIT.

On October 9, 2020, ISN leadership was apprised by its U.S. Army Research Office program manager of an impending Request for Information (RFI) from the National Nanotechnology Initiative (NNI) for the purpose of providing inputs and guidance for the NNI Strategic Plan. Furthermore, a restructuring of the NNI would be under consideration, so RFI responses could be particularly valuable and timely.

ISN leadership sent to its approximately three dozen Principal Investigators — all of whom are professors or research scientists at MIT— an invitation to provide comment for submittal. Their replies follow, having been minimally edited for clarity and format. These responses are applicable to the request for "priority topics to inform the future directions of the NNI."[1]

- **Meeting the DoD Energy Generation and Resilience Needs through Nano-Scale Control of Matter**

  The Department of Defense consumes large amounts energy, both in support of mobile operations and stationary facilities, and new technological solutions that can improve energy generation, storage, transmission, and use are paramount to enable enhanced performance and reduce potential vulnerabilities.

  Two promising approaches to addressing the existing energy needs include: (i) technologies that enable autonomous self-powered devices for night-time of round-the-clock energy harvesting and (ii) passive technologies for thermoregulation of personnel and facilities (including temporary shelters, vehicles, and buildings) to reduce energy use on heating and cooling. To advance technological solutions in both areas, new device design concepts combined with the multi-scale material modeling and nano-fabrication efforts are needed.

  (i) Solar energy provides a portable, carbon-neutral means of power generation, but is limited to daytime operation. Recently, several technological concepts have been proposed to generate power during nighttime, by harnessing radiative energy transfer from the Earth surface (300 K) to outer space (3 K), which include radiatively-cooling thermoelectric devices and thermoradiative cells. While practical realizations of these technologies have been limited to few low-efficiency low-power lab-scale prototypes, thermoradiative cells can operate near the Carnot efficiency limit, providing the most efficient possible power generation capability, much higher than the theoretical Shockley-Queisser limit of the solar cell operation. As such, new nano-scale engineered materials and micro-scale-engineered device configurations can yield a new generation of functional energy harvesters that would provide low-cost and high-efficiency complement to conventional solar cells for nighttime operation, providing much needed additional clean power generation capacity and resilience[2,3].

(ii) Massive energy use for heating and cooling the internal areas of the buildings and shelters can be reduced by meso-scale engineering of new lightweight materials for passive thermoregulation of the building or personal envelope. Emerging textile engineering technologies enabling thermoregulation via control of radiative heat transfer, evaporation, and conduction can provide much needed solutions to reduce the energy use footprint[4,5,6]. These technologies will be especially beneficial in the off-grid locations and disaster zones, and can additionally provide signature reduction capabilities for operational security.

- **Combining nanophotonics with microfluidics**

  One recent direction that we are excited about exploring is combining nanophotonics with microfluidics, e.g. for ultra-compact large-scale flow cytometry. There are many existing devices that pass blood or colloidal suspensions through microfluidic channels in order to characterize things like red blood-cell counts, nanoparticle size distributions, and other information — but they are typically combined with bulky conventional optics (microscope objectives). By combining these designs with nanophotonics optimization — integrated sensors and light focusing structures — there is the potential to not only dramatically miniaturize and scale up the technology, but also to incorporate spectral and polarization information that is lost in macroscopic optics in order to improve sensitivity and expand functionality. Currently, the nanotechnology communities in optics and fluidics seem to be largely disconnected, and so there are potentially a lot of opportunities in bringing the two areas together.

- **Comprehensive mapping of defect-solute binding energies**

  In nanostructured solids, the energetics of the system depend heavily upon details of the chemical configuration of the system. In particular, there is typically a high density of defect sites in nanostructured materials (grain boundaries, surfaces, stacking faults, etc.), and these interact chemically with the various elements in the material to dictate the structure. The interaction energies (or binding energies) between solutes and defects have a large impact on the total system energy and the equilibria that are possible in nanostructured states. Yet, these quantities are largely unknown and exist in a vast multidimensional space that cannot be exhaustively searched (because defects are complicated and diverse, and there are many possible combinations of elements). A major effort to map all possible defect-solute binding energies for all possible materials and defects would open the door to design of nanostructured materials from atoms-up.

- **Develop non-equilibrium phase diagrams**

  Most nanostructured and nanocrystalline materials are formed through non-equilibrium processes, which represent a balance between an equilibrium tendency of the system and a non-equilibrium driving force that adds entropy and activates the presence of nanostructure. These two effects may balance in a steady-state process (like deposition, milling, etc.), and typically the process is tuned semi-empirically to achieve a desired outcome with a nanostructure. It would be highly desirable to develop non-equilibrium phase diagrams that quantitatively include the axis of 'driving' entropy, so that the possible steady-states and corresponding nanostructures could be mapped, and regimes of their stability identified. In the same way that equilibrium phase diagrams have dramatically helped guide the design and development of conventional materials, such nonequilibrium diagrams could be enabling of a broad field of new nanostructured materials.

- **Plasmonics**

  Plasmonics offers a great ability to dramatically shrink the wavelength of light. This could provide tremendous opportunities. Some of these opportunities are already explored e.g. for chemical sensing. Unfortunately, most of the possible exciting applications of plasmonics are still unrealized because all plasmonic systems are extremely lossy. If one could nano-engineer a material-system that would enable lossless (or low loss) plasmonics, enormous plethora of extremely important applications could be enabled, including in the areas of: chemical and biological sensing, quantum computing, telecommunications, optical signal processing and more. There are no theoretical physical reasons why low loss plasmonics cannot exist, and a few promising ideas have been theoretically proposed yet. This is an extremely high payoff research area that should be much more encouraged (through funding and otherwise).

- **Plant Nanobionics as Sensors and Lights**

  Nanomaterials can be incorporated into plant microstructure to confer new capabilities.[7] Functional nanoparticles migrate to different plant compartments based on their size and charge.[8] These material properties can be manipulated in order to deliver devices selectively to specific regions of the plant structure. We and others have designed various microscopic devices from nanomaterials that can interface with the biological machinery of living plants,[9] from chemical sensors that report plant and soil conditions[10] to targeted gene delivery agents.[11] Of particular interest is the ability to harness the natural energy supply of plants to convert plants into deployable devices that do not require external energy sources. To that end, we develop nanobionic light-emitting plants by incorporating nanoparticles that perform the same chemiluminescent reaction as is seen in fireflies.[12] This reaction is sustained by the plant's natural production of adenosine triphosphate and coenzyme A. This nanobionic system has been demonstrated in many different plant species. Light-emitting plants are appealing as a replacement to traditional lighting because they consume, rather than produce, carbon dioxide and do not need to be connected to an electrical grid.

- **Carbon Fixing Materials as Self-Healing Materials**

  Inspired by the self-assembly and self-repair displayed in living plant systems, we seek human-synthesized analogues which can achieve these higher functions, all-the-while operating under non-biological conditions. These systems will use ambient solar energy and atmospheric carbon dioxide to grow, strengthen, and reinforce. As a proof of concept, we have realized the first carbon fixing material system through a composite of nanoceriastabilized extracted chloroplasts and graphene oxide[13]. This system produced a self-healing hydrogel of gluconolactone cross-linked amino propylmethacrylamide which continually expanded and strengthened under illumination. We are further exploring the use of robust inorganic photocatalyst to use formaldehyde obtained through the photocatalytic reduction of carbon dioxide as a monomer source for high-strength high-value polymer materials. Through trimerization of formaldehyde to trioxane, and subsequent polymerization of trioxane, the engineering thermoplastic polyoxymethylene can be obtained. This polymer has a variety of industrial and consumer uses, and its high thermal and chemical stability render it appropriate for use as a protective coating, or structural component. Further, formaldehyde as a monomeric feedstock obtained from carbon dioxide can be expanded to a broad set of polymerization chemistries to produce insulating foams, thermoset plastics, and saccharides—which shows the large potential for carbon fixing material systems.

- **hBN for Quantum Sensing and Communications**

  Employing the laws of quantum mechanics for real-world applications has emerged as one of the most intriguing and rapidly growing research fields in recent years. Quantum systems are extremely sensitive to environmental disturbance, which leads to many challenges for certain applications such as quantum computing and cryptography. The unprecedented level of sensitivity, however, could well become an advantage and be exploited in sensing. In particular, photon-correlation-based sensing platforms are very appealing, with the integration potential utilizing many existing optical characterization tools compatible with chemical and biological systems. One of the major obstacles in photon-based quantum sensing is searching for stable, bright and room-temperature single-photon emitters. Very recently, two-dimensional (2D) hexagonal boron nitride (hBN) has been explored as a new class of materials exhibiting single photon emission at room temperature. Here we propose sensing schemes that harness photon antibunching—a quantum correlation effect of photons[14]. Quantum emitters in hBN could replace conventional fluorescence dyes as biomarkers and sensing arrays. Such quantum sensing schemes are expected to not only increase sensitivity and accuracy significantly, but also provide new insights about underlying mechanisms of various bio/chemical systems.

- **2D Polymerization for High Performance, Light-Weight Materials**

  Forcing fragments to concatenate in two-dimensional (2D), rather than in three-dimensional (3D) structures is the key to achieve 2D organic/inorganic materials. Typically, synthesis of 2D materials requires an additional 2D constraint such as a flat metal surface or restrictive reactions in an immobilized 2D lattice. However, such approaches suffer from minuscule synthetic and transfer inefficiencies. An alternative strategy is to introduce microscopic reversibility, at the cost of bond stability, to achieve 2D crystals after extensive error corrections. As a consequence, resulting materials typically have low chemical stabilities, which further lead to problematic processabilities. We recently demonstrated that, by combining several key modifications, it is possible to synthesize 2D organic molecules via irreversible 2D polymerization without any additional 2D input. The resulting 2D polymer is chemically stable, highly processable, and easy to form highly oriented, ultra-strong (2.52 GPa) thin films. We also develop new methods for characterizing the film surface nature and molecular alignment. A manuscript on this work is currently in preparation.

[1] Murphy, Stacy L., "Request for Information: National Nanotechnology Initiative Strategic Planning," Office of Science and Technology Policy, Notice, Document number 2020-22556, Pages 64535-64536, Document citation 85 FR 64535. Filed 2020-10-09; Published 2020-10-13.

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[13] Kwak SY, Giraldo JP, Lew TTS, et al. Polymethacrylamide and Carbon Composites that Grow, Strengthen, and Self-Repair using Ambient Carbon Dioxide Fixation. *Adv Mater.* 2018;30(46):1-10. doi:10.1002/adma.201804037

[14] Kozawa D, Rajan AG, Li SX, et al. Observation and Spectral Assignment of a Family of Hexagonal Boron Nitride Lattice Defects. 2019. http://arxiv.org/abs/1909.11738.

Comments from Jason C. White

Mechanisms

- What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?

  My understanding is that funding to the various agencies was initially robust but has been flat over the last several years. That is a mistake; the US is risking falling behind other countries/regions such as China, India and Europe

- How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

  Expanded funding out of Congress; individual agencies should have continued flexibility on how to target the funding but new programs such as "moonshot" requests for proposals would be ideal

- What key elements and intersections are necessary to form an agile framework that will enable response to new developments along the nanotechnology continuum, from discovery and design to development and deployment?
- How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

  Greater embrace of social media; this is how to reach stakeholders in 2021 and beyond, particular younger generations

- How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

- What are exemplary models (domestic or international) for accessing NNI resources, including user facilities and laboratories?

  Programs to encourage and expand international collaborations would be good. Most of us have international collaborators but the lion share of funding for those activities come from the international partners

Communication

The NNCO serves as the public-facing entity of the NNI in addition to and in support of NNI agency communication efforts. NNCO maintains *Nano.gov* and shares information through numerous communication means. However, the NNI community is complex and multifaceted, and diverse stakeholder groups consume information in different ways.

- How can the NNCO facilitate communication and collaboration throughout the nanotechnology R&D ecosystem to enhance research and ultimately commercialization? How can the NNI/NNCO best communicate opportunities, resources, and advancements to the community? How can the NNI/NNCO best engage with the stakeholder community to understand their advancements and needs?

  I think NNI/NNCO does a pretty good job here. Perhaps an annual NNI conference that focuses on work across multiple disciplines. Could be a virtual conference with dedicated sessions for young faculty

- Beyond the media platforms used by NNCO, what additional means should be considered to better reach the public and various stakeholder groups?
- What are effective strategies for improving communication of desired nanotechnology workforce skills and capabilities between industry and academia?
- How can the NNI participating agencies or NNCO best raise awareness among teachers regarding the educational resources that have been developed over the past 20 years and help get these resources into their classrooms?

  Funding dedicated staff that can lead this effort, including interfacing with researchers (academic, government, industry) and educators

Topics

- What are the high priority open scientific questions in nanoscience and nanotechnology?

  Global food insecurity is going to be one of the most significant challenges we as a species will face in the next 30 years. Climate change will make this worse. Nanotechnology can be applied to alleviate these impacts but targeted funding is needed.

- What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

  Nano-enabled agriculture

- What nanotechnology-enabled “moonshots” should be considered?

  Nanotechnology incorporated with synthetic biology and alternative proteins

- How does nanotechnology support other foundational fields/initiatives? What future technical topics are likely to emerge from advancements in nanotechnology?
- What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)? What other tools are necessary to conduct nanotechnology R&D?
- What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

    Safe and sustainable application of nanotechnology in the food and agriculture industry. Effective risk communication will be key

- As concepts surrounding responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?

    Put science first; a robust and flexible regulatory framework is needed as well

Regarding the National Nanotechnology Initiative (NNI) Strategic Plan:

One area of research that is in need of more direct attention in the NNI Strategic Plan is in the fields of Earth and Environmental Nanoscience. The opportunities and needs for an initiative to promote nanoscience in Earth and Environmental Science was clearly articulated in the 2019 Science article: (and attached)

Hochella, M.F., Mogk, D.W., Ranville, J., Allen, I.C., Luther, G.W., Marr, L.C., McGrail, B.P., Murayama, M., Qafoku, N.P., Rosso, K.M. and Sahai, N., 2019. Natural, incidental, and engineered nanomaterials and their impacts on the Earth system. *Science*, *363*(6434).

In the Strategic Plan, I would hope to address topics presented in this article such as 1) the impact of nanoparticles on natural global biogeochemical cycling; 2) role of nanoparticles in environmental issues ranging from air quality to water quality in civic water supply systems to acid mine drainage; 3) direct impacts of nanoparticles on human health; 4) role of nanoparticles in proposed plans for geoengineering to mitigate climate change; and 5) role of nanoparticles in the evolution of life, and the overall Earth system (fundamental research largely ignores the role of nanoparticles in most mesoscopic processes).

In the strategic plan, we need special attention to the following related issues in the Earth and Environmental. Sciences:

1. Supporting infrastructure to do this research; the EES community is in desperate need of appropriate sampling and analytical instrumentation to do nanoscience research. We simply do not have access to instrumentation including TEMs, FIBs, dynamic SIMS, and even more conventional analytical facilities such as XRDs, SEMs (and field emission), Raman spectroscopy, and many more are simply out of date and need of upgrading.
2. Professional development programs for current faculty and researchers in related fields (mineralogy, geochemistry) who could refocus their research programs towards nano-inspired research.
3. Curriculum development in nanoscience for the Earth and Environmental Sciences—we need to train the best and the brightest students to prepare for careers in this most important area of research.

Thank you for the opportunity to provide input to the NNI Strategic Plan.

David Mogk
Professor of Geology
Dept. of Earth Sciences
Montana State University, and
Co-PI NSF/NNCI MONT project

Jack Rust | Merrimack Account Manager

Huntsman Advanced Materials | 57 Daniel Webster Highway | Merrimack, NH 03054 | US

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What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

Nanotechnology is poised to make significant contributions in addressing challenges posed by greenhouse gas emissions, unsustainable housing, rare earth metals scarcity, and the need for lighter, more efficient batteries. All of this may soon be enabled by a family of carbon nanotube (CNT) materials branded MIRALON®. Nanocomp Technologies, Inc. of Merrimack, NH is the sole producer of MIRALON® materials. This bulk CNT material has been available for over a decade. Made from methane, a powerful greenhouse gas, MIRALON® materials enable carbon sequestration in products ranging from carbon nanotube rope, electrical wires, and cables to bulletproof armor, pressure vessels, and spacecraft structures. To date, this has only been done on a small scale yielding small amounts of material at great expense. Now Nanocomp is scaling up proven chemical vapor deposition (CVD) technology to build bigger, more efficient reactors that may improve production volume by orders of magnitude and slash manufacturing costs tenfold within three years. Success will open the door to a wide range of applications beyond today's small customer base of early adopters in the aerospace and defense industry.

As part of this scale up, Nanocomp is working on ways to convert flare gas from oil fields into clean, low cost hydrogen fuel and high value carbon. At present, over five Quads of potentially valuable natural gas (equivalent to 5% of annual United States energy consumption) is flared off globally each year; all because at today's low natural gas prices, storage and transport to market is simply not cost effective. However, the CO2 emissions from flaring and methane leaks in the field and pipeline infrastructure are a tremendous contributor to climate change. The production of MIRALON® materials uses processed natural gas as feedstock and could help address this challenge. Nanocomp is currently working with ARPA-E to scale the production process to create clean hydrogen and structural MIRALON® materials from processed natural gas on a large scale. The focus of this project is to design field transportable systems to convert flare gas into clean, valuable hydrogen and strong, inexpensive multifunctional carbon for use in vehicles, buildings, and infrastructure.

According to Mark Goulthorpe, Associate Professor at the Massachusetts Institute of Technology Department of Architecture, approximately one million people per week worldwide will require housing between now and 2050. The number of buildings on the planet is expected to double by midcentury. Extraction, processing, refinement, and transportation of wood, metal, and minerals used in present day construction involves massive amounts of energy, water, and pollution that strain limited resources and significantly impact the environment. Goulthorpe envisions a world in which today's building materials are replaced by energy efficient, strong, lightweight carbon fiber composites and thermoplastic fiber tape enabled by CAD/CAM design-to-build protocols using automated construction. The high strength, lightweight, thermal, and electrical performance of MIRALON® materials make it well suited; not just for structures, but also for wiring, heating, insulation, and acoustic applications that serve as the basis for Goulthorpe's CarbonHouse initiative.

"CarbonHouse offers an alternate base-material architecture, drawing on the remarkable rise of polymeric composites as a sophisticated new manufacturing paradigm; but that is extended to emerging forms of carbon, especially those that support hydrogen production. A carbon ontology would establish the organic legacy as the primary material as well as energy resource, where the allotropic polyfunctionality of carbon would offer a sophisticated new minimalism: more from less. CarbonHouse looks to witnessing this in nascent form, but mindful of building performance needs and the reality of very basic fabrication protocols in most global regions."

https://www.ornl.gov/event/carbonhouse-towards-carbon-ontology

Rare earth metal supply chains pose another challenge that may soon be addressed by nanotechnology in the form of MIRALON® materials.

"Advanced electronics and clean energy technologies are becoming critical, irreplaceable components of modern life. As the world pushes toward a carbon-free future and new technologies increasingly rely on rare earth and specialty metals (e.g., Nd, Co, Li), concern is rising around the economic, environmental, and socio-geopolitical stability of the long-term supply of these materials. With demand approaching and exceeding our current supply rates, and over 90% of global production of these raw materials coming from undesirable locations, the world has labeled rare earth and specialty metals as critical with respect to their supply risk. As a result, there has been a movement toward better material management practices to create a secure, secondary source of these metals here in the United States to protect our future in clean energy advancements. Many of the electronic waste (e-waste) streams could serve as viable secondary sources of these metals, yet less than 5% of these valuable materials are recycled today!"

https://www.nthcycle.com/

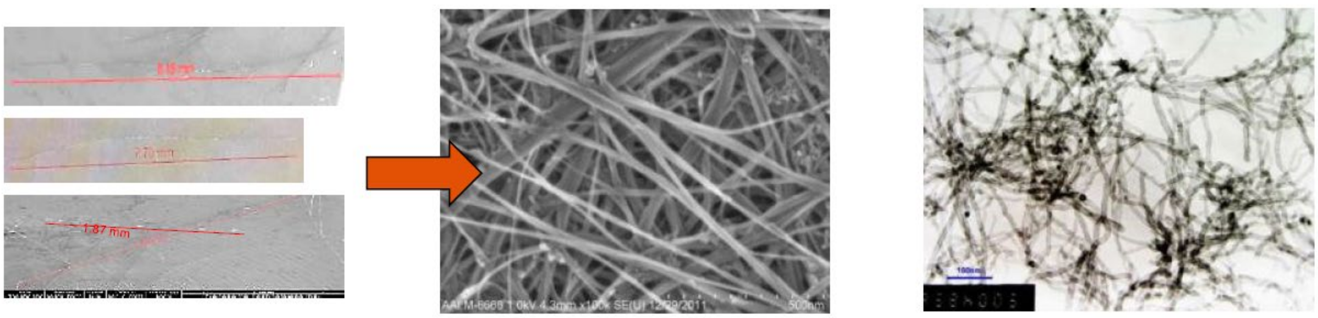
Nth Cycle LLC intends to redefine these supply chains through low-cost electronics recycling using filters comprised of MIRALON® meshed carbon nanotubes. The electrical conductivity and high surface area per unit mass of MIRALON® materials enable Nth Cycle to miniaturize its electrochemical deposition process by many orders of magnitude. In this process, the mesh filter is electrically charged. A solution containing material to be recycled passes over it and rare earth metals are precipitated as solid materials on the mesh. The process separates bulk elements from rare earth elements and enables electronics manufacturers to reclaim metals from their manufacturing floor as well as from discarded products returned by customers.

From cell phones to laptops to electric cars, rare earth metals are key to a future quality of life enabled by renewable energy and lightweight energy storage. As prices of cobalt and other rare earth metals continue to rise owing to international tensions or the environmental degradation that comes with mining them, MIRALON® materials and the recycling they enable will be key to rare earth supply chain sustainability.

Performance limitations in state-of-the-art batteries pose the final and perhaps most immediate challenge that can be addressed by MIRALON® material nanotechnology. It is a challenge which plays to CNT's multifunctional strengths; lightweight, fatigue resistance, electrical and thermal conductivity. But

MIRALON® materials offer something more. While most CNTs have impressive properties at the nanoscale, their adoption into commercial applications has been hampered by the lack of an interconnection between individual nanotubes. This fundamental limitation is addressed by the MIRALON® family of products which have a unique extended network of branched bundles of indefinite lengths.

The length and unique interconnection between bundles that make up MIRALON® products translate into enhanced properties. This structure drives increased strength, conductivity, and toughness at low density, with significant performance benefits vs 'standard' networks of carbon nanotubes. This can be seen in the following electron microscope images comparing various carbon formats.



Miralon bundles 1-10mm long

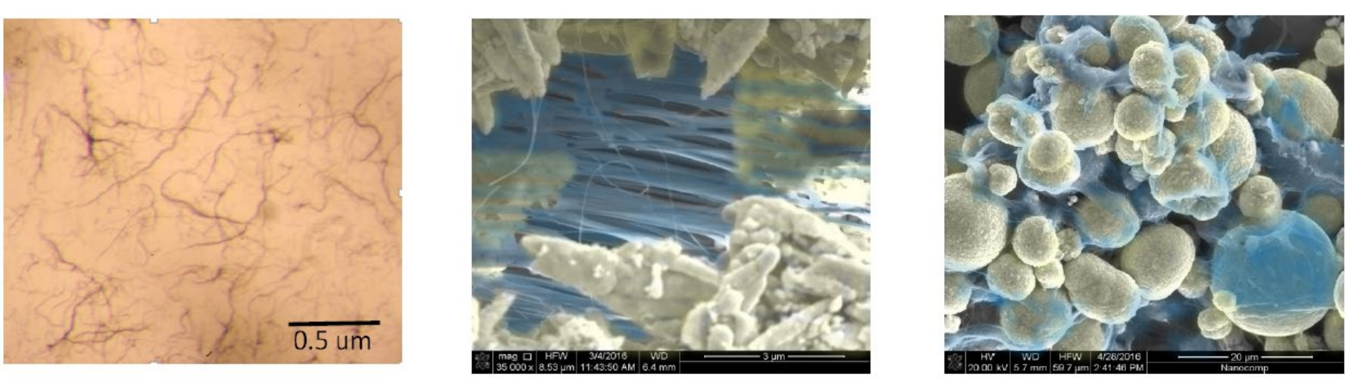
MIRALON® structure: interconnected bundles

VS

Conventional nanotubes: powder form

In batteries, MIRALON® pulp is combined with a binder (e.g., PVDF) and solvent to make a slurry. The slurry is dispersed with active material and spread onto a current collector to make an anode or cathode using standard methods.

When used in the cathode, the increased stability of a MIRALON® pulp-based solution over incumbent materials leads to increased cathode life. MIRALON® dispersions make hierarchical structures unlike anything seen with powder CNT. It forms long-range interconnections of branched bundles in the active



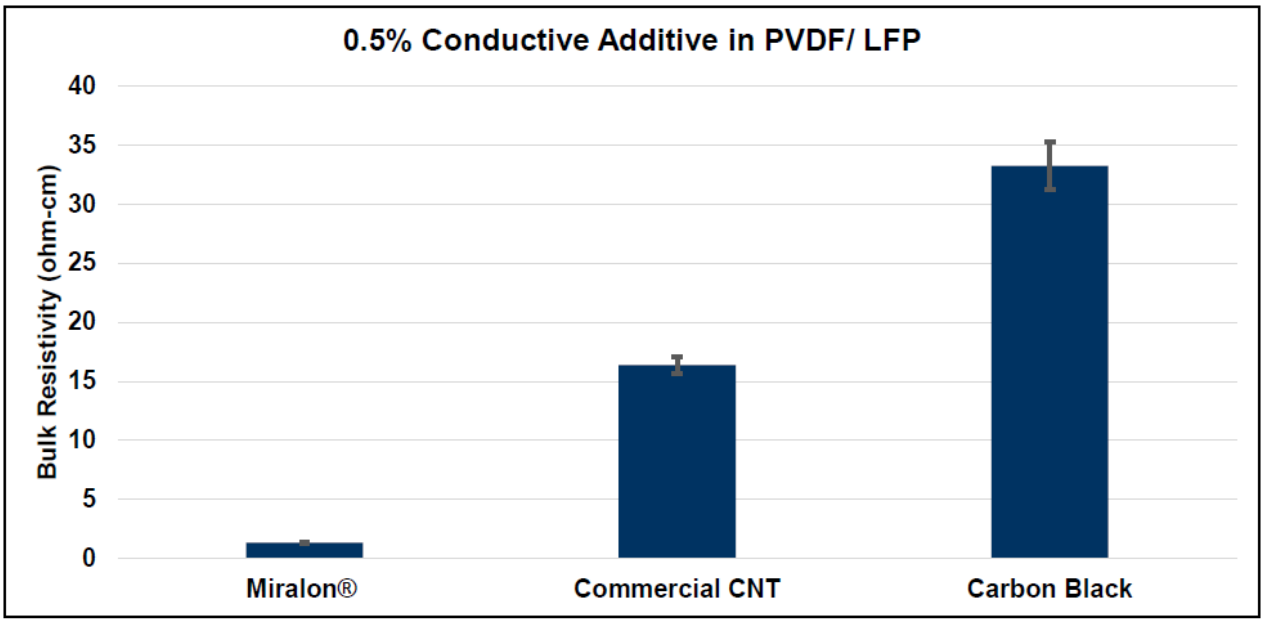
Miralon Pulp Disperson

0.5% Miralon Pulp
3% PVDF in LFP

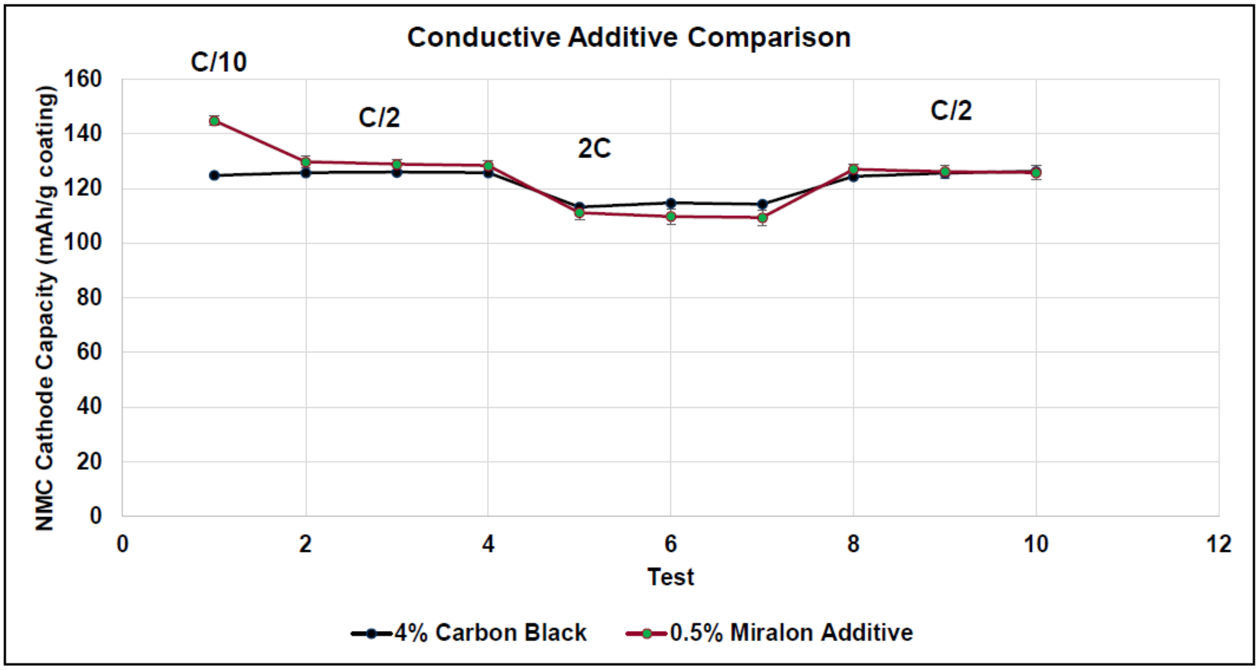
0.5% Miralon Pulp
3% PVDF in NMC

material, wraps around the Nickel-Manganese-Cobalt (NMC) particles & holds them together while making electrical connection as shown below.

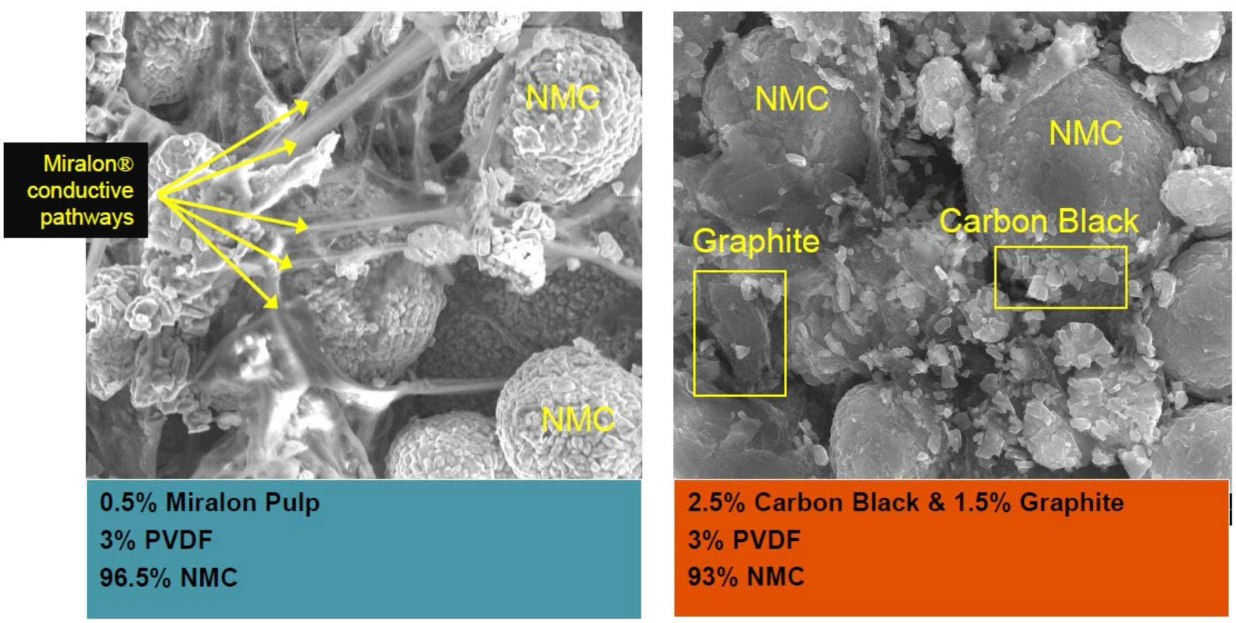
MIRALON® pulp increases the active component in the cathode. So, less additive is required for the same performance. Electrical conductivity of cathode composites containing MIRALON® pulp is far better than for cathodes containing carbon black, or commercially available high-quality powder CNTs. Therefore, less MIRALON® conductive additive is needed for a given performance. Bulk resistivity of MIRALON® pulp versus typical CNT and carbon black is compared below.



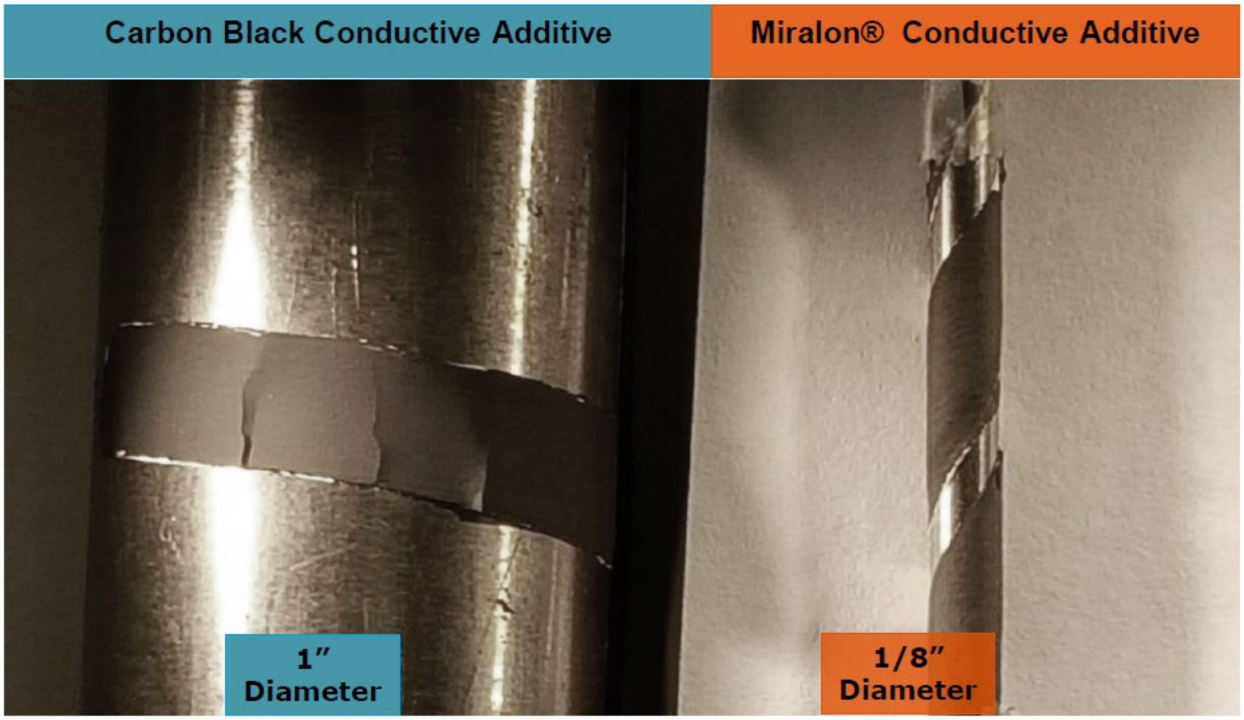
In tests, MIRALON® pulp has been demonstrated to deliver identical performance to carbon black at only one eighth the loading.



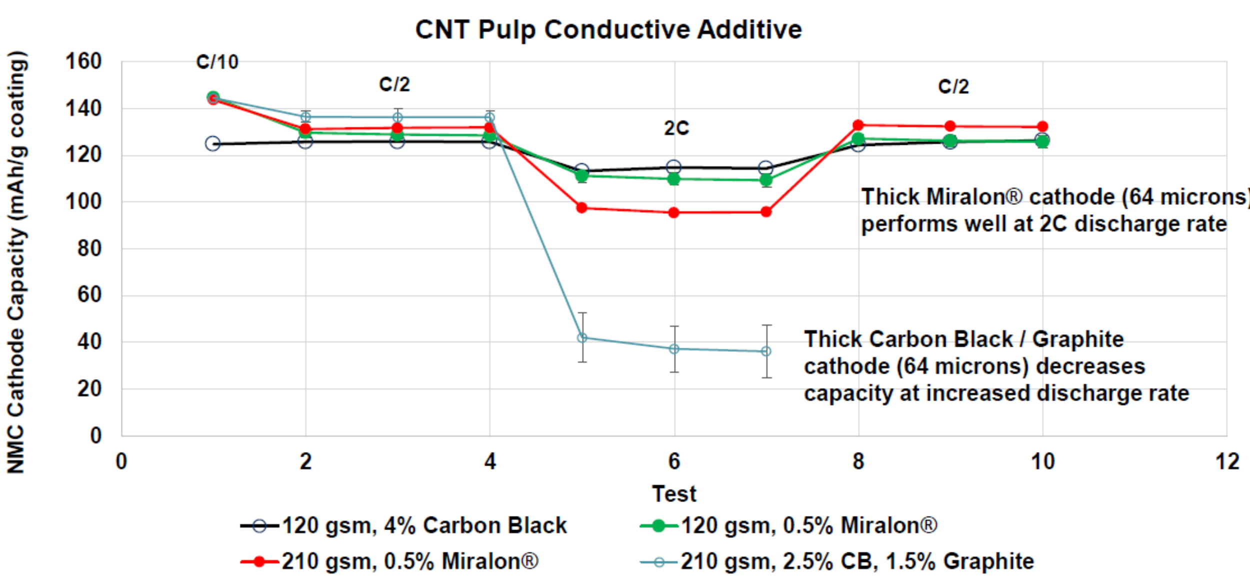
MIRALON® pulp can enable thicker cathode layers with conductive pathways that increase cohesion within the coating. Lower concentration of conductive additive enables more active material (96.5% NMC vs. 93%) as shown below.



Solutions made with MIRALON® materials exhibit strength and flexibility, as shown below right, to enable longer life and thicker cathode layers. Carbon Black, below left, causes brittleness and cracking at high loading. MIRALON® pulp adds conductivity without degrading flexibility, allowing for thicker active media in a smaller volume.



A thicker cathode means fewer layers, less separator / current collector, mass, and volume. Results depicted below show no significant drop in performance with double cathode thickness (120 gsm cathode = 37 microns thick vs. 210 gsm cathode = 64 microns thick).



CNTs have much higher surface area than traditional conductive additives, but are also much more thermally conductive. The inherent thermal conductivity of the networked CNT structure of MIRALON® materials means significantly reduced risk of overheating. Tests with MIRALON® materials have shown as much as a 40% drop in exothermic energy release.

MIRALON® pulp enables increased capacity when incorporated into anodes. The strong, web-like, flexible networked structure connects silicon particles to the current collector, increasing the number of working silicon particles. Aqueous CMC MIRALON® dispersions have been shown to enable higher Si nanoparticle loading for increased anode capacity. Silicon-coated MIRALON® pulp may enable as much as 90% Silicon anodes, resulting in 10X improved capacity over graphite, and enabling higher charge rates.

In short, using MIRALON® materials means lighter, safer, more powerful, longer lasting batteries that can be recharged more quickly and need fewer resources to produce.

Given continued successful scale up and development, MIRALON® nanotechnology is poised to meet the challenges of a sustainable, more energy efficient, but prosperous future for all human civilization.

November 9, 2020

Response of The MITRE Corporation to the NSTC Request for Information to Inform Development of the 2021 National Nanotechnology Initiative (NNI) Strategic Plan

For additional information about this response, please contact:
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Introduction

The MITRE Corporation is a not-for-profit company that works across government to tackle difficult problems that challenge the safety, stability, security, and well-being of our nation through its operation of multiple federally funded research and development centers (FFRDCs), as well as public-private partnerships. Working across federal, state, and local governments, as well as industry and academia, gives MITRE a unique vantage point. MITRE works in the public interest to discover new possibilities, create unexpected opportunities, and lead by pioneering together for public good to bring innovative ideas into existence in areas such as artificial intelligence, intuitive data science, quantum information science, health informatics, policy and economic expertise, trustworthy autonomy, cyber threat sharing, and cyber resilience.

MITRE has been performing broadly based research and development (R&D) in nanotechnology since 1992, with a focus on systems engineering that starts at the molecular scale. Our inter- and multi-disciplinary work has included the development of systems such as nanoelectronic circuits for memory, processing, and sensor systems, nano-enabled energy and power storage devices, and the modeling and simulation of nano-scale phenonmena. Our researchers have access to state-of-the-art facilities in on our main campuses in McLean, Virginia and Bedford, Massachusetts.

Since its inception over 20 years ago, the National Nanotechnology Initiative (NNI) has been successful in bringing nanotechnology to the forefront of R&D efforts across numerous U.S. Government departments and independent agencies. It is responsible for the discovery and development of numerous scientific and engineering phenomena and has led to the U.S.' preeminent position in the study of the nanoscale. However, as the NNI enters its third decade, MITRE believes a reassessment and refocusing towards a more industry- and application-centric approach will be required for the nation to realize the full promise of nanotechnology. This viewpoint drove our responses to the specific questions posed in the RFI, in the following section.

Please let us know if you have any questions on this submission, or if we can help you succeed in any other way.

MITRE's responses to questions posed in the RFI

Mechanisms: How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

The commercialization and proliferation of nanoelectronic devices could be accelerated via public-private partnerships. NNI investments and other basic research initiatives over the last twenty years have demonstrated conclusively that pure academic research is necessary but insufficient to produce a transformative change within the microelectronics industry.

For over twenty years, industry has recognized the pending end of its "Moore's law," yet also incrementally postponed this end to being perpetually five to ten years out. At the formation of the NNI in the late 90's, that end date was forecast as a "red brick wall" residing in the mid-2000's with no known solutions for semiconductors to break through that wall. This motivated investment into emerging research devices that radically departed from the mainstream approach to semiconductors, as documented in the Interagency Working Group on Nanoscience reports in 1998-99. Notably, however, the research approaches and topical areas identified in those documents at that time all proved speculative and none has since matured to widespread adoption.

Commercial economic growth since that time has placed broad, transformative electronic capabilities even further out of reach of pure Government investment in research. In 2018, US semiconductor firms spent $38.7 billion on R&D. This is in stark contrast to the aggregate nanoscience and nanotechnology Federal investment that year of approximately $1.8 billion. The 2018 industrial investment was further supplemented by $32.7 billion in capital.[1]

Where Government has a unique and fruitful investment angle is in infrastructure, workforce development, and policy that would enable public-private partnerships to be formed and to succeed. Three significant examples of this approach are embodied in the SUNY/Albany NanoTech/Marcy Nanocenter complex (in upstate New York), IMEC (the European Union's interuniversity microelectronics center), and the EUV LLC (which enabled the development of 2020-era advanced lithography equipment via partnership between industry and the US DOE). These institutions have greatly accelerated the development of commmercializable nanotechnologies for applications in areas such as AI and quantum computing, whose current mindshare was not anticipated at the initiation of the NNI.

Topics: What are the high priority open scientific questions in nanoscience and nanotechnology? What nanotechnology enabled moonshots should be considered?

Nanomanufacturing at scale is a dominant and open question in nanoscience and nanotechnology. This includes the ability to reliably and repeatedly create nanostructures over an unconstrained 2D area and across a variety of surfaces. Limitations of nanomanufacturing at scale impact both the types of applications where nanoscience and nanotechnology can be enabled in the lab as well as commercialization opportunities for these applications. Nanomanufacturing at scale is not a new challenge for the nanoscience and nanotechnology community but it remains an open one. The solution may lie in larger scale partnerships between academia, national laboratories and industry.

There are a variety of techniques in the bottom up and top down realms that may provide paths to at-scale nanomanufacturing. Within bottom up fabrication, innovative new techniques such as DNA self-assembly may provide a path towards nanomanufacturing at scale. Nanostructures are often fabricated in sub-millimeter size areas defined by the field-of-view of high resolution instruments like electron microscopes. Over the last ten years, researchers have begun to harness the self-assembly properties of DNA to produce complex, user-defined nanoscale structures as one way to overcome the small area fabrication challenge. This field of study is referred to as DNA origami since it allows construction of complex patterns. Independent of technique, once at-scale nanomanufacturing is available it will facilitate applications within the fields of medicine, chemical and temperature sensors, and electromagnetic propagation control.

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[1] *The 2019 SIA Factbook: Your Top Source for Semiconductor Industry Data*. 2019. Semiconductor Industry Association, https://www.semiconductors.org/the-2019-sia-factbook-your-top-source-for-semiconductor-industry-data/

Topics: What are the gaps in the fabrication, characterization and modeling and simulation tools available through the NNI user facilities?

To achieve the efficient use of NNI funds and the continued development of nanotechnology, there is a need to review the requirements for, and focus of, NNI user facilities. While they were undoubtedly a key driver to the NNI's early success, since these facilities were first established, fabrication, characterization and modeling and simulation tools for nanoscience have become much more common across the academic and industrial landscape. Many of these non-NNI academic capabilities also serve as user-facilities where researchers may pay for access to tools and instrumentation. The NNI should evaluate what capabilities are truly necessary or difficult to access and re-focus its facilities toward those requirements, thereby potentially opening up resources for newer priorities.

America is in the middle of a trust quandary when it comes to science. While surveys indicate academic scientists are trusted, the last administration has sown seeds of doubt about government sponsored science, from climate change to pandemics. This systemic trust problem needs to be better understood especially as it applies to future initiatives like the NNI. We may need social science more than ever. We need a data driven initiative to build public trust in public science.

We must continue to find new and better ways to outreach and engage younger generations as well as more mature publics if we anticipate continuing a policy of government support for technologies that have ROI profiles that exceed the interests of standard investors, capital investment companies, and even government terms in office. Nanoscience is a size-based platform technology and efforts to go smaller have been challenged by the quantum world. Nanoscience will have a role in the future just as chemistry and engineering will. I expect the NNI will downsize in a way and converge with other initiatives, but it retains value as an investment by government sponsored science.

The NNUN begat the NNIN and the NNIN begat the NNCI all of which opened up facilities to young researchers and entrepreneurs. We are seeing colleges and universities offering a range of courses in nanoscience and some degrees as well. We are also noticing some significant developments in nanomedicine and the use of nanoscience in precision agriculture, geoengineering, convergent biotechnology, as well as the traditional fields of coatings, lubrication, fire retardants, and so on. We will need to make certain our next generation of young scientists have access to the best technology regardless where they happen to reside and learn. What the next generation of the NNCI might look like is hard to foretell but there will probably be a need for some face to face options as well as the next generation of online facilities.

Thank you for reading this. I plan to serve the science community by continuing my efforts to find new data driven ways to make the process of scientific discovery and engineering as human friendly as possible.

David M. Berube, Dept. of Communication.
Prof. of Science and Technology Communication, NCSU.
Dir. PCOST (Public Communication of Science and Technology Project) 2008-present.
Member Faculty Assembly to UNC System, 2020-2022.
Faculty Fellow, GES (Genetic Engineering in Society) NCSU. 2014-present
Associated Core Faculty, Climate Change and Society Program. NCSU 2015-present.
Dir., Assessment & SEIN at RTNN (Research Triangle Nanotechnology Network) - 2015-2025.
Member-At-Large - General Interest of Science & Engineering - AAAS 2017-2021.
Member, Board of Scientific Counselors, National Toxicology Program. 2018 - 2022.

5141 Hunt Library, Centennial Campus.
Mailing address: Campus Box 7565.
Berube/PCOST.
1070 Partners Way.
Suite 5100, Hunt Library.
North Carolina State Univ.
Raleigh, NC 27606-7565.

RFI Response: NNI Strategic Planning

Submitted by Hal Stillman, Director Technology Development and Transfer, International Copper Association, Ltd.

This response focuses on the high-priority moonshot topic of developing enhanced electrical conductors through the research, development, and manufacturing scale-up of electronically hybridized metal/nanocarbon composite materials and structures.

- *What nanotechnology-enabled "moonshots" should be considered?*
- *What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?*

Research into copper-graphene conductors has demonstrated encouraging increases in electrical conductivity at room and elevated temperatures. Recent laboratory samples have shown up to 18% improvement in IACS (International Annealed Copper Standard) conductivity. Improvements in electrical conductivity result in lower electrical losses and ohmic heating at all size scales, ranging from large electrical machines to microelectronic devices. These improvements are an enabling technology for high-performance products and would be especially desirable in a low carbon electrified economy. Some example applications are: electric vehicle propulsion motors that are lighter, and permit increased range; improved energy efficiency and size/weight/cost reduction in renewable power generation; and denser microelectronic systems with reduced thermal management requirements. However, all research lacks a deep scientific understanding of how a material consisting of nano-carbon and a metal such as copper can be synthesized to form an electronically hybridized composite with increased conductivity. There is currently little understanding of how metal-to-graphene interfaces behave – how graphene induces structural changes in copper and how the high electron density of copper combines with the higher charge mobility in graphene to create a new class of conductive materials. Laboratory samples exist but methods to scale-up production to millions of tons of wire do not exist.

Our future world will run primarily on electricity, yet there have not been any significant advances in electrically conductive materials for over 100 years. Future research directions in this area should focus on underpinning the science of conductivity improvement in metal-graphene conductors and utilizing this knowledge to realize scalable manufacturing of ultra-conductive metals. It is worth mobilizing resources to achieve the moonshot of high-volume production of conductors with significantly enhanced conductivity.

An overview paper "**Advanced Electrical Conductors: An Overview and Prospects of Metal Nanocomposite and Nanocarbon Based Conductors"** describing technical approaches that have been investigated can be found at https://arxiv.org/abs/2011.03090 Importantly, this paper points out that the U.S. is lagging China advanced conductor research as measured by an analysis of the number of the patents since 2012. There has been an increase in the number of patents on nano-carbon metal composites mentioning electrical conductivity as a characteristic: 30 in 2012, 35 in 2013, 42 in 2014, 71 in 2015, 83 in 2016, 94 in 2017, 134 in 2018, 118 in 2019. It is noteworthy that most of these patents are from China.

On March 3, 2016 the U.S. Department of Energy, Advanced Manufacturing Office released a Funding Opportunity Announcement (FOA) Number: DE-FOA-0001467 Next Generation Electric Machines:

Enabling Technologies describes the opportunity to improve the performance of electric motors through the application of advanced conductors. Table 1 of this FOA describes the potential energy savings opportunity from deployment of enhanced conductor technologies in U.S. motor systems as nearly 1% of the total U.S. electricity use.

Table 1: ***Potential energy savings opportunity from deployment of three identified enabling technologies in U.S. industrial motor systems.***[5]

Topic Areas	Technical Target	Performance Metrics	Potential Energy Savings in GWhr/Yr & % of Total US electricity		
			Industrial	Non-Industrial	Total
High performance conductors	>33% reduction in stator I^2R losses	Electrical conductivity at 150°C > 59.52 MS/m	2,861 & 0.09	22,772 & 0.87	25,633 & 0.96

On November 9, 2020, the U.S. Department of Energy Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Program released a SBIR FOA including an extensive section (starting on page 86) on enhanced conductors. This can be viewed as confirming the significance of innovations in advanced electrical and thermal conductors. The SBIR FOA is clearly aimed at engaging industry in creating innovative conductive materials and applications. Industry engagement will be necessary to develop and commercialize advanced conductor technology.

The reader should keep in mind that scientific research into enhanced conductors is necessary and should focus on understanding the science of conductivity improvement in metal-graphene conductors and utilizing this knowledge to realize scalable manufacturing of ultra-conductive metals. This has the potential to improve energy efficiency, create a new manufacturing industry in the U.S., and enable innovation in a broad range of applications. It is for these reasons that the topic of electronically hybridized metal/nanocarbon composite materials and structures should be promoted by National Nanotechnology Initiative.

RFI Response: NNI Strategic Planning

National Nanotechnology Coordination Office (NNCO)
Doc Citation: 85 FR 64535

Submitted: November 9, 2020
NNIStrategicPlanning@nnco.nano.gov

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RFI Response Summary:
This response focuses specifically on suggested actions, models and mechanisms to support and accelerate science and technology commercialization. TechConnect is providing only a high-level overview of a proposed organizational structure and function in response to this RFI. If there is interest from the NSET Subcommittee or from the NNI, TechConnect is more than willing to provide a more detailed proposal.

In summary, TechConnect proposes the establishment of the National Science & Technology Accelerator; a new private-sector managed membership organization to support expanded commercialization of U.S. funded research, intellectual property, SBIR/STTR awardees and startups. There currently exists the opportunity and mechanism to launch an organization that blends both private-sector industry and investment commercialization programs (as currently delivered by TechConnect), with a new multi-agency accessible Other Transaction Authority (OTA) funding vehicle aligned with the NNI's broad range of technology focus domains.

Variations of the model described above exist within the U.S., however they have limitations in their structure as they are typically focused on delivering on specific technology topics (e.g., medical, energy, sensors, etc.) for specific agency sponsors (i.e. components of the DOD). This proposed OTA contracting vehicle would allow for multi-agency and multi-domain prototyping in order to support the significant range of domains and industry sectors addressed by the NNI.

* **OTA Background:** Other Transaction Authority (OTA) are authorized under Section 2371b to title 10 of the US Code. OTs are legally binding instruments used to engage industry and academia for a broad range of research and prototype projects and include the option to extend to production. OTs are typically defined by what they are not: they are not standard procurement contracts, grants, or cooperative agreements. As such, they are generally not subject to the federal laws and regulations that apply to government procurement contracts (e.g., FAR/DFARS). OTs have been used by the government to access and fund non-traditional private-sector innovations for rapid prototyping since the late 1950s. There has been a recent and significant increase in OTA use by the government in order to access and keep up with the rapid pace of private-sector innovation. Funding levels passing through OTAs are now surpassing total SBIR/STTR funding, with individual prototype funding levels ranging from tens-of-thousands, up to hundreds of millions (e.g., new space technologies, or the recent Warp Speed vaccine development programs).

Combining both private-sector commercialization opportunities with a multi-agency rapid prototyping OTA funding vehicle, allows for NNI related innovations to access multiple and blended routes for commercialization through this single entity. This proposed model allows for all participating NNI agencies/offices use of this OTA vehicle to support rapid prototype funding for their respective interest areas. The proposed new entity would work in partnership with TechConnect's existing industry scouting and venture investment community to provide dual-route commercialization opportunities for member organizations and technologies engaging in this process. These combined funding and commercialization opportunities provide the foundation for this new National Science & Technology Accelerator and its membership structure, attracting members from across the entire Innovation Ecosystem including; universities, national/federal labs, technology transfer/commercialization offices, research centers, incubators, startups, investors and multi-national corporations. The NNI User Facilities would additionally be integrated into the membership programs, providing a direct promotional campaign to the entire innovation ecosystem related to the user facility opportunities and access.

Another unique benefit of the proposed model is that it would deliver the opportunity for improved and expanded inter-agency collaborations for prototyping and commercialization. In addition to supporting individual NNI agency needs, by working directly in support of the full portfolio of NNI agency technology needs, the proposed structure would enable multi-agency teams within NNI to identify and pursue jointly aligned opportunities and position its OTA funding requests alongside a broader cross-section of industry developments. The supporting OTA funding vehicle becomes an active inter-agency collaboration tool in addition to being an active commercialization tool in support of the NNI's mission.

The proposed National Science & Technology Accelerator would be financially self-sustaining through both membership fees and a portion of standard management fees associated with OTA transaction management. Depending upon the final business structure, TechConnect offers to provide its resources in support of this new initiative, including TechConnect's events, staff, technology challenges, technology sprints, technology match-making platform, industry and investment client engagement and TechConnect's existing innovation ecosystem and database.

About TechConnect:
TechConnect is a technology acceleration and prospecting organization, including technology Challenges, Sprints and match-making events for hundreds of multi-national clients and most all U.S. universities, labs and federal agency partners. TechConnect annually vets and connects thousands of innovations with multi-sector corporate and agency clients through its TechConnect Ventures prospecting services and its match-making events, including annually hosting both the spring and fall SBIR/STTR Innovation Summits. In 2020 TechConnect was awarded a 5-year NASA Open Innovation Services (NOIS2) contract, and is currently producing tech-scouting programs for NASA, TSA and DOD. Our global Innovation Ecosystem includes nearly 500,000 members from over 400 technical disciplines across 80 countries.

Answers to Selected RFI Questions (Commercialization focused):

Mechanisms (commercialization focused response)

- Q: How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

  A: The NNI is uniquely positioned in the U.S. government to support a new multi-sector commercialization initiative in support of the NNI's mandated broad technology portfolio and its engagement of over 20 federal agencies. TechConnect proposes to create a new national technology-commercialization membership organization based on TechConnect's existing innovation ecosystem and industry/investment commercialization programs. TechConnect additionally suggests the creation and integration of a multi-agency, multi-sector rapid prototype funding vehicle (Other Transaction Authority OTA) to be used by all 20 of the NNI participating agencies for rapid prototyping of technologies aligned with their respective domains. Through this model, the NNI would be supporting a truly unique national commercialization acceleration model that blends both private-sector industry based commercialization with federal funded prototype development.

- Q: What key elements and intersections are necessary to form an agile framework that will enable response to new developments along the nanotechnology continuum, from discovery and design to development and <u>deployment</u>?

  A: To support deployment/commercialization across the large range of technology domains represented under the NNI portfolio, a new multi-sector innovation ecosystem model must be put into place. In order to attract the innovation community into such an ecosystem, there must be "active" commercialization, match-making and funding opportunities available to the innovators for them to participate. As such, TechConnect proposes to combine its existing innovation-industry matchmaking programs (e.g., Challenges, Sprints, Events, etc.) with a rapid prototype funding vehicle (OTA) to support dual-routes of commercialization housed under a single national membership organization.

- Q: How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual <u>commercialization</u>? What are some best practices for this kind of engagement?

  A: The best practices for engagement with industry and academia are still founded upon active programs such as Conferences, tech-Challenges, tech-Sprints, tech-Awards, and funding initiatives. As the NNI's participating agencies and technology portfolio range is so diverse, a truly diverse and multi-sector membership commercialization organization with active commercialization programs is required. Such an organization does not currently exist that we are aware of. Our proposed model would allow for all of the NNI agencies to use the described OTA prototype funding vehicle, while providing industry/investment commercialization exposure for all of their funded R&D.

- Q: How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

  A: There are a number of domain specific commercialization consortium models that have proven to be successful. However, the breadth of the NNI's technology domains is so broad that we are unaware of any existing organization that is delivering value at the scale we think is possible under the new model we have described. With regard to existing OTA consortium organizations, they do not typically provide industrial commercialization opportunities to their members in addition to their OTA funding programs. As TechConnect has provided tech-scouting programs for a number of these organizations, we would be happy to discuss their functionality in more detail upon follow-up.

Communication (commercialization focused response)

- Q: How can the NNCO facilitate communication and collaboration throughout the nanotechnology R&D ecosystem to enhance research and ultimately commercialization? How can the NNI/NNCO best communicate opportunities, resources, and advancements to the community? How can the NNI/NNCO best engage with the stakeholder community to understand their advancements and needs?

  A: We believe that the NNCO is providing an excellent job of communication. However, the primary draw for the tech-commercialization community is defined by what commercialization action or funding opportunities are being announced. The new national innovation commercialization membership model TechConnect has proposed would allow for a significant increase in marketing attention generated through industry scouting and OTA funding opportunities. This marketing responsibility would fall primarily on the new proposed membership organization; however it could work hand-in-hand with the NNCO in content generation and promotion.

Topics (commercialization focused response)

- Q: What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

  A: Under the new National Science & Technology Accelerator membership model described above, any technology topic from any of the participating NNI agencies could be incorporated and promoted out to the national innovation ecosystem. The point of the multi-domain, multi-sector, multi-agency blended commercialization model is to be able to target any type of technology request to the innovation community. The focus of the new organization, and its accompanying OTA, would be aligned with the broad set of NNI focused technology domains. The collaborative nature of this program would allow for greater transparency regarding dual-use opportunities for non-traditional technologies. The proposed structure would serve as an aggregation and matchmaking point not just for the innovative technologies that the government is seeking, but also as an aggregation-matching platform for identifying synchronous needs and opportunities across the broader cross-section of NNI agencies in general.

November 9, 2020

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Mechanisms

What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?

The creation of the National Nanotechnology in 2000 by the Federal Government signaled the importance of nanotechnology to the country's future. First, the NNI has provided coordination among its Federal agency members to keep the national nanotechnology strategy coherent and strong. While there may be differing immediate needs and development timelines across these agencies, NNI's coordination has aided optimization of the government's and country's resources in this important area. Second, the NNI provides an important face to the outside (i.e. non-government) world for nanotechnology. This ranges from providing a place for school children to learn the basics of nano to supplying updates on the latest nanotechnology developments for researchers and funding agencies. Finally, the coordination of a national nanotechnology strategy through the NNI provided a coordinated, informed voice on priorities that can promote nanotechnology research and applications.

The federal government supports nanotechnology research across its mission driven federal agencies which are also members in NNI. This has resulted in diverse and multi-disciplinary nanoscience and nanotechnology research across the Federal Government. This has been through multiple funding mechanisms from single investigator grants up through large, multi-institution, center grants. Another important aspect has been the partnering of Federal Research dollars with corporate sponsors to advance fundamental research and deliver technology with real-world applications. A good example of this is Federal Coordination with the Semiconductor Research Corporation (SRC). SRC already brings together multiple semiconductor companies to support and guide new research. These types of federal - private partnerships have advanced important areas, such as semiconductor and microelectronics.

How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

Nanotechnology will continue to be a vital area of research and development into 2030 and beyond. The funding mechanisms, through the existing federal agencies, can build on the coordination successes of the NNI. Nanoscience and nanotechnology encompasses a broad area of research that is fundamental and critical to enabling other future technologies in such areas as microelectronics, quantum information systems, and biomedical applications. Vital across all of these is having internal discussion and alignment on technology support, an understanding of the needs from the private sector, and communication of a well-defined strategy to the White House and Congress on funding priorities for nanotechnology research.

The NNI has a unique position to suggest and coordinate center level research that can bring together multiple disciplines, universities, government labs, and industries to advance nanotechnology research and the future's biggest challenges. Multi-disciplinary, multi-institution efforts often lead to the biggest advancements. This could certainly be through center type funding mechanisms already offered through agencies like NSF and DOE.

How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

Public-private partnerships are germane to advancing the NNI goals. These partnerships offer the ability to connect fundamental research to real world applications. This can lead to solving existing problems and advancing life in ways not necessarily envisioned. The NNI has goals to advance world-class nanotechnology research and transfer it to commercial and public benefit. These collaborations can deliver new technologies and applications to industries with expertise in scale-up, optimization, and commercialization. These collaborations also fit with the NNI's third goal of developing educational resources and developing the next generation workforce. Through these partnerships, companies can guide the development of new curricula by universities producing scientists and engineers that can bring these new technologies to life for consumer benefit. These partnerships also provide a stream of new graduates with the requisite expertise to provide significant contributions.

A good example of this type of partnership is the Semiconductor Research Corporation (SRC). This group, formed in the early 80's, brings together semiconductor device companies to support mutually beneficial research projects. SRC's projects bring together faculty and students from multiple universities to make advancements in areas like semiconductor, microelectronics, and computing research. The university research has oversight and input by scientists and engineers from the SRC member companies. These projects directly link university researchers with companies and aid in a pipeline of students for the involved, member companies. In addition to SRC funding of these projects, Federal Agencies, such as DARPA and NSF, are often involved in supporting and guiding these projects providing benefit to the government, universities, and the SRC member companies.

Communication

How can the NNCO facilitate communication and collaboration throughout the nanotechnology R&D ecosystem to enhance research and ultimately commercialization? How can the NNI/NNCO best communicate opportunities, resources, and advancements to the community? How can the NNI/NNCO best engage with the stakeholder community to understand their advancements and needs?

The NNI fulfills an important role as the face of nanotechnology in the US. It should continue to utilize the internet and social media platforms to share information. It should, however, look for more ways to build community among nanotechnology researchers and solicit their feedback on future research directions. NNI could sponsor more workshops, roundtable discussions, or panel discussions to bring together the academic, federal agency, and industrial communities. Input from these meetings could be used to influence national strategic direction for nanotechnology. These sessions, whether virtual or in-person, will not only serve as a mechanism to engage with and receive feedback from the greater nanotechnology community, but it also brings this community closer together.

Topics

What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

Our nation and the world face multiple challenges in the future where nanotechnology can have a major impact in providing solutions. These challenges include access to clean water[1-4], energy poverty[5,6], and data and information security[7-9].

The need for access to clean water will continue to drive innovation of technologies that can provide water solutions to communities including both waste water treatment and purification for human, agricultural, and industrial use. New materials, like membranes and nanocatalysts, will drive improvements to water access through clean-up of waste water[10], removal of contaminants and pathogens in drinking water[11], and water desalination[12]. Materials are being designed and modified at the nanoscale[13-15] to deliver more effective and efficient solutions for water treatment. These advances at the nanoscale will be crucial in delivering cost-effective, viable solutions to the global population.

Access to reliable, sustainable energy continues to be a struggle for many around the world. Improved energy efficiency and advanced energy storage capability[16] are two areas that will be important in meeting this energy demand. Nanoelectronics will play an increasing role through control and power management systems[17] and the continued evolution of low power computing[18]. These advances can lead to cost-effective distributed power generation and the availability of increased computing power to a larger segment of the global population.[17] Improved energy storage capabilities will be a game changing technology for improving energy reliability[19,20]. For example, batteries provide a buffer against intermittent energy generation and/or transmission establishing batteries as essential for areas with unreliable energy delivery. These storage technologies will also be key to the future application of distributed generation methods like solar or wind[20]. Nanotechnology will play an important function in the design of battery materials.[21,22] Nanoscale advances in design and fabrication of these materials can enable longer storage times, shorter charging periods, and lower costs which all can help enable energy security to a greater extent of the global population.[15]

With the continued advancement of computing and microelectronics especially towards the realization of quantum computing, data and information security will be paramount for both personal protection and national security.[7,8] The advent of quantum computing with its significantly advanced computing power is expected to render current security protocols and encryption ineffectual.[7] For example, this could have a significant impact on the commercial and defense sectors as hostile countries, terrorists, or criminals could potentially access secure information to cause financial damage to a person or company or cause harm to a country. Nanotechnology is already making an impact here through the design and growth of quantum materials and the creation of nanoelectronics and systems that will enable this new technology to be harnessed. Future investment and support of quantum information systems and nanoelectronics will help ensure our nation's preparedness for potential threats to information and data security.

The development of the next generation workforce will be key to meeting all the challenges previously stated. The nation should continue to invest in research and education programs that instruct nanoscience and nanotechnology fundamentals and develop new programs that prepare students to meet these particular issues. This will include continued innovation in nanotechnology related curricula and access for student researchers to facilities, instrumentation, and equipment. These next generation programs can be strengthened by collaboration between industry and universities. This focus on interdisciplinary education in nanoscience and nanotechnology can develop the scientists and engineers to meet the world's most formidable challenges.

What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

In the area of nanoelectronics, there are four areas where we believe nanotechnology will play a major role and whose development will be accelerated from public-private partnerships. Those four are listed below.

Devices utilizing phase transitions. There are many materials which transition from one phase to another at energetically exceptional points. These transitions points have been widely charted in materials science, often denoted by critical temperatures in a phase diagram. Phase transitions can be triggered by electric and magnetic fields which offers new opportunities for electronic and photonic devices which can use the energy exchanged in these transitions to enable low energy transistors, sensors, and memories. There also exist semiconductors that can be electrically triggered to ferroelectric, superconducting, ferromagnetic, or other collective states, which are inaccessible in traditional semiconductor materials. This brings new opportunities in electronics and photonics that are largely untapped with commercial and defense applications.

Manufacturing of electronic material interfaces with atomic control of defects. Interfaces, and surfaces are the critical structures determining the reliability and performance of electronic and photonic components. It is the time to reconsider fundamental manufacturing methods with the aim to build in defect control in integrated circuit processes. Defects ultimately limit performance and reliability in electronics. Fundamental processes need re-examination at the atomic scale, coupling computation and experiments, to identify processes which induce self correction and mitigate defect formation in electronics. Breakthroughs in device processes which impact manufacturing are critical to maintaining technical leadership in computing, communications, solar energy, power conditioning, medical diagnostics, environmental monitoring, and health. Innovations in this direction are also needed at the soft/hard material interfaces, e.g. between biological materials and semiconductors.

Technology gaps in nanoelectronics/photonics. There are many areas where the limitations of existing technology have been identified and innovations are needed. Bright, broadband infrared sources are needed for medical diagnostics and targeted therapies, as well as for environmental sensing, and threat detection. Spectral extensions of optoelectronic devices to the ultraviolet and deep ultraviolet are needed to allow new applications. Power conversion devices and materials are needed to drive reduced size in high efficiency converters needed for sustainable energy generation, energy storage, and electrification systems. Real-world (analog) information processing devices to reduce data bottlenecks in networks, data servors, and systems. Innovations in electronic materials and devices are needed to enable future digital and information processors, including selectors, nonvolatile analog weight storage devices, materials for 3D integration, and back-end-of-line active devices.

Organic/bioelectronic device technology

Electronic and photonic systems that can be formed on flexible substrates can substantially broaden the application space for semiconductor materials and devices. Earlier approaches explored thin-film semiconductors on low-cost substrates, such as metal foils, plastic sheets or paper[4]. More recent approaches achieve a fuller integration of organic and inorganic materials, incorporating various organic, polymeric and elastomeric materials, as well as hydrogels.[25-26] The combination of small-scale semiconductor electronic and photonic devices integrated within thin, compliant and stretchable form factors have advantages for applications of physiological monitoring and diagnosis, by virtue of the more intimate contact of multiple devices with the biological system.

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9 November 2020

Lisa Friedersdorf, Ph.D.
Executive Director
National Nanotechnology Coordination Office
Washington, DC

Via email

Dear Dr. Friedersdorf,

I am pleased for the opportunity to provide input to the NNI Strategic Plan. Two specific recommendations are highlighted here: 1) reinvestment in nanosafety research to advance the state of knowledge and methods for the next generation of advanced materials, and 2) active coordination and promotion of public/private partnerships to advance innovation, particularly for pre-commercial safety evaluations.

As a member of the nanosafety community for more than 15 years and a committee member of the 2020 NASEM Quadrennial Review of the National Nanotechnology Initiative, I first wish to express confidence in the efforts of the NNCO and the NSET to date, particularly on responsible innovation. Most of the comments I wish to make regarding the NNI Strategic Plan are reflected in a recent opinion published in Nano Letters: "*The current infrastructure and resources in nanosafety have been critical to advancing nanomaterial applications and now require adaptation toward the next generations of nano-enabled technologies that will refine methods, advance knowledge, and accelerate commercial adoption….Through coordinated efforts of the National Nanotechnology Initiative (NNI) and related international coordination over the last 15 years, there has been deliberate focus and investment on advancing knowledge and methods about environmental health and safety of novel nanoscale materials."*[1]

Now the most pressing issues relate to **investment in the development of methods and policies for the next generation of advanced materials and technologies**: evaluation of health/environmental risks across the product life cycle under realistic exposure conditions; the need for future orientation toward safety evaluation of more advanced materials; and the development of reliable and relevant New Approach Methodologies that evaluate safety with reduced mammalian testing. These are further described in the reference opinion.

As the founder of a small business focused on proactive safety demonstration of new technologies to overcome barriers and advance commercialization, my organization has successfully developed and coordinates several **public private partnerships.** These partnerships bring the shared interests of entrepreneurs together with experts and aligned

[1] Shatkin, JA. 2020. The Future in Nanosafety *Nano Letters* 20(3), 1479–1480. https://dx.doi.org/10.1021/acs.nanolett.0c00432 .

federal agencies to share the cost of developing new safety testing methods and develop data sets needed to demonstrate safety for market and regulatory stakeholders. It is crucial to structure these public private partnerships in a way that is a 'win-win' for participants and also provides benefits to individual organizations, the collective consortium, as well as the field more broadly. For example, protecting the IP of individual participants, while creating methods and data that are useful to the broader community. Typically, the first step in creating these partnerships is to create a safety roadmap identifying and prioritizing the most critical knowledge gaps that will need to be filled by the time of commercialization.

One successful example has been the P3Nano partnership between the US Forest Service Forest Product Laboratory and the private US Endowment for Forestry and Communities. Each organization shares the goal of advancing forest products in the economy and have partnered to invest in research on cellulose nanomaterials. Vireo Advisors has been a grantee of P3Nano since 2014, and has developed a diversity of resources for entrepreneurs including a safety roadmap, safety data sheet templates, and practical handling guide, among others. Since 2016, Vireo has been serving as coordinator of an industry partnership with P3Nano that has focused on adaptation of safety test methods, and development of data sets in support of commercial applications.

As discussed in the NASEM Review, the NNCO has helped to create several successful examples of such partnerships through the NSET, where government agencies have cooperated on common goals, and in cases, involved technology providers as well. I recommend the NNCO bring together potential public and private partners to facilitate needed safety studies, for example for emerging 2D materials such as graphene, or to advance the development of toxicity screening approaches in support of safer manufacturing with pre-commercial, early stage toxicity testing. Such efforts would support innovation and give entrepreneurs, investors, the public and others greater confidence in the commercial viability of new technologies and is a critical component of moving from the lab to commerce.

Thank you for the opportunity to comment on the next NNI Strategic Plan.

Sincere regards,

Jo Anne Shatkin, Ph.D.
President, Vireo Advisors, LLC.

White House Office of Science and Technology Policy (OSTP)
National Science and Technology Council
National Nanoscale Science Engineering and Technology (NSET) Subcommittee

Request For Information (RFI): 2021 National Nanotechnology Initiative (NNI) Strategic Plan[1]

November 9, 2020

Submitted Electronically to NNIStrategicPlanning@nnco.nano.gov

The Institute for Agriculture and Trade Policy (IATP) is pleased to have the opportunity to provide information to assist the NSET Subcommittee in the development of the 2021 draft Strategic Plan. IATP commented on the previous draft Strategic Plan[2] and responded to the OSTP "Grand Challenges" for nanotechnology.[3] We have been the beneficiary of participation in several excellent NNI sponsored webinars and workshops, a few of which we have reported on.[4]

Responsible development of nanotechnology

Of the many questions posed in the RFI, IATP will first respond to that concerning the NNI goal of the "responsible development of nanotechnology." The RFI asks, "As concepts surrounding

[1] https://www.govinfo.gov/content/pkg/FR-2020-10-13/pdf/2020-22556.pdf
[2] Steve Suppan, "Comment on the National Nanotechnology Initiative Draft Strategic Plan," Institute for Agriculture and Trade Policy, December 20, 2013. http://www.iatp.org/documents/comment-on-the-national-nanotechnology-initiative-nni-draft-strategic-plan
[3] http://www.iatp.org/files/OSTP%20Nanotechnology%20Grand%20Challenges.pdf
[4] E.g., Steve Suppan, "Future of U.S. federal nanotechnology: 'safe by design' product commercialization," August 29, 2019," Institute for Agriculture and Trade Policy, https://www.iatp.org/blog/201908/future-us-federal-nanotechnology-safe-design-product-commercialization; "Supporting science to advance the responsible development of nanotechnology," Institute for Agriculture and Trade Policy, February 23, 2017, https://www.iatp.org/blog/201703/supporting-science-advance-responsible-development-nanotechnology; "Nano. Inc.? There's been an accident on Highway 15," Institute for Agriculture and Trade Policy, July 28, 2016. http://www.iatp.org/files/OSTP%20Nanotechnology%20Grand%20Challenges.pdf; and Suppan, "Nanotechnology without the hype," Institute for Agriculture and Trade Policy, September 29, 2014. http://www.iatp.org/blog/201409/nanotechnology-without-the-hype

responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?"

In the 2016 NNI Strategic Plan, an important objective to realizing responsible development was to "Support the creation of a comprehensive knowledge base for evaluation of the potential risks and benefits of nanotechnology to the environment and to human health and safety." (Goal 4.1, p. 22) The National Nanotechnology Coordinating Office (NNCO) has organized or hosted dozens of activities over the past five years in support of this goal and associated sub-goals. Perhaps the most ambitious of these activities is the U.S. EU Communities of Research work on a nano-informatics platform to standardize and systematize the reporting of nanotechnology and nano-science research. The application of nano-informatics data and methodology to EHS risk assessment and to "safer by design capabilities" has been demonstrated[5] and should become an objective of the 2021 Strategic Plan. How can the nano-informatics platforms, built thus far on a budgetary shoestring and the pro bono contributions of mostly academic scientists, be scaled up for use across NNI agencies?

One of the benefits of the process of developing nano-informatics platforms is the interdisciplinary convergence that has been an NNI hallmark. However, to scale up the building and application of such platforms for EHS application, a more comprehensive framework is needed to formulate NNI consensus nano-EHS questions and technically and financially support EHS research beyond what is accessed and standardized in the nano-informatic categories. NNI agencies have not published a collective EHS strategy since 2011. The draft Strategic Plan should commit NNI agencies to review the EHS literature of the past decade towards contributing to an EHS Research Strategy that anticipates EHS research and associated infrastructure that will be needed over the next decade.

Although NNI continues to publish reports from its excellent EHS workshops and to present a broad array of EHS studies in its webinar series, the 2011 NNI EHS Research Strategy has not been reviewed since 2014.[6] Some individual NNI agencies have published summaries of their EHS research.[7] However, the convergence of NNI agencies to develop a research strategy for the next decade would have the budgetary advantage of reducing duplicative research and infrastructure needs and expense.

A new NNI EHS Research Strategy would include a review of what was accomplished and what was intended but not accomplished in federally funded EHS research since the 2014 review of

[5] Christine Ogilvie Hendren and Fred Klaessig, "A Case Study in Convergence and Team Science," National Nanotechnology Coordinating Office NanoEHS Webinar Series, November 12, 2019. https://www.nano.gov/sites/default/files/NNNIwebinar-Nanoinformatics-Convergence-TeamSci-Nov2019_final.pdf

[6] https://www.nano.gov/node/1157

[7] E.g., Debra L. Kaiser and Vincent A. Hackley, "NIST Nanotechnology Environmental, Health and Safety Research, 2009-2016," National Institute of Standards and Technology, NIST Special Publication 1233, November 2018. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1233.pdf

the 2011 EHS Research Strategy. NNI EHS research funds have been historically concentrated in a few agencies, above all Health and Human Services, National Science Foundation and Environmental Protection Agency[8], so a survey of EHS research in the NNI agencies would not show uniform scale of results. However, all NNI agencies might benefit from a process to identify EHS research accomplishments and needs. One way to focus a new Strategy would be to determine any EHS research needs, including any new infrastructure, for achieving current and prospective NNI Signature Initiatives. Because each Signature Initiative involves research and development in more than one agency, developing EHS Research Strategy for those Initiatives could engage multiples agencies.

IATP strongly prefers that a new NNI EHS Research Strategy be a stand-alone process and a stand-alone document. However, if the NSET Subcommittee decides that the objectives of a new EHS Research Strategy should become part of the 2021 Strategic Plan, we urge the NSET Subcommittee to propose launching a separate NNI EHS Research Strategy by the end of 2021.

The "Supporting Information for the NNI Strategic Planning" identifies "potential ethical legal and societal implications" (ELSI) of nanotechnology as crucial, along with EHS research, to achieving the goal of "responsible development." However, there are no budget lines or program components for ELSI research in the "NNI Supplement to the President's 2021 Budget." IATP has not reviewed all the past NNI budgets, but to judge by the titles of NNI workshops dating back to 2003, there have been no ELSI workshops and just one on "public engagement" (2012) that could concern societal implications.

If the 2021 Strategic Plan is to retain the "responsible development" goal, the NSET Subcommittee should outline how ELSI research has been used and might be used in the future to achieve that and other Strategic Plan goals. The NSET Subcommittee could propose that the NNI organize one or more workshops to consider how ELSI research could advance realization of the NNI Signature Initiatives. For example, regarding the Food and Agriculture Signature Initiative, ELSI researchers could evaluate industry consultations with the Food and Drug Administration concerning FDA voluntary guidance documents on engineered nanomaterials in food, food ingredients and food contact surfaces.[9] In its most recent nanotechnology report, FDA explains that it applies a "science-based product-focused regulatory policy" to regulating nanotechnology products.[10] A sample research question: have such consultations about specific products resulted in responsible development of food related products that incorporate engineered nanoscale materials? Or regarding the Nano-biosensor Initiative, ELSI researchers

[8] E.g., "The Nanotechnology Initiative: Supplement to the President's 2021 Budget," October 2020. Table 2: 2019 Actual Agency Investments by Program Component Area, at 6. https://www.nano.gov/sites/default/files/NNI-FY21-Budget-Supplement.pdf

[9] https://www.fda.gov/science-research/nanotechnology-programs-fda/nanotechnology-guidance-documents

[10] "Nanotechnology—Over a Decade of Progress and Innovation," Food and Drug Administration, July 2020, at 6. https://www.fda.gov/media/140395/download

might report on ethical and legal issues arising from the development and use of such sensors, e.g., concerning how and when sensor-generated data should be anonymized.

If the NSET Subcommittee decides that ELSI research is no longer necessary to achieving the "responsible development" goal, it should state so clearly and explain the reasons in support of such a determination.

Speeding up the commercialization of nanotechnology products

The Quadrennial Review of the National Nanotechnology Initiative by a committee of the National Academies of Science Engineering and Medicine has recommended to the NSET Subcommittee the continuation of the NNI and its reorganization to accelerate the commercialization of nanotechnology products.[11] Although the National Academies report criticizes NNI's performance in achieving its first three goals, the report authors praise the NNI achievements: "on Goal 4 the committee considers that the NNI has performed exceptionally well and is recognized internationally for its leadership in responsible nanotechnology development and for leveraging international collaborations, although agency engagement appears to be waning." (p. 3) As the NSET Subcommittee considers the recommendations of the National Academies report, IATP advises it to support strengthening the international collaborations that have been crucial to U.S. leadership in responsible nanotechnology development. The Subcommittee should not propose that achievement of all four NNI goals will be realized by applying an industry Return on Investment analysis as the final arbiter of the success of NNI collaborations with and support for industry and entrepreneurial academics. Among the questions for the Subcommittee to consider is how the advocacy for accelerating commercialization may impact NNI agencies' already "waning engagement" in responsible development.

The RFI poses several questions that bear on the recommendations that the NNI be reconfigured to direct more public funds to programs to accelerate the "lab-to-market" delivery system. We select just two questions to answer:

> What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?
>
> How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

It is not much of an exaggeration to say that researchers in the various science and engineering disciplines became the "nanotechnology community" because of the organizational, research and investment initiatives of the Federal Government. As is well known to the NSET

[11] National Academies of Sciences, Engineering, and Medicine 2020. A Quadrennial Review of the National Nanotechnology Initiative: Nanoscience, Applications, and Commercialization. Washington, D.C.: The National Academies Press, at 3-4. https://doi.org/10.17226/25729.

Subcommittee, the participating agencies of the NNI provide a huge range of public services to the "nanotechnology community," ranging from building and leasing nanotechnology infrastructure; grant-making for nanoscience; EHS research workshops applicable to a broad range of products; federal agency product development transferred to the private sector for commercialization; regulatory, commercialization and patenting advice, particularly for small and medium scale enterprises; educational outreach, e.g., via science museums and secondary school STEM programs; and prototype manufacturing and testing services. In sum, the nanotechnology work of the NNI, the National Nanotechnology Coordinating Office (NNCO) and the grant-making agencies comprise a paradigm of what Mariana Mazzucato has called "the entrepreneurial state."[12]

One of the problems of reorganizing the NNI to prioritize accelerating the commercialization of nanotechnology enabled products is that such a reorganization or reorientation may ignore or even disinvest in the public goods research, e.g., in infrastructure development, nano-informatics, EHS research or ELSI research that might result in commercialization delay. Governments have often invested in research that was too financially risky for most private enterprises to undertake, e.g., in the development of pharmaceuticals or cyber-infrastructure. NNI agencies should continue to perform this essential government function. Taxpayers financing NNI research should receive a public return on investment in the form of public goods, such as potable water and affordable medicines benefitting from robust EHS research. Nanotechnology return on investment should not be defined or calculated merely in terms of products brought to market, much less numbers of patents granted.

Mazzucato is one of the architects of the European Union's Horizon 2020 research planning. She has proposed elsewhere that government research agencies need well-defined missions to be more entrepreneurial and innovative.[13] A mission defined as simply to serve the needs of the private sector, as defined by the private sector, to facilitate product commercialization will serve neither the NNI agency nor the academic or industrial entrepreneur well. NNI agencies should not only maintain a robust research agenda as part of their mission, but also have a right to innovate, particularly in those areas of nanoscience and ERS research in which the private sector is unable or unwilling to invest.

A best practice for stakeholder engagement that NNCO and NNI agencies should scale up is hosting workshops at which products at an early stage of development are put to a manufacturing, value proposition and life cycle analysis tests that would take the product of out the lab and into its market and utilization environment. As far as IATP knows, the nano-biosensor is the most prominent example of NNI stakeholder engagement in both value

[12] Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*, (London, Anthem Press, 2014), 84-86.
[13] João Medeiros, "The Economist Has a Plan to Fix Capitalism: It's Time We All Listened," *Wired* October 8, 2019. https://www.wired.co.uk/article/mariana-mazzucato

proposition analysis[14] and the challenges of scaling up a product prototype in an industrial manufacturing process.[15]

NNI agencies, e.g., FDA and EPA, offered workshop presentations to stakeholders on "Navigating the Regulatory Process." Another best practice would be for NNI agencies to share with product developers NNI agencies' EHS and ELSI research to help product developers anticipate and avoid EHS risks, e.g., by taking advantage of NNI "safe by design" research.

Conclusion

IATP hopes that this response to the RFI will assist the NSET Subcommittee in drafting the Strategic Plan. We look forward to commenting on the draft Plan.

[14] "NNI Sensor Fabrication, Integration and Commercialization Report," September 11-12, 2014, at 4-8. https://www.nano.gov/sites/default/files/pub_resource/nnisensorsworkshopreport.pdf

[15] "Nanosensor Manufacturing Workshop: Finding Better Paths to Products," National Nanotechnology Initiative, June 13-14, 2017. https://www.nano.gov/sites/default/files/pub_resource/Nanosensor%20Manufacturing%20Workshop%20Summary.pdf

Response by John N. Randall and James H.G. Owen of Zyvex Labs

Preamble discussion on precision and accuracy:

In this response, precision in nano fabrication/manufacturing is a key concept that is used in a variety of contexts and can be confusing. In general, precision in manufacturing can be defined as the tolerance (spread of measured size) of repeated measurements of a manufactured item. For example, a machined piece of metal designed to be 10mm and repeated measurements of that manufactured piece are always within +/- 1 micron of an average size of **11mm,** it can be said to have micron precision which is very good precision for machining but poor accuracy, because accuracy is about variation from a design specification (**10mm**).

There is also an important concept of relative precision. If the design specification is 10nm and the average of repeated measurements is 10nm +/- 1nm, then the accuracy of the manufacturing process is excellent and the absolute precision is excellent but the relative precision, that is the precision of the manufacturing process as a percentage of the design specification is +/- 10% which is poor. Depending on what is being manufactured (say digital electronics) this poor manufacturing precision may be acceptable. But for most manufacturing processes a relative precision of +/-10% is a disaster. Imagine trying to build a house or an internal combustion engine with +/-10% relative precision.

There is also confusion around the term 'atomic precision'. Strictly speaking this would suggest a precision of +/- a single atom. However, for many, the definition of atomic precision is "every atom exactly where the design specifies". Others, ourselves included, will use atomic precision to mean that we are achieving an accuracy of +/- 1 atomic spacing or lattice position in a crystalline material. Still others will use atomic precision to mean a precision that is roughly on the atomic scale.

So far, we have ignored the precision of the measurement tool which in practice is convolved with the precision of the manufacturing process. At the atomic scale, where measurement is challenging, there is a great opportunity to digitize the measurement (of crystalline materials at least) by simply counting atoms or molecules. Similarly we will talk about the advantages of digital atomic-scale fabrication where we can much more easily achieve not only very high precision but, at least in principle, should be able to achieve absolute accuracy where the manufactured object is designed and manufactured accurately in units of lattice spacings.

In this document, we will use the following definitions:

- **relative precision:** manufacturing size variation as a percentage of the average size
- **atomic precision:** manufacturing variation on the scale of an atom of the material being manufactured
- **absolute accuracy:** atoms where you want them according to the design

Defects are a separate issue that we will touch on briefly in what follows. In our discussion absolute accuracy in manufacturing does not have to be synonymous with no defects.

- **How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization?**

By recognizing that nanotechnology, with all of its many successes in developing improved and novel materials, has hugely underperformed in commercializing complex nanosystems. The single biggest limiting factor, and one that the NNI can significantly impact is the lack of manufacturing precision and accuracy at the nanoscale. The NNI should encourage a huge initiative to develop ultra-high precision and accuracy fabrication, analysis, metrology and inspection tools first for research and niche commercial applications and later an effort to scale those techniques to much larger manufacturing scales and a wide range of applications.

But wait, the astute reader might say. We are already doing nanomanufacturing at a grand scale creating systems of enormous complexity in the semiconductor industry. However, we must admit that this is a highly specialized case and has succeeded without much help from the NNI. This is not a fault of the NNI, because by the turn of the century the semiconductor industry had already defined its path to nanomanufacturing and had enormously larger resources at its disposal.

Semiconductor industry success is a double-edged sword. Optimized for classical digital electronics it has pushed large scale manufacturing into the single digit nanometer resolution regime. But it has done so with the poor relative precision permitted for digital electronics.

We have accepted the highly developed the suite of semiconductor manufacturing tools as our principal toolbox. Walk into virtually any nanofabrication facility at virtually any university, national, or industrial lab and you will find primarily tools designed for semiconductor fabrication, metrology, and inspection. This has occurred quite naturally because the inexorable march of Moore's Law required semiconductor firms to turn over its tool set regularly to stay competitive. This has produced "relatively inexpensive" cast-off tools available to laboratories eager to explore the wonderfully large nano technology parameter space. The problem is that these tools have been optimized to make digital electronics at the highest possible throughput while achieving merely "good enough" relative precision for digital electronics.

Let us consider the impact of poor relative precision on MEMS development. While we can point to MEMS as a very successful example of using semiconductor processing equipment to create valuable devices, this has been possible in spite of the poor relative precision. MEMS devices could be far more useful if high precision and accuracy fabrication at the microscale was possible. I will give two examples.

- Poor relative precision has made rotary bearings impractical. Actuation is essentially limited to flexure motion with all of its limitations.
- Prof. Clarke Nguyen of Berkeley, while he was a program manager at DARPA pointed out the huge advantage (many orders of magnitude) MEMS resonators had in quality factors compared with electrical circuit resonators. These made for dramatically better circuit elements for filtering and other signal processing [1]. The problem that has

significantly limited the uses of MEMS resonators for these uses is the fact that sloppy (poor relative precision and accuracy) semiconducting fabrication processes do not permit good control of the frequency of these resonators.

For many simple applications, simply being small is good enough. However, for complex devices and systems this lack of precision and accuracy in semiconductor fabrication tools is a significant problem that has kept many wonderful nanotechnology designs and even demonstrations in laboratories from commercialization simply because we do not have manufacturing tools with sufficient precision and accuracy.

Let us turn to a concrete example of dramatic national importance and already significant industrial interest. We refer to quantum technologies, in particular quantum information technologies. The signing of the National Quantum Initiative Act (NQIA) in late 2018 has encouraged significant activities in academia and in national laboratories that resemble the early exploration and excitement created by the NNI. However, there is also a dramatic difference in the response of industry to the NQIA compared with the industrial response to the NNI. While there was unquestionably some industrial interest in nanotechnology that has grown over the last two decades, it pales in comparison to industrial involvement with quantum technologies.

A specific example would be of the activities and membership of the Quantum Economic Development Consortium (QED-C) [2] set up by the Department of Commerce even before the NQIA was signed. One only has to look at the current signatories to judge the level of interest of major companies in this field. Not only are the major companies that you would expect to be in such an extremely high tech consortium: ARM Research, AT&T, Google, HRL Laboratories, IBM, Intel, Microsoft, Palo Alto Research Center, and SRI International, but also other industrial giants, Amazon, BAE Systems, Boeing, Corning, GE Global Research, General Dynamics Mission Systems, Honeywell, Lockheed Martin, Northrop Grumman, Raytheon-BBN Technologies, and United Technologies Research Center. There are even (maybe not surprisingly) financial firms like Accenture, Citi, Pay Pal, and Wells Fargo that have joined, no doubt because of the implications for financial transactions of secure quantum communications.

All told there are 152 industrial and 49 universities and other institutions that are signatories expecting to be members soon. While some quantum efforts particularly in quantum computing by Google and IBM are fairly well known, there are many more serious efforts that conservative estimates suggest are far outspending (already!) what the NQIA is pumping into quantum technologies. One example is that Honeywell has a dedicated effort at making ion trap quantum computers in Colorado that employs in excess of 100 personnel. This amounts to a very large financial commitment.

In short, there is a large interest in quantum technologies in academia and national labs, and industry is willing to spend large sums of money on developing and commercializing that technology. But is this the same scenario as with the semiconductor industry where the path was set by industry and their resources along their path has made efforts in non-industrial research labs along other paths unimportant? The answer is definitely not. While industry is willing to commit significant resources, they are near term focused and the path forward to quantum computing, communication and sensing is anything but established. Industry is charging ahead with the nano manufacturing tools that are available which are primarily semiconductor fabrication tools. These tools have been developed and optimized for classical digital electronics which have been engineered to be extremely tolerant of fabrication variations. However, quantum technologies are extremely sensitive to fabrication variations. Many quantum effects are directly or even exponentially dependent on the absolute size of quantum device dimensions. The end result is that semiconductor tools in even the most advanced fabs have woefully inadequate precision and accuracy for quantum devices. While we might expect that semiconductor tool makers could turn their considerable talents and resources to improving the precision and accuracy of their tools, they are unlikely to do so while the technological path is not yet clear and the timing of the emergence of reasonable sized markets is uncertain[3].

While there is a lot of research in this area that is not directly related to nanotechnology, the NNI is better positioned than any other organization to develop the fabrication processes that are needed to do research and development in the short term and manufacturing in the long term of quantum devices.

Therefore one excellent answer to the question, "*How the government should engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization?"* Is to develop nanofabrication tools with dramatically better precision and accuracy than the current set of nanofabrication tools. The nanofabrication technology must be scalable, but the target should not be similar to current semiconductor tools that make consumer electronics, but scalability should be considered for quantum technologies where the size of the market will start off small just as semiconductors did. The government has the opportunity to fund the development of ultra-high precision and accuracy fabrication tools for the quantum industry. The great success of the US government supporting the development of integrated circuits and the tools to fabricate them can and should be repeated.

We believe the engagement should work to pair efforts to develop specific useful nanoapplications developers with enabling nano-tool developers. But at the same time engage with ultra-high precision and accuracy nanofabrication tool developers that may not yet know exactly what their fabrication might enable. The value of supporting basic science development, where the technological impact of the science is not yet known. is well established. This engagement should recognize the value of supporting basic technology development.

- **What are some best practices for this kind of engagement?**

We have been engaged with multiple government agencies over the last 4 decades and have been fortunate to get great support to do valuable research much of which has been commercialized. In my opinion, the organization with the best approach to encouraging and funding research is DARPA. The aspects that we believe make them the best research funding agency are:

  - Program managers that are recruited with very high standards, out of industry, academia, national labs, and the government for limited terms. These PMs have excellent support, create the programs that make the most sense to them and are the decision makers.

- o The outsourcing of the managing of the research contracts to other government agencies so that DARPA can concentrate on the technical issues rather than the administration of the contract.
- o The outreach that DARPA has used in meetings of all DARPA offices or of their separate offices. At these events, their program managers are in attendance and encouraged to talk to anyone with an idea. The accessibility of these PMs to researchers is a key factor.

Other funding agencies have attempted to emulate DARPA's approach which is a good idea and has made them better, but in my experience, DARPA is still the best at this approach.

- **What are the high priority open scientific questions in nanoscience and nanotechnology?**

As indicated above there is an opportunity that is extremely high priority for the nation in developing ultra-high precision and accuracy fabrication, metrology, and inspection techniques for quantum and other devices.

- **What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?**

As Moore's Law has run its course, the semiconductor industry once dominated by the US is now a global industry. Although the leader in sales for semiconductor devices, according to a report produced for the U.S. Air Force in 2019, "Close to 90% of all high-volume, leading-edge IC production will soon be based in Taiwan, [China], and South Korea, with the U.S. share of global IC fab capacity falling to 8% by 2022, down from 40% in the 1990s."[4] The US can no longer count on having the significant advantage that we have enjoyed being the unquestioned leader in information technology. Quantum information technology holds the promise of dramatic advantages in computing, communications, and sensing technology. As indicated above the manufacturing tools with the required precision and accuracy for quantum computing and other quantum technologies do not currently exist. <u>Nanotechnology is the answer</u> to develop the tools to enable quantum information technology.

While our discussion would appear to center on fabrication of solid-state quantum devices, the increase in precision and accuracy in manufacturing for virtually any quantum device would be extremely valuable and quite possibly required. In fact, the current two front runners in the quantum computing race, superconducting qubits and trapped ion qubits, are not solid state integrated electronic devices. The superconducting Qubits use as their quantum element microwave photons, and ion trap qubits are more or less vacuum tubes. Both have qubits that are (really) huge compared to current CMOS transistors. The National Academy Press in its 2019 report Quantum Computing Progress and Prospects" concluded that neither of these technologies were likely to produce the universal quantum computers that are desired [5,6]. We believe that it is entirely consistent to think of these early technologies as the equivalent of the vacuum tube technology that classical digital computers started with and were eventually replaced by integrated solid-state electronic devices. While it is not a foregone conclusion that quantum computers will eventually emerge as integrated solid-state circuits, it would be dangerous to bet against that outcome given the advantages of integrated solid-state devices that have driven their almost universal adoption in information technology. Having said that, any manufacturing process for any type of promising quantum information technology should be targeted for driving to ultra-high precision and accuracy.

- **What nanotechnology-enabled "moonshots" should be considered?**

While there is no question that improved precision and accuracy fabrication tools could have an enormous impact on enabling quantum technology tools, there are many different approaches to quantum technology and many different processes to produce any one of them as well as many other exciting nanotechnology applications. But how to get to improved precision and accuracy is an open question. We do have a proposal, but we first would like to point out that I believe that nanotechnology is about where our information technology was when it was principally analog in nature. We had telephones, televisions, radios, plastic disks with wiggly grooves, cassette tapes etc. There was no doubt that it was valuable at the time. But the impact was nothing like it was after digital information technology replaced the analog technologies.

We contend that our current nanofabrication techniques including those in our most advanced semiconductor fabs and research nanofabrication facilities are essentially analog fabrication. While our fab processes take great advantage of the chemical nature of atoms and molecules, they do not take advantage of the wonderfully invariant size of atoms and molecules to control the size of what is being fabricated. There are a few counter examples. Atomic layer deposition and diblock copolymer lithography do take advantage of the size of molecules to control the size of what is being fabricated. But they do not yet represent the programmable high accuracy manufacturing processes that will enable a new industrial revolution.

We would therefore argue for the development of digital atomic-scale fabrication, that is fabrication processes that take advantage of the discrete sizes of atoms and molecules, would be another digital revolution that could replace our current analog fabrication techniques for many of the same reasons that that digital information technology replaced its analog predecessors. We believe that the criteria for digital atomic-scale fabrication can be defined as follows:

- Binary operations that are the making and breaking of chemical bonds.
- A digital (spatial) address grid (either absolute or relative) that can be used to control where those binary events happen.
- Technologically accessible tolerance in those addressable binary functions that result in a workable yield that can be maintained by,
- Error detection and correction techniques which will need to be developed.

The question of defects is a complex one. In some products there are regions where the existence of any defect negatively affects the product performance, while in other regions there is tolerance to defects that will not impact the overall performance. This concept of digital atomic-scale fabrication which includes error detection and correction allows defects to be eliminated where they would compromise the desired properties of the product.

There are a growing number of researchers who are exploring atomic scale fabrication [7-15] some have even begun to embrace the value of including error detection and correction [16,17]. More details of digital atomic-scale manufacturing including some existing examples of this sort of technology have been published [16]. The digitization of the fabrication process can be accompanied by the digitization of metrology, inspection and analysis tools that each can take advantage of the quantized nature of matter. This can lead another digital revolution that succeeds for many of the same reasons that digital information technology has, but is not restricted to information processing. Digital atomic scale manufacturing could produce a wide variety of physical products that take advantage of the ability to create atomically accurate materials and structures with remarkable attributes.

It is also worthwhile to consider that we are nearing the end of the road of one of the most powerful methods of technological progress, the exponential improvement of manufacturing accuracy. Norio Taniguchi, who coined the term nanotechnology, studied the historical trends of manufacturing accuracy several decades ago and fairly accurately predicted its progress [18]. His data predicted that in the past 100 years that manufacturing accuracy will have improved in an exponential behavior by approximately 100,000 times and will be approaching the atomic scale. While the bleeding edge of manufacturing accuracy is roughly where Taniguchi predicted it would be today, we should be clear that this is restricted to a single dimension (thin film deposition) and is not yet widely available and is still analog processing. The fact that our precision and accuracy is approaching the quantized nature of matter presents a major problem (and an opportunity). To mis-quote Richard Feynman, we are running out of room at the bottom. Because of the quantized nature of matter, we will soon lose the ability to exponentially improve manufacturing precision and accuracy. One can make the case that this limitation is the primary reason that Moore’s Law has ground to a halt.

We believe that digital atomic-scale fabrication can result in a new exponential trend in manufacturing that we refer to as an Inverse Moore’s Law [16]. Where instead of increasing the value of a product by improving manufacturing precision (downscaling) we achieve the ultimate in accuracy which is atomic accuracy (a process that puts atoms and molecules exactly where we want them) first at the nanoscale, and then maintain atomic accuracy and increase the value of our products by upscaling to ever greater physical volumes and product complexity in many applications including information processing but expanding to produce a wide range of applications. This can be a manufacturing trend that provides a path to drive our science and technology for the next 100 years.

Therefore, we believe that the most impactful nanotechnology moonshot would be to develop digital atomic-scale fabrication/manufacturing as defined above for a variety of material systems.

- **How does nanotechnology support other foundational fields/initiatives? What future technical topics are likely to emerge from advancements in nanotechnology?**

Recognizing that semiconductor manufacturing is nanotechnology, and realizing what solid-state electronics has done to enable our information technology with all of its impact on science and technology, it is clear that nanotechnology has been hugely influential to virtually all of the technological and scientific progress hade in the past 50 years. In addition, the improvements of fabrication, material analysis, metrology, and sensing at the nanoscale has provided dramatic advances in science and technology.

Looking forward, we believe that nanotechnology will play a dominant role in unravelling the mysteries of quantum mechanics, biology, and other scientific endeavors. Some form of digital atomic-scale fabrication will inevitably emerge and start a new industrial revolution that will provide the technology that will allow us to make the scientific and technological advances that will benefit all of humankind.

- **What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)? What other tools are necessary to conduct nanotechnology R&D?**

As mentioned above, we need a tool set that goes beyond what is available from the semiconductor industry for nano fabrication, metrology, material analysis, etc. that provides and supports atomic precision and accuracy fabrication and analysis.

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Respectfully Submitted

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White House Office of Science and Technology Policy (OSTP)
National Science and Technology Council
National Nanoscale Science Engineering and Technology (NSET) Subcommittee
Request For Information (RFI): 2021 National Nanotechnology Initiative (NNI) Strategic Plan[1]

November 9, 2020

Submitted Electronically to NNIStrategicPlanning@nnco.nano.gov

From: Jaydee Hanson,
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The International Center for Technology Assessment (ICTA) is pleased to provide information to assist the NSET Subcommittee in the development of the 2021 draft Strategic Plan. ICTA commented on the previous draft Strategic Plan and responded to the OSTP "Grand Challenges" for nanotechnology. We have been participating in the NNI review of the nation's work on nanotechnology since 2005. We have participated in many excellent NNI sponsored webinars and workshops.

Responsible development of nanotechnology

ICTA will first respond to the NNI goal of the "responsible development of nanotechnology." The RFI asks, "As concepts surrounding responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?"

In the 2016 NNI Strategic Plan, an important objective to realizing responsible development was to "Support the creation of a comprehensive knowledge base for evaluation of the potential risks and benefits of nanotechnology to the environment and to human health and safety." (Goal 4.1 p. 22) The National Nanotechnology Coordinating Office has organized or hosted dozens of activities over the past five years in support of this goal and associated sub-goals. Perhaps the most ambitious of these activities is the U.S. EU Communities of Research work on a nano-informatics platform to standardize and systematize the reporting of nanotechnology and nano-science research. The application of nano-informatics data and methodology to EHS risk assessment and to "safer by design capabilities" has been proposed[2] and should become an objective of the 2021 Strategic Plan. How can the nano-informatics platforms, built thus far on a budgetary shoestring and the pro bono contributions of mostly academic scientists, be scaled up for use across NNI agencies? ICTA has been one of the few US non-governmental/non-academic organizations participating in the Communities of Research. This is a project that would benefit from still more non-governmental involvement. At most meetings only ICTA and IATP are present to represent the NGO community. In Europe, many more NGOs have been involved in the review of nanotechnologies.

One of the benefits of the process of developing nano-informatics platforms is the interdisciplinary convergence that has been a NNI hallmark. However, to scale up the building and application of such platforms for EHS application, a more comprehensive framework is needed to formulate NNI consensus nano-EHS questions and technically and financially support EHS research beyond what is accessed and standardized in the nano-informatic categories. Although NNI continues to publish reports from its excellent EHS workshops and to present a broad array of EHS studies in its webinar series, the 2011 NNI EHS Research Strategy has not been reviewed since 2014. Some individual NNI agencies have published summaries of their EHS research. However, the convergence of NNI agencies to develop a research strategy for the next decade would have the budgetary advantage of reducing duplicative research and infrastructure needs and expense.

We do understand that part of the problem is that EHS research has not been a priority of agencies working on nanotechnology.

A new NNI EHS Research Strategy would include a review of what was accomplished and what was intended but not accomplished in federally funded EHS research since the 2014 review of the 2011 EHS Research Strategy. NNI EHS research funds have been historically concentrated in a few agencies, above all Health and Human Services, National Science Foundation and Environmental Protection Agency[3], so a survey of EHS research in the NNI agencies would not show uniform scale of results. However, all NNI agencies might benefit from a process to identify EHS research accomplishments and needs. One way to focus a new Strategy would be to determine any EHS research needs, including any new infrastructure for achieving current and prospective NNI Signature Initiatives. Because each Signature Initiative involves research and development in more than one agency, developing EHS Research Strategy for those Initiatives could engage multiples agencies.

ICTA agrees with our colleague group IATP and we both strongly prefer that a new NNI EHS Research Strategy be a stand-alone process and a stand-alone document. However, if the NSET Subcommittee decides that the objectives of a new EHS research strategy should become part of the 2021 Strategic Plan, we urge the NSET Subcommittee to propose launching a separate NNI EHS Research Strategy and the end of 2021.

The “Supporting Information for the NNI Strategic Planning” identifies “potential ethical legal and societal implications” (ELSI) of nanotechnology as crucial, along with EHS research, to achieving the goal of “responsible development.” However, there are no budget lines or program components for ELSI research in the “NNI Supplement to the President’s 2021 Budget.” ICTA staff has reviewed all the past NNI budgets since 2005, and notes that the budgets have not funded ELSI workshops and just one on “public engagement” (2012) that could concern societal implications.

If the 2021 Strategic Plan is to retain the "responsible development" goal, the NSET Subcommittee should outline how ELSI research has been used and might be used to achieve that and other Strategic Plan goals. The NSET Subcommittee could propose that the NNI organize one or more workshops to consider how ELSI research could advance realization of the NNI Signature Initiatives. For example, regarding the Food and Agriculture Signature Initiative, ELSI researchers could evaluate industry consultations with the Food and Drug Administration concerning FDA voluntary guidance documents on engineered nanomaterials in food, food ingredients and food contact surfaces.[4] In its most recent nanotechnology report, FDA explains that it applies a "science-based product-focused regulatory policy" to regulating nanotechnology products.[5] A sample research question: have such consultations about specific products resulted in responsible development of food related products that incorporate engineered nanoscale materials? Or regarding the Nano-biosensor Initiative, ELSI researchers might report on ethical and legal issues arising from the development and use of such sensors.

If the NSET Subcommittee decides that ELSI research is no longer necessary to achieving the "responsible development" goal, it should clearly explain the reasons. Failure to do so will underscore the belief on the part of many that even science based agencies no longer support scientific review of the effects of emerging nanotechnologies and rather are just cheerleaders for the new technologies without serious review of the effects.

"Speeding Up the Commercialization of Nanotechnology Products"

The Quadrennial Review of the National Nanotechnology Initiative by a committee of the National Academies of Science Engineering and Medicine has recommended to the NSET Subcommittee the continuation of the NNI and its reorganization to accelerate the commercialization of nanotechnology products.[6] Although the National Academies report criticizes NNI's performance in achieving its first three goals, the report authors praise the NNI achievements: "on Goal 4 the committee considers that the NNI has performed exceptionally well and is recognized internationally for its leadership in responsible nanotechnology development and for leveraging international collaborations, although agency engagement appears to be waning." (p. 3) As the NSET Subcommittee considers the recommendations of the National Academies report, ICTA advises it to consider whether the evaluation of NNI is best conducted in terms of industry Return on Investment analysis, as advocated by the National Academies. Among the questions for the Subcommittee to consider is how the policies advocate for accelerating commercialization may impact NNI agencies' already "waning engagement" in responsible development, due to concerns about U.S. global competitiveness.

ICTA's sister agency, the Center for Food Safety has developed a data base showing which food related nanotechnologies are available in the US market. The more than 400 products in that database are generally unapproved by any federal agency that should be reviewing these products. The NNI needs to push the FDA, EPA, CPSC and the USDA to perform strong EHS reviews of these products. [7]

The RFI poses several questions that bear on the recommendations that the NNI be reconfigured to direct more public funds to programs to accelerate the ‘lab-to-market’ delivery system. We select just two questions to answer:

> What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?
>
> How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

It is not much of an exaggeration to say that researchers in the various science and engineering disciplines became the “nanotechnology community” because of the organizational, research and investment initiatives of the Federal Government. As is well known to the NSET Subcommittee, the participating agencies of the NNI provide a huge range of public services to the “nanotechnology community,” ranging from building and leasing nanotechnology infrastructure; grant-making for the most advanced nanoscience; EHS research workshops applicable to a broad range of products; federal agency product development transferred to the private sector for commercialization; regulatory, commercialization and patenting advice, particularly for small and medium scale enterprises; educational outreach, e.g. via science museums and secondary school STEM programs; and proto-type manufacturing and testing services. In sum, the nanotechnology work of the NNI, the National Nanotechnology Coordinating Office (NNCO) and the grant-making agencies comprise a model of a program to promote new technologies, but fail to include the need EHS research. In short, it is a model that largely promotes the nanotechnologies without do a good job of using science to assess the potential down sides of the nanotechnologies. The Human Genome Program included ELSI research from its very beginning, the NNI should have done likewise.

One of the problems of reorganizing the NNI to prioritize accelerating the commercialization of nanotechnology enabled products, is that such a reorganization or reorientation may ignore or even disinvest in the public goods research, e.g. in infrastructure development, nano-informatics, EHS research or ELSI research that might result in commercialization delay. Governments have often invested in research that was too financially risky for most private enterprises to undertake, e.g. in the development of pharmaceuticals or cyber-infrastructure. NNI agencies should continue to perform this essential government function. Taxpayers financing NNI research should receive a public return on investment in the form of public goods, such as potable water and affordable medicines benefitting from robust EHS research. Nanotechnology return on investment should not be defined or calculated merely in terms of products brought to market, much less numbers of patents granted.

A mission defined as to simply serve the needs of the private sector, as defined by the private sector, to facilitate product commercialization will serve neither the NNI agency nor the academic or industrial entrepreneur well. NNI agencies should not only maintain a robust research agenda, but must invest in those areas of nano-science and ERS research in which the private sector is unable or unwilling to invest, including EHS and ESLI research.

A best practice for stakeholder engagement that NNCO and NNI agencies should do a better job with are the workshops at which products at an early stage of development are put to tests of how the products will affect consumers, the environment and the ethics of the nation.

Some NNI agencies have offered workshops to stakeholders on "Navigating the Regulatory Process." NNI agencies should also present workshops to share with product developers NNI agencies' EHS and ELSI research to help product developers anticipate and avoid EHS risks, e.g. taking advantage of NNI 'safe by design' research. The EPA has done this to some extent with its green chemistry program. NNI agencies need to do likewise.

Conclusion

ICTA thanks NNI for the chance to respond to the RIF to assist the NSET Subcommittee in drafting the Strategic Plan. We look forward to commenting on the draft Plan.

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Our Company Vision and Challenges

OpLet Corporation is a Seattle, Washington Nanophotonic device startup. Our vision is to pick up from where Moore's law leaves off and significantly contribute to the creation of optically supercharged high-speed modulation and computing devices comingled on die with CMOS. Unfortunately, we have been forced to do the research on our devices in Germany and Switzerland because groups there have access to very sophisticated fabrication facilities/processes at low prices and with quick turnaround.

The key to building nano-photonic devices is consistent very high-quality silicon fab work. What is optimal process for CMOS is not necessarily the optimal for nanophotonics. As photonics evolves there will be a growing divide between processes and architectures for photonics as opposed to those having been optimized for electrons. There are many shared user fab facilities around the US, for example the excellent NNCI facilities, in most all significant research-oriented universities.

The challenge of "Shared":

But, "shared" is the problem. The existing network of shared facilities is an impressive necessary foundation for exposing large populations of students and researchers to practical experience in a fab and creating mostly one-off devices. These facilities are also often made available to commercial users which helps fund the facilities. But, there is a lot of non-professional traffic through these facilities!

The problem with "shared" is a single piece of equipment can be used to process a diverse array of materials by operators with limited experience. Even the "Professional" staff does not have significant experience in high quality processes. This results in equipment contaminated or not well dialed into any particular process. Fine featured, repeatable work necessary for nanophotonics is difficult if not impossible to get from shared facilities via the hands of marginally experienced technicians. The result is student and research device designers "creative curiosity" is dramatically affected, modified, and compromised knowing what is possible and common in $B mass production facilities is not possible in shared facilities. A creative mind is expressed via available tool sets and so many device concepts that can be so elegantly modeled are not attempted due to fabrication issues.

In Europe there are many government-funded application-oriented research organizations including IMEC, Fraunhofer, IHP, Leti, VTT, and others who have professional staff and much more tightly controlled processes for nanophotonics. These professional staffs are not only many years highly experienced in the subtleties of operating equipment but more importantly are experienced in the subtleties of materials and techniques for delivering consistently high-quality devices.

As these European institutions have become aware of OpLet technology we have been actively courted by each previously listed organization offering facilities and access to grant and venture funding. The only requirement is for us to form a European Corporation which we regrettably are being forced to do. The other dramatic difference between the US and Europe is Europe has a vision for nanophotonics being a key to future computing and they have committed the continent to being a dominant player in this future. How does Europe beat or at least compete with the US? They early on establish a foundation in optical technology which will inevitably be the basis for next generation computing while the US tends to take the slow road still enjoyed the fruits of conventional electron based computing.

The US also has a spoken to this vision, for example AIM but AIM has a fundamental flaw. It is trying to be all things to all people and from my experience is not held in very high regard in many areas.

I don't know if the US should try to copy these high-quality European research institutions but if the US doesn't do something soon the Europeans will eat our optical computing lunch. They have commitment, highly skilled and equipped facilities and access to grants and venture funding.

Mechanisms

- What key elements and intersections are necessary to form an agile framework that will enable response to new developments along the nanotechnology continuum, from discovery and design to development and deployment?

"Shared" Solution:

I would propose a number of quick-turn rapid prototyping nanophotonic (NanoRP) fabrication facilities be established around the US with professional staff, a limited menu of deliverables but at repeatable production like quality and very quick turnaround. The key is to start with a short list of processes that a facility can deliver at very high quality in a very short time frame. As time and resources allow additional high-quality service will be added. Some facilities might quick-turn different types of devices or processes than other quick-turn facilities.

These need to be isolated from "Shared" lab facilities and designed specifically for nanophotonics and operated by many years experienced professional staff. In VTT-Finland they solved this shared problem by having physically separate facilities between shared and production level quality facilities. Production facilities in this context are not volume oriented but quality oriented which when necessary could be moved to volume production foundries. But the great majority of research devices never reach production but do require repeatable production quality device features to advance the science.

When low cost 3D printing became affordable a decade ago mechanical designers productivity skyrocketed. Clearly it did not do everything mass production molding, casting and CNC facilities could do. But it offered immediate real-world physical feedback to the designer which amplified their productivity. Presently nanophotonic designers have massive delays between idea and testable result. One cause of this delay is funding challenges since high quality device fabrication is very expensive often representing a significant percent of budget for a project. Even with funding the delays with shared runs can be months reducing the testing of ideas down to a single attempt instead of 5-10 attempts possible with rapid prototyping.

In many cases the growth of understanding the physics of a device concept is seriously stunted by being forced to run once or maybe twice in large scale facilities much like taking drivers training during a NASCAR race. Mistakes and design pivots should be affordable and survivable. New science discovery is amplified doing 10 device runs costing $5K with one week turn around than one run at $50K taking 6-12 weeks.

Mechanisms

- How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

Private?:

It is not clear if these facilities should be public or private. The advantage in being private companies is they would be required to deliver on time on budget or they will go out of business. In time there will be competition which adds to the sense of urgency and competitive advantage. They would actively promote their chosen narrow but “production quality” services. They can use profits to expand and improve services being demanded by customers. Their profits come from high volume not high margin infrequent runs. The precedent for the creatively enabling power of affordable quick turn-around can be seen in the story of 3D printers and quick turn printed circuits. Both brought prototyping to the masses not just to employees of large corporations and caused an explosion of new creative products.

Mechanisms

- How can the NNI participating agencies or NNCO best raise awareness among teachers regarding the educational resources that have been developed over the past 20 years and help get these resources into their classrooms?

Student Researcher Nirvana:

The goal is to change from current expensive many months turn around to easily affordable days turn around. This will likely not be quick-turn CMOS but would be effective for much simpler devices that now are forced to be included on much more complex process runs. In a sense there is a significant gap between shared facilities and shared wafer runs in big production foundries. NanoRP would start to fill this gap. Shared facilities force quality compromise in the name of cost and turnaround. Big production foundry shared wafer runs are like putting a jet engine on a Ferrari. Many of the foundry capabilities are not utilized for the prototype device runs other than repeatability.

With a NanoRP facility students can send in projects and get quick turnaround so the device design excitement is not drained off by extensive waiting not to mention prohibitive costs. PDKs for the NanoRP facilities will make it easy for students to mix and match devices which then can be quickly fabricated.

Free-Space Computing: What nanotechnology-enabled “moonshots” should be considered?

The photonic potential for high speed communication is clear and reasonably mature for long haul communication. The challenge for optical computing is orders more complicated. The fabrication challenges are immense for thousands to millions of optical devices on a chip to enable machine learning.. It seems a viable alternative is free-space optical systems. The key here is compact (5mm) SLM devices and a means to assemble a multi-stage system for complex ML and correlation tasks. Given the availability of free-space systems with hundreds of thousands or millions of parallel data paths efficient ML in datacenters and on the edge will be practical.

We would propose a “moonshot” be defined around free-space optical systems.

Thank you..Paul H. Nye

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Request for Information: National Nanotechnology Initiative Strategic Planning

Reponse from Rebecca Klaper, on behalf of The NSF Center for Sustainable Nanotechnology

Topics

What are the high priority open scientific questions in nanoscience and nanotechnology?

The ability to synthesize nanomaterials with control over atomic-level chemical compositions, surface chemistry, size, and shape represents one of the most important advances in the field of chemistry in the last 50 years. This ability has enabled new technologies for a sustainable world, including energy storage and solar energy conversion, improved catalysts, electronic devices, light emitting displays, chemical and biological sensors, and nano-enabled medicine and agriculture. The rapid expansion in commercial production of nanomaterials has prompted worldwide efforts to understand the implications of their intentional and unintentional release into the environment and interactions with biological systems. Studies on the first generation of nanomaterials to be commercially exploited (e.g., titanium dioxide, zinc oxide, silver, carbon nanotubes) have yielded many important insights about roles for nanomaterial properties such as size, charge, and shape on their environmental and biological interactions. Research has demonstrated that nanomaterials chemically transform in environmental or biological matrices, and that adsorbed molecular species such as organic acids, natural organic matter, or proteins can alter a nanoparticle's properties and can dictate interactions with biological systems.

While there has been significant progress towards identifying specific risks for the first generation materials many knowledge gaps remain (see Figure below from Klaper 2020). The characteristics such as charge, size, surface functionalization, chemical composition, and certain transformations are known to be important in determining the interaction of nanomaterials with biological systems and the environment. However, despite that knowledge we are not yet able to make generalizations of risk across nanomaterials. In addition, next generation materials that are more complex and may not have the same interactions as first generation materials and we have only begun to study these materials. In order to make broader generalizations across nanomaterials we need more data on the interactions of nanomaterials and organisms at the molecular level. We also need tools for measuring the dynamics of nanomaterial state and fate in complex matrices. Finally, there remains a significant need to determine how to best estimate exposure as we are still lacking enough tools for environmental monitoring and information on nanomaterials in products.

The nanotechnology sector is constantly evolving; new nanoparticle compositions exhibiting novel and useful properties are continually being developed and are moving towards large-scale commercialization. In many cases, these new applications actively address sustainability goals; examples include transition metal compounds used for energy storage and conversion, nanomaterials intentionally applied to deliver micro- and macro-nutrients to plants, and emerging 2D and "single-sheet" nanomaterials such as MXenes and metal chalcogenides for water purification and other applications. Many of these emerging nanomaterials have complex chemical properties that have not been widely investigated for potential roles in chemical transformations and biological impact, such as multiple oxidation states, 2D quantum size effects, and/or compositions that include elements widely recognized as inducing adverse biological impacts (e.g., Co, Ni). The unique chemical properties of emerging, high-volume nanomaterials lead to important knowledge gaps. For example, we are only beginning to understand how the intricate interplay between oxidation state, coordination environment, and reactivity govern the transformations of redox-active metal oxides. Even less is known about the role quantum size effects play in determining the reactivity of 2D nanomaterial. Addressing these knowledge gaps will require development of methods and instrumentation to characterize physicochemical properties of nanomaterials in realistic media such as natural waters or biological fluids, and experimentally validated computational models for predicting the chemical properties and biological interactions of nanomaterials in the environment.

Basic science that tackles the interaction of nanomaterials and organisms at the molecular and cellular level are still a key gap, particularly for the next generation of materials. Molecular information provides the foundation for developing predictions that can span materials. for modeling and predicting those interactions for new nanomaterials. Key challenges remain in linking the molecular level interactions to subsequent changes in biological function. More specifically research is needed on the interaction with biological entities such as membranes, intracellular molecular complexes, and organelles in intact cells; how these mechanisms of interactions are impacted by transformations of NM properties in complex cellular and environmental systems; and the nature of this molecular interaction for diverse organisms, populations and ecosystems.

Finally, without critical information on distribution and fate of nanomaterials within organisms and environmental compartments, proper estimates of risk cannot be made. Research is needed to improve metrology to understand what factors are important when considering dose and form of the nanomaterial, including corona formation and how that influences fate and effects even though that is not a common measure for other chemicals. We are on the verge of better methods for measuring NMs transport, dissolution, transformation and their breakdown products in complex cellular and environmental media and this research is a potential for growth in technology.

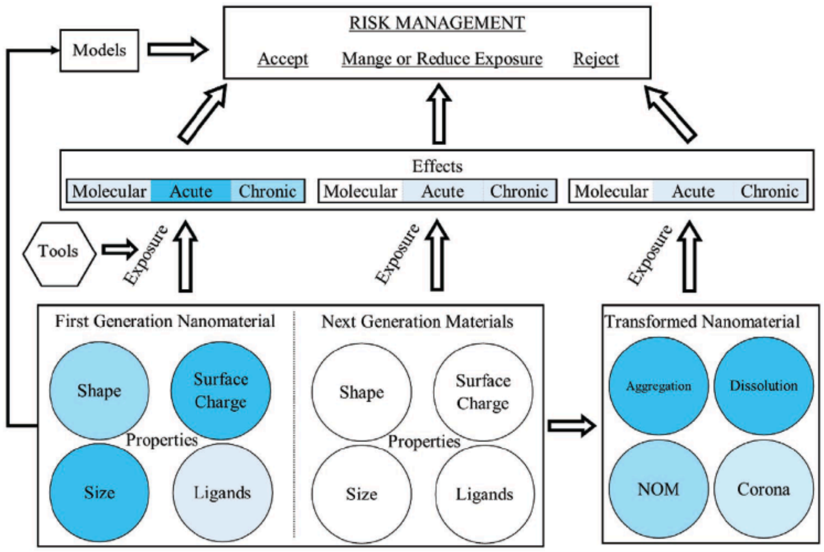

Figure 13. The known and unknowns that feed into determining potential environmental effects and risk. There is significant data related to properties of first generation nanomaterials that relate to the potential for environmental effects. However much less is known about future materials and how transformation impacts risk. In particular there is little information about the molecular impacts related to each of these characteristics that could provide the foundation for models of potential impacts of new nanomaterials without extensive testing. Tools for evaluating exposure to the environment are progressing but more investment is needed to provide an accurate picture of exposure. The darker the coloration the more information that is available to feed into assessing and managing risk.

R. Klaper. *SMALL* 16, 2000690

What nanotechnology-enabled "moonshots" should be considered?

Development of new tools for measuring the state of nanomaterials as they change over time and in different media and their interactions with biological systems at the molecular level would add to the technology portfolio of the NNI. These tools include computational chemistry, advanced imaging methodologies, '-omics' approaches, and other analytical tools to identify the key molecular mechanisms for predicting changes in biological function. Approaches are also needed for characterizing chemical properties of "non-ideal" NMs and how these properties transform after exposure to biomolecules or in the presence of environmental components such as natural organic matter. Overall, combined approaches that provide the ability to "zoom in" on a single NMs interacting with a lipid or protein or "zoom out" to biological processes that impact the function of the organism would accelerate nanotechnology discovery and research by enabling the development of predictive rules for design and synthesis of NMs with reduced environmental impact and new NMs that depend upon such interactions for the technology to be useful.

General molecular–scale questions that could be addressed by a "moonshot" approach include:

1. What is a minimal level of complexity needed in a model system (organism or ecosystem) so that the impact of NMs in more complex natural biological or environmental systems can be predicted? For example:

- What components are needed for a model lipid bilayer to faithfully represent the molecular interactions between nanomaterials and actual cell membranes?
- Can cells in culture be used to make predictions about how NMs interact in whole organisms?
- Is there some combination of organisms and environments that would enable reasonable predictions of how NMs impact ecosystems?

2. Can we identify early mechanistic changes (e.g., gene or protein expression patterns) that predict long-term biological consequences, beyond standard acute toxicity screening approaches and at levels that would not be detected using current screening tools? For example:

- Are there key molecular indicators of biological pathways that lead to predictable adverse outcome pathways that could then be associated with later stage disease due to nanomaterial exposures?
- Are there common pathways that are conserved across environmental organisms in their response to nanomaterial exposures, and are these pathways also relevant to human health?

What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)? What other tools are necessary to conduct nanotechnology R&D?

A key challenge towards building a framework for understanding and assessing the potential benefits or risks of nanotechnology is placing results from individual experiments into a broader scientific framework, since protocols often vary widely between studies (conducted by individual research groups) and most research groups specialize in one or two organisms / end-points or approaches (e.g. genomics). These challenges can only be addressed by multidisciplinary teams of scientists working towards understanding, predicting, and controlling how NMs and their transformation products interact with environmental and biological systems, such as computational and experimental chemists, molecular environmental scientists, and biologists. The vast scope of this scientific challenge requires a mechanism to coordinate the leveraged expertise and distinct capabilities of nanotechnology centers, including co-development of new technological advances and a combined focus on NMs that are relevant to commercial nanotechnologies being developed internationally. There remain several needs in this area:

- There is a need for coordinated efforts between multiple laboratories, even across disciplines, so that best practices can be developed. That way results from a single study can be compiled into a larger model that spans disciplines or research focus areas. An agreed approach to data management, data curation, and ontologies are an essential step here, requiring integration of bioinformatics and knowledge management networks with nanosafety networks.
- Understanding how nanomaterials behave within complex biological or environmental systems requires contributions from multidisciplinary researchers with widely varying expertise. In addition, the methodology for identifying and measuring nanomaterial components in real /

dynamic systems is still under development. Researchers focusing on chemical characterization and metrology have very different perspectives from biological or environmental scientists, but expertise in each of these areas provide important contributions that are needed to establish links between fundamental properties of nanomaterials and their ultimate impact on complex biological or ecological systems. In this case, linking the network of analytical chemists and environmental scientists with networks of nanomaterial scientists is crucial.

- Transcriptomics, proteomics, and other "omics" techniques offer potentially powerful tools for identifying biological mechanisms that are impacted at low level exposures that might not be evident based on standard toxicity screening approaches. Linking mechanistic biological changes to longer-term consequences of exposure will be critical for understanding the potential impact of nanotechnology across generations, and lessons learned would apply to human toxicity and ecosystem-level impacts. However the expertise and resources we have for using these tools, such as data related to gene, protein and metabolite annotations, and the best methods to do these experiments is distributed internationally and often resides in a single investigators laboratory. In addition they may have some nanomaterial related work but often are investigating other aspects of omics. Networks of nanoscience linking to networks of "omics" researchers in this case is ultimately necessary to take full advantage of these fields.

Response to the National Nanotechnology Initiative Strategic Planning RFI

Response submitted by:

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Mechanisms

Q1. What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?

The federal government support in 2000-2010 was exemplary and led the global nanotechnology research worldwide. However, by 2010-2015, that effort was significantly declining, and by 2020 the US is already behind nanotechnology R&D in most developed countries.

Q2. How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

The United States should take the lead again in nanotechnology R&D before we fall far behind. This will not happen by funding single investigators alone. There should be a focus on teams and centers; this is the only way to make significant progress. Also, applications such as utilizing advanced nanomanufacturing for making quantum devices and computing should be a priority moving forward.

Q3. What key elements and intersections are necessary to form an agile framework that will enable response to new developments along the nanotechnology continuum, from discovery and design to development and deployment?

Many countries have mechanism for bridging the great chasm between research and commercialization. The United States have tried to do this with the advanced manufacturing institutes which is a great start but the way they were managed did not meet the great expectations. There is a need to put teams together that will strictly address TRL 3-5 (the Adv. Mfg. Institutes only work with TRL 4-6) to commercialize many of the existing and future nanotechnology breakthroughs.

Q4. How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

The government needs to create partnerships to build new centers and/or institutes in partnerships with DoD, NSF and NIST and other agencies. Industry should participate and not lead (set agenda and priorities) these proposed institutes. In the past, setting agendas by industry has produced mixed results.

Q5. How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

Public private partnership is important but should have a good governance that some current advanced manufacturing institutes lack.

Q6. What are exemplary models (domestic or international) for accessing NNI resources, including user facilities and laboratories?

There are many international examples such as IMEC in Belgium (which was modelled after Sematech) that conducts state of the art R&D including many nanotechnology development besides conventional semiconductor fabrication. Another one is the Fraunhofer Institutes across Germany which is a very successful enterprise that's partially supported by the government. Besides the Advanced Manufacturing Initiative that created several institutes there are no domestic models that focus on commercialization of nanotechnology. The NNI based user facilities offer a great resource to nanotechnology researchers; especially the ones that serve many users although many are underutilized. Most of these facilities do not venture into making tools based on new nanotechnology breakthroughs for manufacturing and/or characterization. All of them use conventional technologies that do not enable researchers to make certain devices or even scale some of their existing nanotechnology based devices. There is a need for new facilities that will provide such equipment for the community.

Communication

Q7. How can the NNCO facilitate communication and collaboration throughout the nanotechnology R&D ecosystem to enhance research and ultimately commercialization? How can the NNI/NNCO best communicate opportunities, resources, and advancements to the community? How can the NNI/NNCO best engage with the stakeholder community to understand their advancements and needs?

The NNCO does a good job providing information on different activities at agencies and academia. However, that is not sufficient. The NNCO should engage the community through conferences and workshops that are focused on future applications that utilize nanotechnology. The goal of these workshops should be to showcase the breakthroughs and try to build nano applications through convergence of the different technologies by facilitating interactions between researchers from academia, government, and industry.

Q8. Beyond the media platforms used by NNCO, what additional means should be considered to better reach the public and various stakeholder groups?

Interaction between researchers is essential for making progress among stakeholders. Workshops and panels focused on the convergence of technologies for applications that utilize nanotechnology will be the most effective way to do that.

Q9. What are effective strategies for improving communication of desired nanotechnology workforce skills and capabilities between industry and academia?

Workshops and panels focused on the convergence of technologies for applications that utilize nanotechnology. This could be done through ideation workshops which work very well since they allow ideas to emerge based on capabilities.

Q10. How can the NNI participating agencies or NNCO best raise awareness among teachers regarding the educational resources that have been developed over the past 20 years and help get these resources into their classrooms?

Most of the efforts by the NNI various grantees and NNCO focus on designing programs that provide education using different methods of delivery and then delivering these program to teachers, etc. From my experience, teacher's input from the onset is essential and could determine whether such a program will be successful or not. It is not about only using experts in education at academic institutions but getting the teachers k-12 to have a say of what and how nanotechnology related materials are introduced.

Topics

Q11. What are the high priority open scientific questions in nanoscience and nanotechnology?

As 2020 has shown and as the news of local electronics manufactures shown that the US is falling far behind competitors in manufacturing most advanced electronics, even though all of the technology was developed in the US. The current semiconductor manufacturing technology is very expensive and presents a significant barrier (as explained in the answer of Q12 below) to the development of new and innovative technologies. The NNI has funded nanomaterials based nanomanufacturing at several academic institutions (NSECs that were focused on manufacturing). These nanomaterials based additive nanomanufacturing techniques have shown that it is possible to make nanoelectronics at a cost reduction of 10-100x, materials reduction by up to 1000x at room temperatures and pressure while eliminating high energy deposition and etching processes and eliminating 100s of process steps. In addition, since these new manufacturing technology are not material dependent, they will allow the designer to use any material that gives them the best performance.

Q12. What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

Funding for nanotechnology based nanomanufacturing that will enable the on-shoring of electronics and medical device manufacturing and put the US industry in the global technological lead. A significant barrier to innovation is a lack of affordable access to fabrication foundries. Current top-down processes require facilities costing over $16 billion. The massive amounts of water and power required to operate a fabrication facility have a major environmental impact. A typical plant uses as much energy in a year as 50,000 homes. Current semiconductor manufacturing processes necessitate high-energy input, vacuum environment, high temperature, highly corrosive and toxic chemicals, and cost $1 billion per year to operate. The future of electronics manufacturing belongs to emerging bottom-up nano-scale directed assembly techniques of material into useful devices.

Q13. What nanotechnology-enabled "moonshots" should be considered?

Recent transformative manufacturing technologies that utilize the precise control of nanoscale particles or other nanomaterials at room temperature and atmospheric pressure to precisely place materials where the structures need to be built. This is accomplished by understanding how to control the forces and surface interactions at the nanoscale through directed assembly using fluidic, interfacial, electric, bio or magnetic forces. This enables the creation of aligned multilayered 2D and 3D structures of any desired material or geometry down to nanoscale structures. Such a nanomanufacturing technology should have the following:
Print crystalline structures for metal and semiconductors at room temperatures.
Reduces materials use by up to 1000x;
Reduce cost by 10-100x
High-throughput: can print one layer per minute on wafers at the nano or microscale
Eliminating high energy deposition processes such as CVD, PVD, ALD, etc.
Eliminating 100s of process steps;
Expanding material choices for specific design needs.

Q14. How does nanotechnology support other foundational fields/initiatives? What future technical topics are likely to emerge from advancements in nanotechnology?

Nanotechnology will be the enabler to new areas that are being pursued currently by the US and globally such as quantum devices, sensors and computing in addition to new electronics that will supports Artificial Intelligence. Nano materials based nanomanufacturing allows researchers to use novel materials in various geometries and on various substrates that are not possible using conventional fabrication processes.

Q15. What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)? What other tools are necessary to conduct nanotechnology R&D?

There is a need to explore nanomaterials based nanomanufacturing that is more robust and not material dependent compared to conventional nanomanufacturing to democratize nanomanufacturing and allow the use of various materials and substrates.

Q16. What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

One technology that was supported by the NNI from 2004-2014 and results in tens of patents is a nanomaterials based transformative nanomanufacturing technology. This technology utilizes bottom up directed additive approach that utilizes the precise control of nanoscale particles or other nanomaterials at room temperature and atmospheric pressure to precisely place materials where the structures need to be built. This is accomplished by directed assembly of particles or other nanomaterials. This requires the understanding how to control the forces and surface interactions at the nanoscale through directed assembly using fluidic, interfacial, electric, bio or magnetic forces. This enables the creation of aligned multilayered 2D and 3D structures of any desired material or geometry down to nanoscale structures.

The advantage besides extremely low cost, environmentally friendly compared to conventional nanofabrication is providing device designers and researched to use a variety of materials and processes that are not possible using conventional approaches. Expanding material choices for specific design needs allows the designers to take a full advantage of the novel and unique properties of existing and/or future nanomaterials.

Q 17. As concepts surrounding responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?

Much good work has been done on responsible development which is definitely needed but we need to fund development before we can practice responsible development.

Raytheon
BBN Technologies

Request for Information Response: National Nanotechnology Initiative Strategy Planning

Organization: Raytheon BBN Technologies

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This response is written based on the author's research experience, mostly on 6.1 projects, as Principal Investigator in both academia and commercial industry. Specifically, the author is addressing these observations:

1. Most of the research is only taking place in academia and government, in sharp contrast to the past when researches were also conducted in large fractions in commercial industry, such as General Electric, Ford Motor, Philip Research, Xerox, Bell Laboratories, IBM, etc.
2. The rising capital cost in research has limited the possibility and potential of a more vibrant research and development ecological system.

Actions can be taken by NNI to flatten the field to foster a more healthy growth of nanotechnology for the prosperity of Americans.

1. Mechanism: How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

While the academia-industry-government collaboration is encouraged, the natural barrier to an efficient cooperation between the institutes remains insurmountable. A prime example of the collaboration barrier is the Research Agreement, a document that details how should the intellectual property be assigned or how should the insurance be covered when a collaborator working in the laboratories of other team members. Due to lack of standardization, the negotiation between contract offices can take months, if not years. Obviously, small businesses cannot even afford this at all.

Furthermore, the rising capital cost has been forbidding most businesses from the research and development in nanotechnologies. Although there are user facilities in national laboratories, the day-to-day research activities to fabricate nanoscale devices are located in cleanroom facilities. Currently, there is steep price discrimination in cleanroom services for non-academic users based on the assumption that the commerical industry is making profits. This price discrepancy can amount to more than a 300% increase in usage fee. Unfortunately, the research and development usually takes years before commercialization. This has created another insurmountable barrier for industry to participate, especially for smaller organizations, in the rise of nanotechnologies because the cost of research is abnormally high for industry to use cleanroom facilities run by universities. As a result, industry can only focus on research that can bring short term profit, and small research groups may be prevented from participating entirely.

If we believe the role of the government is to level the field and provide opportunities for all practitioners, some terms will need to be built into the contracts of the funding to foster the collaboration of industry and academia. Otherwise, the frequently used term, “technology transfer”, is merely a slogan that could not be implemented in practice.

2. What are exemplary models (domestic and international) for accessing NNI resources, including user facilities and laboratories?

One of the exemplary models of a joint venture between academia and industry research is Low Noise Factory and its foundry in Chalmer University in Sweden. Originally, the key products of Low Noise Factory, the low noise amplifiers (LNA) in microwave frequencies, were only produced at Caltech in the USA. For decades, they have been the essential instruments in radio-astronomy. However, with the rise of quantum technologies, they have also become the working horse of measuring superconducting qubits and, more recently, in various detectors for faint chemical traces and infrared photons. These high sensitivity amplifiers rely on transistors made in the foundry in the US initially. While the commercial foundry has little incentive to improve the cryogenic performance of these transistors, academic facilities have little reason to allow industrial research in their facilities at a reasonable rate. However, the deadlock has been broken between Low Noise Factory and Chalmer University by Swedish government acting as the deal moderator. They are now producing some of the best LNA in the world and have overtaken the leading role of the US in this important future technology that has wide applications. This over-simplified story above is to illustrate the importance of academia-industry-goverment collaboration in optimally utilizing the research infrastructure and in reducing capital cost of performing nanotechnology research here in the US.

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… on behalf of the *NanoFabNet* Project[1]

NanoFabNet
international Hub for sustainable industrial-scale Nanofabrication

To: *NNIStrategicPlanning@nnco.nano.gov*

Brussels, 9th November 2020

Subject: **RFI Response: NNI Strategic Planning**

Background:

The ***NanoFabNet*** Project is one of two projects awarded funding under the European Union's Horizon2020 Programme's 2019 solicitation on sustainable nanofabrication intended to *'establish industrial-scale manufacturing of functional systems based on manufactured nanoparticles with designed properties for the use in semiconductors, energy harvesting and storage, waste heat recovery, medicine, etc.'*, as quoted on page 25 of "A Quadrennial Review of the National Nanotechnology Initiative"[2]. The ***NanoFabNet*** Project will create a strong international hub for sustainable nanofabrication, whose structure, business model, detailed strategies and action plans are designed, agreed and carried by its international stakeholders during the Project duration, in order to yield a self-sustaining collaboration platform: the *NanoFabNet* Hub.

In support of the international nature of the *NanoFabNet* Hub, the Project Team[3] includes two strong US Partners: **Virginia Tech** and **Georgia Tech**, and the Project's External Advisory Board (EAB) includes representatives from the University of South Carolina (US), the Japanese National Nanofabrication Platform, the EU's EuroNanoLab Initiative, as well as large industry and SMEs.

[1] *NanoFabNet* has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 886171.

[2] A Quadrennial Review of the National Nanotechnology Initiative - Nanoscience, Applications, and Commercialization (2020).

[3] The ***NanoFabNet*** Project is a 24-months coordination and support action (CSA), co-funded under the European Union's H2020 Research and Innovation Programme in the area of Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing (NMBP). The *NanoFabNet* Project is coordinated by AcumenIST (AIST) and supported by 14 other partners (Karlsruhe Institute of Technology (KIT), Institut Catholique d'Art et Metiers (ICAM), BioNanoNet Forschungsgesellschaft (BNN), Laboratoire National de Métrologie et d'Essais (LNE), CEITEC Brno University of Technology (CEITEC), Steinbeis 2i (S2i), Luxembourg Institute of Science and Technology (LIST), Fundacja Wspierenia Nanonauk I Nanotechnologii (NANONET), COPT @ University of Cologne (COPT), MateriaNova (MANO), Consiglio Nazionale delle Ricerche (CNR), Norges Teknisk-Naturvitenskapelige Universitet (NTNU), Virginia Tech Applies Research Corporation (VT-ARC), Georgia Tech Research Corporation (GTRC)) from 9 European countries (Belgium, Germany, France, Austria, Czech Republic, Luxemburg, Poland, Italy, Norway) and the United States.

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Mechanisms

What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?

With the inception of the NNI in 2000, the US federal Government has established one of the first national strategies in nanotechnology worldwide, and repeatedly renewed and maintained this strategy as a decidedly ring-fenced "technology-push" policy much longer than most other countries and regions.[4] Over the course of the last two decades, the amount of funding across the NNI's participating departments and agencies has changed in both relative and absolute terms, but the NNI today remains one of the last and longest-running nanotechnology-specific strategies.

How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

The *NanoFabNet* Project supports the Quadrennial Review's recommendations calling for an increased focus on nanotechnology as a responsible, enabling technology in support of federal research and development priorities (currently incl. security, artificial intelligence, quantum information sciences, manufacturing, bio-based materials, water, climate change, space travel, exploration, inhabitation, energy, medical innovations, and food and agriculture) (Key Recommendation 1); special attention should be given to supporting the development of future sustainable methods of manufacturing and strengthening fabrication and characterisation facilities (Key Recommendation 3), especially through investment in infrastructure (maintenance).

What key elements and intersections are necessary to form an agile framework that will enable response to new developments along the nanotechnology continuum, from discovery and design to development and deployment?

The Quadrennial Review already identified and discussed the main parameters that should be strengthened, in order to provide medium- and long-term continuation of the NNI as a successful R&D driver:

- Re-focussing of nanotechnology as an 'enabling' technology that helps to advance other, priority-oriented science- and technology-disciplines,
- Investment in and support of technology-transfer initiatives, industrial pilot-lines and scale-up facilities,
- Increased efforts to attract, train and retain the best students to *'studies in relevant nanoscience/nanotechnology science, technology, engineer ing, and mathematics disciplines to ensure a diverse world-class workforce to support U.S. national interests and security, including via public-private partnerships that support student fellowships'*, and
- Investment in the development of new and the maintenance of existing infrastructures, fabrication and characterisation facilities.

In addition, the *NanoFabNet* Project would like to urge the NNI to consider the re-establishment of international collaborations (both public-to-public (P2P) and public-private-partnerships (PPP)) as a means to support all of the abovementioned factors.

[4] **Trend-analysis of science, technology and innovation policies for BNCTs**, S. Friedrichs, (2018), OECD Science, Technology and Industry Working Papers, 2018/08, OECD Publishing, Paris. http://dx.doi.org/10.1787/1566a6ce-en.

How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

The OECD Testing Programme of Manufactured Nanomaterials[5] is a good practice example of long-term collaboration between stakeholders in industry, academia (i.e. characterisation- and test-laboratories), environmental NGOs and CSOs, labour organisations, as well as the nanotechnology standardisation community (e.g. ISO/TC 229). For over 13 years, this initiative has been working towards informing the future uses and safety concerns of manufactured nanomaterials, in order to advance their R&D and market access in a responsible, collaborative manner.

What are exemplary models (domestic or international) for accessing NNI resources, including user facilities and laboratories?

The *NanoFabNet* Project has been funded in order to establish a viable model pertaining to the same question; the Project proposes to target the following specific impacts:

- Integrate nanoscale building blocks into complex, large scale systems that will become the basis for a new European high-value industry,
- Link and consolidate existing infrastructure, create a sustainable community of stakeholders managing information and communication within and outside the group and develop an EU-wide research and innovation strategy,
- Establish a network of existing EU funded projects and initiatives, which will solve common issues through cross-project collaboration, and will strengthen technology take-up across Europe, and
- Establish international cooperation in particular with the nanomanufacturing programme of USA-NSF and the NNI Signature initiative of Sustainable Nanomanufacturing.

An existing excellent model for the alignment and sharing of infrastructures is the EuroNanoLab Initiative - a new distributed research infrastructure consisting of over 40 state-of-the-art academic nanofabrication centres across Europe.[6] In addition, the National Nanotechnology Coordinated Infrastructure (NNCI), which the *NanoFabNet* partners Virginia Tech and Georgia Tech are a part of, comprises the most comprehensive set of networked facilities for nanoscale fabrication and characterization in the United States. NNCI typically assists more than 13,000 research users annually from 200+ academic institutions, companies from start-ups to international corporations, and government labs.

[5] OECD Testing Programme of Manufactured Nanomaterials
[6] EuroNanoLab Initiative

Communication

How can the NNCO facilitate communication and collaboration throughout the nanotechnology R&D ecosystem to enhance research and ultimately commercialization? How can the NNI/NNCO best communicate opportunities, resources, and advancements to the community? How can the NNI/NNCO best engage with the stakeholder community to understand their advancements and needs?

Beyond the media platforms used by NNCO, what additional means should be considered to better reach the public and various stakeholder groups?

The *U.S.-EU NanoEHS COR (Communities of Research) Workshop: Bridging Insights and Perspectives*, held on the 16th and 17th September 2020, was a well-received and much praised example of lively and constructive engagement within the community. Professionally organised and hosted by the NNCO, the workshop brought together a large number of experts from various disciplines pertaining to nanosafety and beyond, and encouraged and supported a detailed exchange (both between and within the US- and the EU-communities) of recent advances, current challenges and future research plans.

The *NanoFabNet* Project would wish for more events organised in this fashion; future events could allow a topical focus (e.g. the CoR in sustainable nanomanufacturing, since this topic could not be covered during the abovementioned CoR workshop). It needs to ne noted, however, that face-to-face events are necessary prerequisite to successful networking and possible collaboration and value creation; online-events should remain to be used as back-ups or added functionalities to face-to-face meetings.

The NNI should furthermore consider the implementation of the Quarterly Review's Key Recommendation 5, pertaining to the strengthening of the Nanoscale Science, Engineering, and Technology Subcommittee and the National Nanotechnology Coordination Office (NNCO), in order to guarantee the continuation of its important organisational, coordinating and convening role. As soon as the *NanoFabNet* has been established and registered as a not-for-profit organisation (anticipated incorporation date: October 2021), *NanoFabNet* would be delighted to establish the recommended partnerships with the NNCO; until then, the Project can take the role of a partner in a limited capacity.

What are effective strategies for improving communication of desired nanotechnology workforce skills and capabilities between industry and academia?

How can the NNI participating agencies or NNCO best raise awareness among teachers regarding the educational resources that have been developed over the past 20 years and help get these resources into their classrooms?

While the NNCO has developed some innovative teacher nanoscale science and engineering (NSE) resources (such as annual contests), distribution could be accelerated through partners such as the NNCI and NACK network which reach large numbers of teachers. Likewise, the NNCI and NACK resources should be shared by NNCO.

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Topics

What are the high priority open scientific questions in nanoscience and nanotechnology?

Over the past years, nanotechnology has increasingly established itself as a problem-solving technology, whose enabling character is specifically well-suited to improve existing technologies (e.g. with regard to their raw-material resource efficiency, energy-consumption, or their reliance on solvent-based processes) in an evolutionary fashion, and provide step-changes to advancement of new technologies (e.g. the introduction of graphene as a novel material) in a revolutionary fashion.

High priority should therefore be given to (a) the integration of nanotechnology-based solutions into other technologies, (b) the technology-transfer and scale-up of established processes with a specific view to advancing complex, large-scale systems that will become the basis for new high-value industries, and (c) the long-term support of nanoscience and nanotechnologies and their resulting products and processes through technology validation, harmonisation and standardisation activities.

What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

What nanotechnology-enabled "moonshots" should be considered?

As outlined under '***Mechanisms***' (see above), the *NanoFabNet* Project supports Key Recommendation 1 of the Quarterly Review; specific 'moonshots' could be based on targets pertaining to the current priorities of bio-based materials (e.g. circular economic use of a minimum percentage of bio-products and wastes of agricultural processes, or minimum percentage of circularly-sourced secondary raw materials to replace fossil-based materials), climate change (e.g. carbon neutrality of specific processes of regions), or medical innovations.

What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)? What other tools are necessary to conduct nanotechnology R&D?

One well-recognised problem affecting the fabrication, characterisation, and modelling and simulation tools of nanoscience and nanotechnology is the increasing cost of these highly specialised tools in the absence of adequate facility-sharing collaborations and 'virtual infrastructure' models, one specific problem noted by the NNCI is the lack of funding for replacement of 'work-horse' tools and equipment which make up the large majority of the user facilities, while funding is often reserved for the latest, state-of-the-art tools.

The *NanoFabNet* Project aims to devise models to tackle the abovementioned problem; a collaborative approach in partnership with the NNCO would be most welcome.

What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

Public-private partnerships (PPPs) help to overcome the problem of increasingly costly laboratory infrastructures; especially highly-innovative SMEs are often hampered during the proof-of-concept and scale-up phases, if the necessary fabrication, characterisation and modelling tools are prohibitively expensive. PPPs should focus on providing access (e.g. innovation vouchers) to SMEs that are financed either though public means or through private, pre-competitive collaboration networks (arranged by research topics); Open-Innovation Test-Beds are ideal infrastructures for such pre-competitive collaborations.

As concepts surrounding responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?

The concepts of 'trust', 'transparency' and 'participatory decision-making' represent some of the most prominent examples of the responsibility of any process. Within the context of science, technology and innovation, the conducting party (i.e. the scientist, technologist, engineer, product developer, trader, formulator, regulatory risk-assessor, etc.) is advised to be prepared to answer to these principles at every step along the value-chain, without jeopardising confidentiality, intellectual property or trade secrets. The most recent concept that was developed for nanomaterials and that is now also applied to other emerging technologies (e.g. synthetic biology, gene editing, etc.) is that of 'Safe-by-Design' – a collaborative approach, during which innovators and regulatory risk-assessors approach the 'uncertainties' pertaining to a new nanotechnology-enabled product (or process) through the exchange of knowledge and the problem-based learning process of improving both the product or process and the risk-assessment process that is able to allow it (and following similar products and processes) onto the market as 'safe (within foreseen use)'.

In a broader context, the 'responsible development of nanotechnologies' also includes the consideration of all aspects of sustainability, and both scientist, innovators and product-developers are well-advised to adhere to such concepts, in order to assure their customers, who have the final say about the success of a process or product.

The *NanoFabNet* Project is currently in the process of defining those aspects of sustainability that are specifically important to high-tech nanotechnology and nanofabrication.

Christina M. Sloat

November 9, 2020

Considering "Covid-19", a Brief Response to **: Request for information: National Nanotechnology Initiative Strategic Planning**

A key problem to the US's response to the "CoVid-19" situation is that there has been much oppression of free speech regarding a sudden worldwide "outbreak" of illness and death. Fortunately, however, we live on a planet that is orbited by telecommunications satellites, and covered with quantum servers that can easily communicate with one another and with our wireless laptops and phones, and thus discussing this wildly free-ranging (apparently), and, purportedly, wildly contagious "virus", candidly and unreservedly, should be quite easy to do. However, as many can attest, both private and public ponderances, contemplations, or ruminations on how and why this "virus" has required extraordinarily serious measures has not been considered welcome or socially acceptable in many online communities. It has not been possible to invite any speculation or suggestion that ingestible and injectable technologies, spread by processed foods, GMO's, beverages, and intentionally planted (poisonings during restaurant and home invasions or breaking and entering) that receive and send wifi signals. Developments in nano-neurotechnologies (w/transistors, transmitters, transducers, electrodes, which can destroy neural tissue and cause confusion, memory loss, hearing loss, and loss of taste), miniature silicon particle accelerators, the enzymes, GMO's and nano-optics that allow for in-vivo gene editing; ingestible and injectable biosensors that can sense viruses, and nanotechnologies (shells) as protein/virus carrier.

Considering the above, how can the NNI meet its purported #4 goal, to support responsible development of nanotechnology?

It does not appear that the National Nanotechnology Initiative has openly involved the appropriate agencies and the appropriate researchers in considering and investigating the likelihood of nanotechnologies that allow for wifi contact, such as nano-routers, nano-mirrors, nano-laser, that channel or create light, and that can be used in conjuction with other nanotechnologies, to cause cellular cascades or bio-chemical events, such as pleurisy and neural apoptosis.

The NNI might do well to push for an increased role for the FDA: were there more public awareness and discussion, there would be a public demand for foods free from anything that might play a significant role in a malicious nanotechnology cocktail or assembly, particularly commonly ingested additives such as silicon dioxide, silicon, titanium dioxide, gold, cellulose, cellulose gel, et.al. which might serve as a carrier or scaffolds for nanotechnologies that could be assembled in the body, creating devices meant to destroy cells, alter genomes, identify, import, exacerbate, or incite viruses, disease or illness.

nano-routers, nano-mirrors, nano-lasers

TO: NNI Staff, RE: **Request for Information: National Nanotechnology Initiative (NNI) Strategic Planning**
This is a reminder that the Nanoscale Science, Engineering and Technology (NSET) Subcommittee is seeking public input to inform the development of the 2021 National Nanotechnology Initiative (NNI) Strategic Plan. A restructuring of the NNI is under consideration, and the NSET Subcommittee seeks feedback from the community to help identify effective mechanisms, strategies for communication, and priority topics to shape the future directions for the initiative. Full information on the Request for Information (RFI), including detailed instructions, is available here.
Responses are requested by 11:59 pm ET today. Please submit responses via email to NNIStrategicPlanning@nnco.nano.gov and include "RFI Response: NNI Strategic Planning" in the subject line.
Thank you for taking the time to respond to this Request for Information. Your input is appreciated.

FROM: The Work Health and Survival Project RFI Response: National Nanotechnology Initiative (NNI) Strategic PlanningWashington, DC 20024
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How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement

STATEMENT OF INTEREST

WHS gladly offers potential partnerships, coordination, and management mechanisms to advance nanotechnology research and development. Throughout two decades of research and stakeholder participation in the development of nanotechnology law and policies the WHS moral compass has been the question:

How can the benefits of nanotechnology be realized while minimizing risk?

To this end the Work Health and Survival project has self-funded without any financial assistance whatsoever its participation in the US-EU COMMUNITY OF RESEARCHERS since 2011. The Work Health and Survival project, (WHS) founded in 1999 has addressed legislative questions in the USA at the state, federal and municipal level, and the United Nations agencies and in several foreign nations including Denmark, France, Switzerland Portugal and Japan at various levels of government. This testimony supports the work that has followed USA National Institute of Occupational Safety and Health (NIOSH) Public Comments regarding Carbon nanotubes and nanofibers (2011) "LEGAL BASIS AND JUSTIFICATION: NIOSH RECOMMENDATIONS PREVENTING RISK FROM CARBON NANOTUBES AND NANOFIBERS" and WHS on behalf of several stakeholders comments to the World Health Organization (2012) Stakeholder Comments for UN Background Paper, WHO Guidelines on "Protecting Workers from Potential Risks of Manufactured Nanomaterials" (WHO/NANOH), on Behalf of the Work Health and Survival Project Geneva Switzerland March 2012; Stakeholder

Comments to the USA Executive Office of The President of the United States Office of Science and Technology Programs, (OSTP) National Nanotechnology Initiative (NNI) proposing the Grand Challenge to Eliminate or Reduce Maternal Mortality During Pregnancy and Childbirth on behalf of the Work Health and Survival Project Sept 2016; (published in BAOJ Nanotechnology 2016) UN Special Magazine, March 2011, « Forecasting Nano law » p 36-37 (Doctoral thesis proposal in international relations, about regulatory dilemmas for emerging risks) Bulletin electronique, Ambassade de France « Politique scientifique Gestion des risques liés aux nanotechnologies Cooperation UE Etats-Unis. assembly.coe.int/nw/xml/News/News-View-EN.asp?newsid=5892&lang=2&cat=133 Law and Science of Nanotechnology: Perfect Together? ON YOUTUBE Museum of theHistory of Sciences, Park Perle du Lac, Geneva Switzerland Aug 17 2013 A Bi-lingual PublicDiscourse about Emerging Technologies Ilise L Feitshans JD and ScM Nanotechnology: Science Protecting Public Health, the book Global Health Impacts of Nantoechnology Law (Panstanford 2018) and the official report of the Parlimentary Assembly of the Council of Europe, 2013, "Nanotechnology: Balancing benefits and risks to public health and the Environment" available on the web free of charge in English French Russian and Spanish and subsequently accepted unanimously http://assemblycoeint/ASP/NewManager/EMB_NewsManagerView.asp?ID=8693&L=2.

I. Looking Backwards to Look Forward: TWENTY YEARS OF NNI MISSION

The NNI has made an impressive imprint shaping the future of humanity in the two decades of its existence. Nanotechnology programming was but a twinkle in the eye of legislators when the program was established, and now nanotechnology devices, nano-enabled commercial products, and nanotechnology research and training are ubiquitous throughout society. Promising new medicines, strong packaging to protect goods from contamination, cheaper consumer products and new commerce from their trade, nanotechnology has been heralded as a revolution, « likely to change the way almost everything – from vaccines to computers to automobile tires to objects not yet imagined".

This prescient comment in the 1999 NNI report to the President of the United States was written by people who did not know about the 2020 pandemic of Covid-19, but its language made room for attacking the problem. Envisioning international use of nanomaterials in the 21st Century forecast a global impact "at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century".

NNI has played a pivotal role in fostering and advancing a dynamic nanotechnology ecosystem in support of the initiative's four goals: advance world-class research, foster commercialization, develop and sustain research infrastructure, and support the responsible development of nanotechnology. Building on this strong foundation, experts across the nanotechnology community shared their views about the key elements required for the nanotechnology discovery and innovation to thrive in the years ahead. Small things add up: millions of products applying nanotechnology, sold globally for over a decade represent a huge slice of daily economic life expected to represent $14 trillion within the next 2 years. NNI' s illustrious achievements inevitably raise the question whether the job is over, now that nanotechnologies have been launched in almost every university and many high school programs, and are applied in outer space, health care, defense, aviation, small and middle sized industries, and in personal care products and foods. Now that nanotechnology reaches from cosmetics to the cosmos, is the Mission over***; should the initiative fold up the tent and accept congratulations for a job well done?*** Is that enough?

II Filling the Gap With On the Ground Stakeholder Input

The National Academies was authorized to issue a report in 2020 offering analysis and recommendations to the NSET Subcommittee of the National Science and Technology Council and to NNCO. The National Academies of Sciences, Engineering, and Medicine sought community input for the quadrennial review of the NNI, with a view to understanding the relative position of the United States nanotechnology research and development compared to other nations, identify critical research areas where the United States should be the world leader,. New or revised goals for the NNI; New research areas and technical priorities for the future. Potential partnerships, coordination, and management mechanisms to advance nanotechnology research and development and consider whether the NNI should continue.

Whether NNI should continue is a fair question during a global pandemic when millions of professionals are unemployed to to collapse of économies worldwide from pandemic disruptions causes by covid19. The unfinished work of outreach and public engagement through small stakeholder organizations such as the work health and survival project holds the key to determining whether a reorganized NNI can or should continue along a path to achieve its clearinghouse Mission. ***The path ahead is all but uncertain in the Era of the Covid19 pandemic of 2020. The key policy décision whether NNI should continue must be weighed on light of several factors. It can be assumed for example that big data, ai and a variety of nanoenabled genetic technologies no longer need NNI information support and institutional backing. These impressive achievements have lived from proof of concept to commercialisation and there have a very sécure future funding path and will take on a life of their own.*** Although larger big picture items have been achieved, there is a dearth of public awareness about nanotechnology, its usés, benefits and risks in daily life even though nanoenabled applications permiate every facet of civil .society.Therefore the pivotal discussion that must be had concerns public awarènes dissémination and outreach. As this stakeholder organization is here before you to testify, outreach to stakeholderscompletely hacking in the NNI track record. Furthermore stakeholder engagement involving groups such as our Work Health and Survival Project is far more complex and multidimendional than the straight line analysis of broadcasting information to the public and then occasional asking for focussed information in a survey. A sad and expensive opportunity cost is dérive from using this woefully inadequate straight lune approach-- an old approach that is as self-serving and disrespectful of stakeholder views as a resource for new ideas and vital creativity as it is antiquated

OUR WHSvision for what nanotechnology research and development can enable over the next 15 years is instead completely dépendent upon significant stakeholder participation as NNI has never encourage before. Not merely asking for information or surveying multithousand member groups but gojng to the grass roots and including the Work Health and Survival Project at the decisionmaking table. The first step for the future is to look back carefully with a critical review of achievements and weak spots in the strategy as it was eventually implemented. This approach is not typical for USA agencies but in Europe, especially in France, there has been a call for a pause in new deeper research in favor of reviewing the nano-enabled applications to commercial products and the so-called “Lab to Market” approach to nanosafety for workers consumers and end-users such as commercial stakeholders as well as the general public. This approach enables gaps analysis of crucial life cycle questions regarding the use and disposal of nanoproducts, their possible alternative benefits and new uses and recycling of nanoproducts. This approach also embraces public health studies for long term epidemiology and short terms clinical applications of nanomedicinesAfter such review WHS expects that NNI will successfully create strategies to approach new areas and technical priorities.• WHS views of New research areas and technical priorities for the future.New research must integrate the law and regulatory framework that has emerged over the past two decades. There is no longer any question whether we in civil society should regulate nanotechnologies, nor is there any question how to do so. A decade ago these questions were vibrant but these questions have been answered in part under the auspices of NNI in the past 15 years. People around the world, however, cared about whether nanotechnology might unleash new harms as easily as it generates new bones and strong packaging for food fungible items and strengthens steel in buildings airplanes drones cares and trains.Consequently the world of nanotechnology law has proliferated like mushrooms with rules regulations and laws appearing everywhere at the local, municipal national sub-national multinational regional and international level. Creators of such laws range from well established federal governments and the EU and treaty bodies such as the OECD to private sector groups such as ISO and a variety of trade organizations. Even the WHO has offered guidelines for workplace exposure to nanomaterials despite the absence of a clear and direct correlation between workplace exposure and adverse health outcomes, having a structure in place in anticipation of potential harms. The latter is a revolutionary preemptory application of precautionary principles not previously seen in global law. But it may bode for nanotechnology laws of the future. Therefore it is not surprising that the EU has created three tracts for exploring Nanotechnology Risk Governance Council or related adjudicatory bodies for complex science questions that must be addressed under law. WHS Executive Director Dr ilise Feitshans is proud to serve as Legal Advisor for the European Commission for one such tract, NANORIGO.

III Nanoregulation Trends: Laws and Guidelines Shaping Global Health

Nanomaterials are ubiquitous in daily life worldwide: nanostructures in food, cosmetics, packaging, 3d printing, vaccines and medical equipment, and communication for telehealth and remote learning[1]. During the 2020 pandemic of Covid19 nanotechnology-enabled devices have been a vital source of information about patients for governments and caregivers, and a lifeline for isolated people. How science and laws interact is a complex but important facet of regulation and policy. Add to this governance admixture the definition of Covid-19-- a moving target whose definition has changed several times throughout 2020. This article discusses how nanotechnology under laws called Nanoregulations can transform disability INTO HEALTH.

A. Bridging Nanotechnology Standards and Robust Science in Daily Life

Bridging public health law and scientific research and innovation must traverse many different fields. Law and science have partnered together in the past, to solve major public health issues, ranging from regulating asbestos use to avoiding nuclear holocaust. Laws embracing new technology and regulating its development despite unquantified risk was a recurring phenomenon in 20th century when "big science" confronted risks from nuclear energy development, genetics, global agricultural revolution, and astrophysics, bringing impressive benefits to humanity. An amazing image embodies the link between scientific principles of nanotechnology and legal principles: a Bridge in Shanghai, China that replicates an ancient structure and thereby operationalizes the notion that nanotechnology is part of everyday life. The 3d printed character of this bridge was easily recognized by Haddonfield middle school children when it appeared in a powerpoint slide in 2019. « That's a 3d printed bridge! » they shouted, adding that it was obvious it was 3d printed because pigments had not yet been perfected . Required to do 3d printing in their science class, they deployed nanotechnology advanced so rapidly that they were not yet born when 3d printing was proof-of concept.

B Civil Society's Legal dilemma: Reduce Risk and Maximize Innovation
Nanotechnology law has evolved to the point where words like "nanostructure" appear in the text of laws: the European Food Safety Authority (EFSA) has detailed guidelines about nanostructures in food and the US Department of Agriculture has regulations about nanostructures in pesticides. Issues raised by nanotechnology are new, but not as novel as they seem. One concrete example… Notre dame de Paris after the big fire of 2019 provides an excellent example of nanoenabled products at the forefront of legislated change. Fire consumed the center of the historic cathedral in just a few hours. Without supporting infrastructure, the cathedral's façade could curmble. Nanotechnology enabled 3d printing can copy the molecular structure of the original wood and recreate the cathedral as it was. Immediately, several proposals appeared for rebuilding, using nano-enabled 3d printing! And the French National Assembly wrote new laws overnight that waived specific requirements for historic preservation in order to expedite the restoration of the Cathedral. The law changed quickly, but new technology raised a real-life example of a classic dilemma in historic preservation: is it more important to faithfully restore the building's original blueprint, or to create functional public space that thrives in a modern, multipurpose context?

B. Governments large or small …state national international…or a new legal regime?
Nanotechnology involves a small nanoscale, but it raises big governance questions. National nanotechnology policies may supersede or usurp local power, may grant authority to states and municipalities, or may become so entangled in geopolitics that there is a need for treaty-based consensus under international law. Although global treaties such as the Global Harmonization of Chemical Safety (GHS) already exist to address known adverse health impacts from nanomaterials in products, there may be a UN treaty, or a global treaty from a new multinational governance entity to address the complexities of nanotoxicity. Yet, there is no dearth of international laws to provide a legal basis for implementing precautionary principles while fostering innovation worldwide.

IV. Nanotechnology Law Transforming Disability into Health
THIS PHRASE SHOULD BECOME THE THEME OF THE NEXT ERA OF NNI IF THE ORGANIZATION IS TO SURVIVE
Nanomedicine changed the rules of the game of disability treatment, law for insurance, and long-term prognosis for rehabilitation. Nanomedicine, involving use of nanotechnology applications and nano-enabled devices to advance public health, will therefore require society to rethink ancient notions that are the building blocks of social constructs regarding the nature of disease and its treatment, and the resulting prejudices against by people who are ill. Miraculous developments that sound like science fiction to those people who eagerly anticipate these medical products, combined with the emerging social system for implementing rights of people with disabilities will reshape civil society[4] and collective thinking about health and disability.

A. Shifting Legal Paradigms for Health and Disability MUST BE EVALUTED AND DISCUSSED WITH MEANINGFUL STAKEHOLDER INPUT FROM SMALL ORGANIZATIONS INCLUDING THE WORK HEALTH AND SURVIVAL PROJECT

"Everyone has a disability. Everyone has a gift. .Your job is to find the gift and remove the obstacles of disability" Sylvia Feelus Levy 1974[5]

In parallel to the usa americans with disabilities act of 1990 (ADA)[6], global health has charted National and local laws prohibiting discrimination based on disability. The UN Convention of 2006 complements them, too[7]. Worldwide, therefore, consensus that discrimination based on disability is illégal under law and therefore accommodations must be on place to provide disabled people with equal opportunity to work and thrive. Against a remarkable backdrop of pre-existing social change regarding the rights of people with disabilities nanotechnology *emerges* to fix human impairment caused by injury and diseases. Paradoxically, disability presents the inherent challenge of understanding, accepting and allowing society to benefit from the most individualized of all individual rights.[8] Every individual in society may be ill, recuperate and regain health or lose health again many times in their lifetime. So the population to be considered "disabled" is a fluid social construct, both in daily life and under law. The core population that is considered "disabled" changes across time, even for people with long-term conditions that are disabling; no person lives an entire lifetime devoid of illness, infirmity or physical disability or impediments to their quality of life from genetic conditions or the accidents of nature, daily modern life or war. Conversely, not everyone who is sick experiences consistently declining health. People who are "sick" or "ill" or "disabled" move along a continuum of well-being as they move from treatment to recovery, convalescence to rehabilitation. Nanotechnology offers unprecedented opportunités to move people rapidly along this continuum, regaining the trajectory of health.

Nanotechnology and nano-enabled devices are a key player in making these équitable goals happen. Nanomedicine's novel approach to diagnosis at the molecular level offers the prospect of detecting and locating diseases such as arteriosclerosis at an early stage: Stroke or myocardial infarction may be avoided by means of prophylactic treatment using nano-enabled devices; nanosensors in clothing can spot changes in heart rate or respiration using nanosilverwire circuits in fabric or on a paper business card, These innovations can reduce alert patients and caregivers before these expensive life defining events occur. Doctors can perform surgery using caméras that the patient swallows in a pill. The admixture of new law and nanotechnology promises to be phenomenal: due to the revolutionary change in discrimination laws that require hiring, promoting and protecting people with disabilities as a vital part of the workforce, several fundamental aspects of workplace design, implementation of industrial hygiene protections, training programs will fundamentally change "the way we do business" The arrival of nanotechnology in the workplace implementing such change, because the changes in the demands of work that will come about through the application of new technology and the amazing cool tools that nanotechnology provides will redesign work[9]. Nanotechnology has, for over a decade, also been used to offer innovations that challenge stereotypes about the limitations of people with disabilities, such as the opportunity for a blind and deaf woman to use a driverless car driverless car.[10] It is possible, therefore, with forethought, to use law and scientific innovation to create opportunities that maximize ***the benefits of both the social change in disability laws and the economic and scientific changes to society through nanotechnology***

B. Nanaomedicine may create a revolving door for health care of aging populations. The rightful presence of an identified disabled population within the workforce has therefore changed the nature of many job descriptions, because only the "essential functions" of the job are necessary. Jobs are then custom-tailored to accommodate deficits and to maximize individual productivity. It should not be surprising therefore that the abundance of nano-enabled methods for accommodations for people with disabilities will also have implications for the daily life of retired people, who may wish to remain in the workforce during treatment using nanomedicine. Therefore retirement communities may adopt a "revolving door" approach to long term treatment of chronic illness that was not possible before the existence of nanomedicine, enabling residents and patients to recover from chronic illness and then have new ability to engage in highly productive activities in a manner that was impossible before.

C. Genetic Information as a Precursor for Requiring Treatment Using nanomedicines
Genetics poses hard questions, but it is important for guiding public health. Maniupulating nanoparticles inside proteins and DNA has brought discoveries such as CRISPR with attendant questions about the limits of science under law. . Genetics is a cross cutting issue, but it has particular importance in specific industries, in agriculture, in the global scientific community, and for small business insurance costs The emerging field of"personalized medicine" relies very heavily on genetic information as applied to the available treatments using nanomedicine. Convergence of new genetic technologies as applied through pathbreaking nanotechnology methods may redefine society's collective understanding of « safety » « health » or « disability » and may challenge both the fundamental fairness and scientific underpinning of existing standards. Genetic testing, monitoring and research provokes a discourse fraught with painful social questions about: eugenics, social engineering, stigma, genetic discrimination, and allocation of health care costs. Such concerns must be addressed without bankrupting employers, or saddling them with undue liability, but also without creating an underclass of people who lose their employability due to stigma, discrimination, potential future injury based on genetic propensity, insurance costs or potential liability. Specifically, great challenges will involving legal definitions and the availability of basic areas of social protection that will ensure nanomedicine access and fair use for all [11].

V**. What this means when Nanotechnology Laws Apply to Fighting Covid19**
As NNI predicted, nanotechnology's role in nanomedicines and telemedicine among at-risk populations enables nanosensors and telephone apps to detect asymptomatic patients, and offers health care, instant information and comradery to people who must stay home. This has been crucial for authorities tracking disease and lifesaving for individuals in isolation during the pandemic of Covid19. Nano-enabled tracking of Covid-19, Ebola or HIV/AIDS via global collaborations that were logistically impossible in previously, offers new horizons for the possibility that risk communication will be updated regularly and accurately. In Elizabeth, New Jersey, deploying drones with automated voice messages remind people to keep their distance. In Meriden, Connecticut, drones monitor trails and parks[3]. And drones under development will be equipped with cameras and nano-enabled high tech sensors to detect fever. The information from these nano-enabled products is then looped back to health authorities and the general public, but it is a policy judgement for stakeholders applying sound science to détermine whether applying these nanotechnologies are permissible under law. Early détection is a key to prévention, but also means expanding the scope of disabled populations from a medical

standpoint ad under law. Nanoregulations about nanotoxity and impacts on the environment and human health protected by law also générate invaluable information for stratégic planning to heal damage from covid19 and then heighten pandemic preparedness worldwide. But, concern for the spread of Covid-19 by asymptomatic individuals who may not progress to disease but who can be detected with screening, for example, puts a spotlight on legal and cultural questions of defining health and disability under law if people appear healthy but actually are restricted bcause their bodies harbor disease. Automatic use of apps to test temperature or symptoms of covid19 in public places thus raises heretofore undiscussed issues about tradeoffs between personal privacy, autonomy, informed consent and health as a public good. Nano-enabled big data and AI is also important when shaping insurance and employment laws structuring economic recovery. How these permissions will be granted and used also raises questions of gender differences and whether new approaches will erase or enhance existing inequities regarding womens health. Nanoregulations will therefore be applied to science policy decisionmaking and stratégic planning about

VI. CONCLUSION Nanoregulations Helping Civil Society to Get Well

LAWS governing nanotechnology are here to stay[5] because the profound link between health at work and survival of human society is ubiquitous timeless and knows no geographic bounds. Thus, global commerce and global health need nanoregulations and the related precautionary principle laws, in order to use nanotechnology for its promised advancement of human progress. A long list of major statutes place responsibility on the manufacturer or supplier to conduct stepwise analysis to determine risk and then to shape their own risk management. These statutes are enforcable, have penalties and are self-enforcing because of stepwise obligations and therefore, in the global regulatory context. Even if Covid-19 emergency laws change some of those rules that does not suggest laws will disappear. Science and Policy can join hands to save the world; New law can codify social change or lead the way to transforming society including nanomedicines can approach the capacity enjoyed by people in good health. Covid 19 calls for a response to global tragedy that will apply nano-enabled products to save the world with flexible public health law . Therefore, nanoregulations in the covid 19 era offer civil society an unprecedented opportunity: to correct long standing systemic problems in the access, public awareness and delivery of services associated with public health. If applied with forethought when rethinking these vital social values, two sets of benefits can be realized by civilization at the same time: equitable health care and innovation for economic growth. Not competing interests, but one invaluable social change.

CRITICAL STEPS TOWARDS ACHIEVING THESE GOALS RECOMMENDATIONS FOR POLICY GOALS RELYING ON ENHANCED STAKEHOLDER ENGAGEMENT TO ACHIEVE THE NNI UNFINISHED MISSION OF OUTREACH TO THE GENERAL PUBLIC

Therefore WHS recommends that a ROADMAP key new policy initiative for NNI involves:

1. WHS requests that research towards synthesizing and harmonizing nanotechnology laws at every level of governance become a number one priority of NNI because the failure to do so impedes the free flow of innovations in commerce and undermines the ability to protect public health. Many benefits of nanotechnology for the general public including both commerce and humanity, will be needlessly lost in the event that excellent products or vital safety measures are lost due to litigation concerning conflicts of law. Neither science and commerce innovations

nor protecting public health can advance in the wake of confusing overlapping duplicative conflicting laws or in the wake of surplussage in regulatory language.

2. WHS recommends a technical priority to create a structure parallel with equal to or in collaboration with EU efforts such as NANORIGO so that law-based courts standing alone need not be burdened with complex science questions that require an admixture of training in multidisciplinary science and law. This goal will advance both commerce and the protection of the public health and therefore has implications for the future of NNI and nanotechnologies.

3. WHS believes that the plethora of new nanotechnology laws rules informal guidances, global guidelines and technical standards including but not limited to the ISO standards that are widely adopted throughout global commerce creates a constituency of bureaucrats and private sector administrators whom could be called upon to explain and defend their particular body of nanotechnology rules regardless whether soft law or statutes and treaties

•Mechanisms to address the previously identified need

4. Therefore WHS recommends the establishment under the auspices of NNI an intermediary Community of Legal Experts (similar to the informal Community of Researchers for US-EU discourse in the National Science Foundation, NSF USA) designed to embrace the wide variety of laws and deliberately including those people involved in nanotechnology research and its applications who have no legal training whatsoever but are nonetheless involved in committees of experts, drafting language for rules and guidelines in both the public and private sector and at various levels of government. Such a Community of Legal Experts and stakeholders should be charged with the specific mission of cataloging and categorizing the existing protective rules about nanotechnology with a view to assisting in the synthesizing and harmonizing nanotechnology laws at every level of governance

5. Effective outreach to the public is sorely lacking in the existing roadmap and in the past efforts by NNI. This is due in large part to the state of the art of the research in the last two decades, which began when nanotechnology research and potential applications were not more than a twinkle in the legislative eye. By contrast nanotechnology and its applications now consist of trillions of dollars of global commerce as predicted, in NNI documents and scientific literature. Looping back to the general public and commercial stakeholders who are unlikely to realize that they use nanotechnologies in their products is now essential to move forward the benefits to USA and global commerce and to protect the public health.

6. WHS therefore recommends a new initiative to reach the public, not with publicity and cartoon characters as previously drawn wonderfully by the late genius Stan Lee, but via actual hands on access to nanotechnology applications and related information. WHS proposes that NNI create the school-to-school NANOSCHOOLINK as a major goal, linking students across regions and borders to study the same or related questions of nanotechnology use and benefits across a variety of disciplines.

7. NNI can also have an enormous impact on both the actual health and well-being of new moms and their babies as well as generating invaluable good will around the public knowledge of nanotechnology by developing nano-enabled kits and tools to assist in portable prenatal care and diagnosis of prenatal problems. Attacking Maternal mortality and infant mortality is a millenial task and using nanotechnology and nano-enabled portable emergency products to address this crucial unmet need is a goal whose time has come. Since maternal mortality is a major problem in every nation globally and society cannot survive if moms die in childbirth or pregnancy, much positive popular interest will be generated in nanotechnology and

nano-enabled products by creating programs that specifically use nanoenabled applications to protect women and their children during and immediately following pregnancy.

RECOMMENDATIONS FOR FUTURE STAKEHOLDER AND GENERAL PUBLIC ENGAGEMENT THAT DETERMINES WHETHER NNI SHOULD CONTINUE:

The Work Health and Survival Project recommends that

1. Synthesis and harmonization of laws of nanotechnology followed by the development of a risk governance council in parallel or collaboration with efforts in Europe. Here de offer the resources of the work health and survival project as a conduit for meani ngful stakeholder input. Our reports, books videos and a variety of outreach activités regarding nanotechnology law have been largely ignored bu staff at NNI and NNCO. Sure de have been invited to meetings and even served as surrogate leader of workshops when someone did not appear. but the work health and survival project has never been invited by NNI to lead any discussions, workshops or publications. This opportunity lost must be refound if the NNI interaction with the general public as taxpaying stakeholders is to be effective and to be percieved as sincere. This is the point in the pre-exidting mission where remarkably little has been done. The ability to bring in human décale groups and stakeholders such as we represent instead of massive groups with thousands of members and highly paid infrastructures is the key to determining whether it is worth it for Nni to survive. HS is willing to participate in this discourse and contri ute expertise in law of Europe at the higher level of NNI activity.
2. High school virtual partnering and exchange of information about nano-enabled projects across science and all disciplines including marketing, business, farming, public health, law, teaching, science and creative arts and humanities in the school-to-school NANOSCHOOLINK
3. Tackling the thorny issues of Maternal Mortality and infant Mortality creating programs that specifically use nano-enabled applications to protect women and their children during and immediately following pregnancy. This is a truly life and death matter and harms caused during pregnancy and delivery are an important lingering source of oppression for women. Indeed many women eschew childbearing in order to advance their careers and preserve their bodies, as is evidenced by the comparative economic success of childless women. The next génération will have machine based reproduction so will human pregnancy and childbirth go the way of the horde and buggy?

Bringing it All Together

In conclusion the three WHS goals outlined here are relatively speaking budget neutral consistent with the clearinghouse function of the NNI. The issues of resolving conflicts of laws before they happen by using organization such as the Work Health and Survival project as a policy partner and research resource with transatlantic expertise; educating high schools students about multidisciplinary research and uses of nanotechnology before they broach higher education; and preventing the death of new moms and their infants all are linked to the future of nanotechnology thereby advancing the work health and survival of posterity and greater civil society. The sky is the limit in this realm of potential partnerships and coordination of management approaches because it is hard to posit a professional group, NGO, government or international organization that would not want to be associated with these three key goals: Please feel free to contact me or WHS Assistant Director Dominique Charoy. Thank you for your consideration and time

Respectfully submitted, Dr ilise L Feitshans JD and ScM and DIR, Executive Director The Work Health and Survival Project Haddonfield USA and EuropeWhatsapp USA 917 239 9960 Whatsapp Swiss 0041 79 836 3965 ilise.feitshans@gmail.com

APPENDIX ONE

Biographical Sketch: Dr. Ilise L. Feitshans, JD, ScM, DIR, international lawyer and former international civil servant at the United Nations, Geneva, Switzerland, obtained her masters of science in public health from Johns Hopkins University, USA, and doctorate in international relations from Geneva School of Diplomacy, Switzerland, in 2014. She is a Fellow in Law of Nanotechnology at the European Scientific Institute, Archamps, France (affiliated with CERN and the University of Grenoble), and executive director of the Work Health and Survival Project. She is also a member of the US Supreme Court bar and was acting director of the Legislative Drafting Research Fund, Columbia University School of Law, New York, USA. Her pro-bono activities include Legal Advisor to the Greek National Platform on Nanomedicine, University of Aristotle, Thessaloniki, Greece, since 2015 and Legal Advisor for the European Commission to NANORIGO (Nantoechnology Risk Governance Council) to be developed by2022. Ilise served as coordinatrice for the ILO Encyclopedia of Occupational Health and Safety in Geneva, Switzerland. A graduate cum laude of Barnard College of Columbia University, New York, USA, she was also visiting scientist at the Institute for Work and Health, University of Lausanne, Switzerland (2011–2014). She was honored among "100 Women Making a Difference in Safety, Health and Environment Professions" by the American Society of Safety Engineers in 2011 and received the Ms-JD.org Superwomen award in 2016. Her doctorate in international relations also won the best research prize in social medicine and prevention at the University of Lausanne in 2014.

APPENDIX TWO REFERENCES

[1] Ilise Feitshans Global Health Impacts of Nanotechnology Law, Panstanford Singapore 2018

[2] Ilise Feitshans “Nanotechnology Revolutionizing Public Health in the Covid19 Era” Nanotechnology and Nanomedicine Open Access Journal Accepted April 9 2020 Published August 7 2020

[3] WHO Guidelines on "Protecting Workers from Potential Risks of Manufactured Nanomaterials" (Background paper) 2011. “These Guidelines aim to facilitate improvements in occupational health and safety of workers potentially exposed to nanomaterials in a broad range of manufacturing and social environments. The guidelines will incorporate elements of risk assessment and risk management and contextual issues.”

[4]Patrick Hunziker "Nanomedicine: The Use of Nano-Scale Science for the Benefit of the Patient" European Foundation for Clinical Nanomedicine (CLINAM) Basel Switzerland 2010

[5] ” Sylvia Feelus Levy, 1974 cited in Ilise L. Feitshans and Jay Feitshans WALKING BACKWARDS TO UNDO PREJUDICE: Report of the US Capitol Conference, Including Disabled Students What Works, What Doesn’t, Lambert Academic Press 2019

[6] Americans With Disabilities Act ("ADA") (42 USC 12101 (a) et seq.), According to ADA’s goals and plain language, the US Congressional intent and purposes codified in the federal law, is based on the concept that our society needs the productive individuals who, despite their disabilities, must be educated and employed in order to reach their most achievable potential, in order to be taxpayers, productive citizens, educated voters and able parents in the future. These concepts of health and disability are not straight lines that are parallel or otherwise follow a mutually exclusive path. Nor are they polar extremes or two distinct groups of people in society at any moment in time

[7] United Nations, Standard Rules on the Equalization of Opportunities for Persons with Disabilities, Gen. Assembly Res. A/RES/48/96 (Dec. 20, 1993) (available at

<http:// www.un.org/esa/socdev/enable/dissre00.htm; United Nations, Ad Hoc Committee on a Comprehensive and Integral International Convention on the Rights and Dignity of Persons With Disabilities, Gen. Assembly Res.56/168 (Dec.2002), Eighth session, New York, 1425 August 2006 DRAFT CONVENTION ON THE RIGHTS OF PERSONS WITH DISABILITIES and the Optional Protocol to the International Convention on the Rights of Persons with Disabilities.

[8] Ilise Feitshans, "Diversity and Human Rights: Protections for Neurodiversity and Physical Disabilities Under International Human Rights Law" Invited Presentation, Prepared for: The Center for the Study of Human Rights, Columbia University Seminar “Diversity and Human Rights” Columbia University in the City of New York, November 1 2006 http://www.columbia.edu/cu/seminars/seminars/society/seminar-folder/human-rights.html

[9] WHO World Report on Disability, World Health organization, Geneva Switzerland June 2011

[10] Ilise L Feitshans Harvard University Nanolecture Series 2019-2020December 5 2019 Global Health Impacts of Nanotechnology Law Youtube: https://youtu.be/LZTfaBhCyD0

[11] Ilise L. Feitshans Genetic Predisposition: Request for NIOSH Model For Implementation of Genome-based Occupational Risk Assessment Presented to NORA NIOSH Town Hall, on Behalf of Digital 2000 Productions, US DHHS CDC NIOSH Washington DC March 13 2006

RFI Response: NNI Strategic Planning
International Institute for Nanotechnology
Northwestern University
November 9, 2020

How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

We recommend that the government consider ways to *create the infrastructure* for industry and academia to advance nanotechnology and *facilitate the translation* of nanotechnology advances into the marketplace.

Creating infrastructure

Federal funding agencies should actively seek input from both academic and private sectors and bring these two sectors together for nanotechnology-focused workshops and symposia. These events may include supporting workshops that gather industry and academic leaders and early-career investigators, and result in reports that are accessible to the community.

These events would foster cross talk and collaboration between academic, government, and industry labs. Collaboration and sharing of resources will drive rapid research and development. It would be useful for each party to know and share what is coming out for pharmaceutical investment and the best pathway forward for the pipeline.

Similarly, federal funding agencies could make explicit requests, beyond SBIRs and STTRs, for joint academia-industry grant proposals. Ideally, these would have more rapid turn-around times because the conventional proposal cycle cannot possibly impact a company timeline. This would be a means to encourage funding opportunities for industry-academia collaborations; moreover, incentive programs to encourage university-industry collaborations could be established, with each side benefitting from investment and publicity.

An incentive structure to encourage private-public partnership, especially for translational research and proof-of-concept or pre-competitive initiatives with corporate partnerships, could be drawn as analogous to aggressive and blue-sky DARPA-type projects that led to drone, surveillance, and other technologies.

There has been too little stimulus that specifically pairs funded academic work with industry investment. There have been some situations in which industry is able to provide matching funding for NIH-funded studies. In study sections, funding from industry is often regarded as a negative, but here, there would be a benefit to encouraging matching funding to double the value of the taxpayer dollars. Indeed, true innovation involves translation to the marketplace, with that selective pressure all too often applied late in the ideation and development process. The key is to arrange early interactions with industry to identify needs and technology gaps, and pair those with the most advanced, novel science coming from academia.

Facilitate translation

Having clear and well-defined targets can focus research on academic and industrial levels on those targets. If the government has specific goals for nanotechnology research, development, and commercialization, then allocating funding towards these goals is the simplest and most obvious step. This can look like providing grants for research, providing subsidies or other economic benefits for industries, or even starting research within government agencies. Extending specific STTR/SBIR type programs at that interface between established businesses and academic laboratories could be a route to that kind of interaction.

Government funding agencies should publish more nanotechnology-focused RFAs and assemble special emphasis panels with specific expertise in material sciences and translational nanosciences. The novel and transformative nature of certain types of nanotechnology-related research is oftentimes underappreciated when discussed in regular standing study sections.

Ideally, the government would make targeted investments on topics and themes that are obvious candidates for an interdisciplinary "team" approach to science; for example, not only "disease" based research, but also cross-cutting themes and initiatives that may form "platform" technologies such as genomics, sensing and diagnostics, and theranostics. A similar approach may work for nominal physical science and engineering challenges in areas such as energy, environment, and quantum information sciences.

Grant mechanisms that explicitly include clinical trials and/or IND enabling studies are critical for the advancement of nanotechnology research, similar to the NIH SPORE mechanism ('Nano-SPOREs'). The focus should be on multi-disciplinary collaborative grants, combining the expertise of chemists, biologists, and clinicians.

There is an urgent need for programs that promote interactions between biomedical scientists and life scientists and physical nanotech scientists. Some seed money for this type of interaction is provided by individual institutions, but is generally lacking at the federal level.

Additionally, one of the biggest barriers to implementation of scientific technologies is the economics of implementation. If the government can eliminate this barrier for many technologies and implement necessary policy changes, we could much more easily employ existing and new technologies to solve problems. For example, manufacturing and scale-up is all too often a late stage component of discovery, not inherently built-in from the beginning.

Ultimately, the "valley of death" issue (e.g. gap between an innovative biomedical discovery in an academic lab, and pre-IND studies, scale-up, manufacturing etc.) in biomedical research and patient/bedside considerations must be addressed. Similarly, in engineering and physical science-based technologies, there is a similar “valley of death” in the sense of scale-up and validation of technologies that require large-scale and longer-term investments such as in agriculture and soil or food and environment management. These are massive, Giga-scale challenges that need a government or consortium approach for development.

What are effective strategies for improving communication of desired nanotechnology workforce skills and capabilities between industry and academia?

We hear from many young individuals, including even recent high-school graduates, that they would like to have a career in nanotech and translation, but very few of them know what that means. And there are no formal training programs for these types of endeavors so that transition to industry is facilitated.

In the immediate term, the government could request and maintain a list of specific education programs where undergraduates, graduate students, and postdocs interface with industry. It could also include a dynamic list of such talent needs, collected from employers, to show the needs for nanotechnology skills. This would address the challenge of preparing a nanotech workforce for life in industry and give people a tangible sense of the impact of nanotechnology.

This could be extrapolated into partnerships with employment portals like LinkedIn or Indeed to develop relevant workforce categories and details of training and expectations, akin to how these were developed for the automotive, IT, and energy industries.

In the near-term, conferences and events would present a wide range of opportunities for discourse among academic and industry stakeholders that could be targeted to workforce development, technical skill enhancement, and related issues.

For example, hosting networking events at existing conferences, sponsoring symposia with travel awards for graduate students, organizing joint workshops outlining skill and employment opportunities in the field, having information sessions during on-campus recruiting events, or inviting graduate students to industry sites to meet scientists, see facilities, and present research; all of these would require only initiative and nominal funding.

In the long-term, the most effective strategy is to establish active collaboration and recruitment between industry and academic labs. If you want developing professionals to have some set of desired skills before starting a new job or project in industry/academia, they need to have time and experience developing those specific skills through prior work. This might involve summer internships in industry during a graduate student's PhD, or perhaps an industry-related project for a PhD thesis, or maybe even providing access and courses for graduate students to learn instrumentation or techniques that a specific industry uses.

An example in practice is a program from the U.K. called CASE (Cooperative Awards in Science and Engineering). In a nutshell, an aspiring researcher sought out a co-PI in industry and together wrote up a short research proposal. If funded (for three years), it gave a graduate student a pair of supervisors: at the company and at the university. The student was given the opportunity to spend six months working in the company and the studentship came with a premium salary.

In the U.S. context, one could envisage Graduate Student Research Fellowships in Nanotechnology being earmarked by funding agencies such as NSF, DOE, et al. for which exceptional graduate students could apply. What would be attractive from the point of view of giving graduate students a broad research and outreach experience would be joint projects with the government labs as well as with industry. A similar support system for postdoctoral researchers could also be envisaged.

Ideally, there should be training programs that are specifically designed to bring in graduate students and postdocs to engage in basic and translational nanotechnology research as well as training in intellectual property, entrepreneurship, business, marketing, writing business plans, product development, etc. This would be tremendous for the individuals and the industries looking to hire them.

What are the high priority open scientific questions in nanoscience and nanotechnology?

We suggest that the NNI Strategic Plan needs a plan to promote research that puts nanoscience and nanotechnology into the broader context of science and potential technologies.

In health and medicine:

- How do nanomaterials overcome biological barriers and infiltrate diseased tissue?
- What are the fundamental and specific molecular mechanisms, and what can be learned for the design of next-generation, more effective architectures?
- Can vaccines be rationally designed with a focus not only on components but structural presentation of such components within one construct?
- Can we develop topicals that can be put on skin and clearly serve to penetrate and target effectively? To be able to replicate the revolution with biologics and small molecules by improving small molecule penetration or even get large molecules through, without compromising safety, is still an unmet need.
- Can we develop nanomaterials that can access the brain, thereby making them relevant for treating some of the most difficult diseases (e.g. Huntington's, Alzheimer's, Parkinson's)?
- How do we vastly increase the rate at which we discover new materials? Can we leverage AI/machine learning to map data from cell studies and human trials to discover trends, and vastly streamline innovation and translation?
- How do we explore and define the materials genome when composition, scale, and structure are all variables?

In energy and sustainability:

- Can we find ways to implement nanotechnology in carbon capture, storage, and utilization to help mitigate effects of climate change and environmental pollution?
- A "moonshot": what would it take to make catalyst for CO_2 sequestration at low temperatures and pressures for economic high-value conversion?
- A "moonshot": nanotech to displace Haber-Bosch – can we utilize nanotechnology for the discovery of catalysts for N_2 fixation from air at low temperatures and pressures? Ammonia production from atmospheric nitrogen under low energy conditions would impact billions of people, and eliminate one of the largest sources of CO_2 on the planet, the Haber-Bosch process.
- Can we find ways to implement nanotechnology into renewable energy?
- Can we implement nanotechnology in chemical recycling and plastic clean-up?
- Can we implement nanotechnology for agricultural run-off capture, especially in the case of precious phosphates?

In other research:

- How can we design and control out-of-equilibrium systems? What emergent properties do they have, and how can they be modeled?
- Molecular Nanotopology is new territory that will become a major area of research in the next decade, with considerable implications for the creation of enzyme-like catalysis in wholly synthetic nanosystems based on molecular links and knots.
- Broadly, scientists have become comfortable working on carbon nanotubes, quantum dots, graphene, supramolecular nanostructures, and dendrimers without facing the more challenging considerations of how "functional systems" such as materials, devices, robotics, and health delivery systems can be built with nanostructures as the components.

What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

The United States and the world are poised to unleash a flood of nanotechnology-enabled therapeutics for human disease into the marketplace. A tremendous amount of work has been done, but many of the technologies sit on the wrong side of the "valley of death".

The response should be a focus on the infrastructure, funding, and regulatory environment that enables these breakthroughs to come to patients. For example, in the cancer nanotechnology space, the challenge is to focus on 'simple,' i.e., translatable materials that can reproducibly be scaled and have a clear chance to enter the clinical space.

Nanotech stands poised to make significant contributions to clean water, preventing the next pandemic, and neuroscience, but massive investments are required for scale-up and prototyping, and time horizons can be much longer than usual.

Broadly, we need reliable research, sufficient funding, collaboration between scientists, and pathways to commercialization of new technology. Nanotech infrastructure and facilities must be comprehensive and robust. They must be distributed widely but judiciously to enhance innovation across the country while limiting duplication and redundancy which will promote inter-institutional interactions. This would include enhancing both national laboratory capabilities together with those at universities and research institutes. Critical to this mission is that such infrastructure must be maintained and replaced over time. One-time investments quickly generate waste, as techniques and methods advance beyond those initially developed.

Advanced methods for developing and characterizing nanoscale materials are a key driver of innovation in the field. These are the core enabling tools of science. Other countries and international consortia have begun to overtake the United States in electron microscopy infrastructure, for example. This puts them at a significant advantage not just in nanoscience but also in the biological sciences. It has become increasingly difficult to secure funding for cutting-edge equipment around which institutions are built. A significant and consistent investment in this kind of infrastructure distributed among the top institutions across the United States would be followed by transformational advancements in nanoscience, biomedicine, fundamental biology, and energy sciences. Similarly, investment in the development of novel characterization tools is very much needed in the US. Again, these are the tools that drive innovation; with new tools, we build new materials, and develop new science.

We cannot lose sight of issues around safety, efficacy, and biocompatibility, which can create aversion for risk-taking in the corporate world and hamper acceptance by the public. There is fear out there about nanoparticles and their safety. Regardless of where they are used, the safety issue needs to be addressed; otherwise, it may be some time before nanotechnology is accepted broadly by regulatory bodies, and implemented generally.

What nanotechnology-enabled "moonshots" should be considered?

In health and medicine:

- Cancer therapeutics – specificity and selectivity for aggressive and metastatic disease
- Neurodegenerative disease treatments and diagnosis – many of our most insidious, incurable diseases remain neurological in nature from Alzheimer's to Parkinson's
- Treatment of neuropsychiatric disorders
- Nanotechnology-enabled immunotherapies – vaccines for infectious disease and for cancer immunotherapeutics
- Nanotechnology-enabled nucleic acid-based therapeutics – one of the grand challenges in medicine today
- Nanotechnologies that enable highly targeted CRISPR/Cas9 genome editing
- Nanotechnologies for protein and peptide therapeutics – some of the most underutilized yet promising approaches to medicine today
- Multiplexed gene regulation

- Nanomaterials and delivery systems to overcome biological barriers, including and especially the blood brain barrier and the inherent challenge of evading the immune system for targeting and limited accumulation in peripheral organs
- Implementation in tissue and regenerative engineering to revolutionize surgery and tissue transplant outcomes
- Rapid diagnosis of potentially infectious diseases at early stages, pathogen identification, gene sequencing, and vaccine development
- Autonomous sensing utilizing responsive nanomaterials. With advances in wearable materials and implantable materials with telemetry, comes the possibility of this class of biomedical material with implications in diseases of increasing importance including diabetes and heart disease

In energy and sustainability:

- Functional systems that are photocatalytic but comprehensive in terms of making molecules and super fuels
- Photovoltaics for capturing solar energy
- Solving the plastic pollution problem – nanostructured materials, biohybrid nanomaterials, and biomimicry for tough, robust but degradable systems. e.g. the long sought-after "spider-silk" mimetic materials that are light weight but tough and strong
- Materials with nanostructures that can facilitate CO_2 sequestration coupled with (photo)catalysis for generating high-value carbon-based chemicals and fuels
- Clean-up of areas lost to nuclear waste and superfund sites
- Creation of the "circular materials economy", which has been defined as the move from a traditional "take, make, and dispose" narrative to a manufacturing and consumption model that reduces our dependence on natural resources and minimizing waste by keeping materials in continuous use – thereby reducing waste and carbon footprint

In robotics and space:

- Affordable space-travel – using nanotechnology to help achieve some figure of merit of certain $/lbs. For example, lightweight radiation protective nanomaterials and nanostructured systems for long term space travel – there exist biomaterials that may serve this purpose that remain underutilized and little known
- Microrobots and macroscopic robots with life-like autonomous behavior to perform tasks difficult for humans to do, driven by fuels or external stimuli in which the "internal brain" is built bottom up with inter-connected functional nanostructures across scales. Such intelligent systems could address challenges in advanced medicine, such as devices that "fabricate" tailored cells from stems cells, micro-surgical smart systems, autonomous delivery systems that are more like robots rather than pharma drugs, or targeted nanostructures that encapsulate drugs

How does nanotechnology support other foundational fields/initiatives? What future technical topics are likely to emerge from advancements in nanotechnology?

Nanotechnology holds great potential in biology and biochemistry, both in terms of understanding existing biological systems and in the development of new bio-inspired or biomimetic systems and materials. Areas include regenerative engineering, stem cell and developmental biology, and translational medicine to develop scalable tools for the regeneration or reconstruction of tissues and organs. Some organisms like cephalopods can regrow limbs, completely replicating complex skin patterning. Can we advance tissue engineering to the point where this is routinely possible in humans?

Synergy with new quantum initiatives will be important. There has been an enormous investment in quantum computing without knowing how much of the hype is realistic or will come to fruition over the next few decades. This work should be supported, but it must also be tempered; otherwise opportunities might be lost to countries that will rely on the U.S. to make a gigantic investment in quantum without any concrete new technologies for a long time.

Other areas, as described above include:
Energy production (e.g. advanced solar panel technologies)
Environmental remedies (e.g. CO_2 capture)
Sustainable agriculture (e.g. N_2 fixation for agriculture)
Space travel (e.g. lightweight advanced materials)

What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

The biomedical arena is rife with opportunities such as regenerative engineering. Drug development could also be rapidly accelerated by public-private partnerships. Too many new therapies and therapeutic platforms are sitting on the wrong side of the "valley of death".

Topics like gas storage, gas separations, chemical separations, and catalysis are industrially ubiquitous and will always be needed to some degree. Hence, there is incentive to commercialize nanotech in those areas. For example, separating nitrogen from methane is a long-standing unsolved problem that impacts efficiency in industrial chemical production and other processes fueled by natural gas. Efficiencies in these processes could be vastly enhanced by advancements in nanoscale capture technologies. The nascent materials are being developed including highly porous synthetic systems.

Renewable energy and environmental remediation represent some of the largest unsolved, global problems faced today. These are arising but also legacy problems, that require tremendous investments at a large scale. There are many stakeholders and there should be a lot of interest in diverse applications for nanostructured functional materials (composites, surfaces, coatings). Public-private partnerships can definitely carry a benefit there. Certainly, this is also an area ripe for international collaboration and partnership.

Mechanisms

How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

Responded by Shigeru Amemiya

The mechanisms and programs that can enhance the diversity of students and scientists in STEM fields are important in future NNI R&D portfolio. Nanoscience and nanotechnology are still new and very effective for recruiting female and underrepresented minority students. In the past 20 years, more than 60% of graduate and undergraduate students and postdocs in my research group were female or underrepresented minorities who were interested in applications of nanotechnology in chemistry, especially electrochemistry. The nanoscience and nanotechnology facility of our campus is not supported by NNI but is well equipped to conduct our nanoelectrochemistry research. The technical director of the facility is a female with PhD in chemistry, which helped my female students feel comfortable to use the facility. All other staffs, however, are either a white or Asian male and there is no minority staff member. Many workshops are organized in our campus to attract female and underrepresented minorities to STEM fields and also to help them for pursuing careers in the fields. These workshops, however, are not specifically targeted to nanoscience or nanotechnology, thereby missing recruiting opportunities.

Dear National Nanotechnology Coordination Office (NNCO),

The following items are in response to the request for public input to inform the development of the 2021 NNI Strategic plan. The responses are organized by Topic Area as listed in the RFI.

These responses are from Dr. Khara Grieger, Assistant Professor, North Carolina State University.

Topic Area: Mechanisms, "How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?"

- **Response**: The NNI and its 20 departments and independent agencies should continue their work in all 4 goals that have been defined as 1. Advance a World-Class Nanotech R&D Program; 2. Foster Transfer of New Technologies into Products for Commercial and Public Benefit; 3. Develop and Sustain Educational Resources, a Skilled Workforce, and a Dynamic Infrastructure and Toolset to Advance Nanotechnology; and 4. Support Responsible Development of Nanotechnology. Pursuing these goals are still relevant and important for US R&D and commercial applications. In particular, it will be important to continue research in understanding potential environmental, health, and safety (EHS) as well as ethical, legal, and societal implications (ELSI) in order to ensure that engineered nanomaterials and nanotechnology deliver upon their promises and does not create additional challenges for the environment, health, and society (i.e., benefits are reaped while risks are identified and minimized).

Topic Area: How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?

- **Response**: Both formal and informal engagement mechanisms can be effective in promoting the engagement of government and stakeholders in industry and academia. Formal engagement mechanisms may include federal (and state)-funded grants to conduct research and engagement (e.g. traditional RFA, RFPs). Informal engagements can include collaborations like the EU-US Communities of Research (CORs) that have more informal and often more intimate settings, where researchers can really talk together as colleagues to share ideas, challenges, best practices, etc. Of course conferences, workshops, and other disseminations mechanisms are also effective in having engagement with stakeholders, such as through the Society for Risk Analysis Annual Meetings which are held every 2 years in Washington DC, or through NNI-sponsored workshops and events.

Topic Area: What are the high priority open scientific questions in nanoscience and nanotechnology?

- **Response**: Consistent with Goal 4, and sub-goals of 4.1 and 4.2, it is important to continue research on environmental, health, and safety (EHS) considerations of nanomaterials and nanotechnology. This includes a wide range of R&D activities that span from instrumentations, protocols/processes, and standards activities to conduct physical-chemical characterization of nanomaterials in diverse matrices (e.g. environment, water, organisms, food matrices), methods and tools for exposures assessments (e.g. in diverse environments and matrices), methods and improved approaches for hazard assessments (e.g. strengthening in vitro, in vivo and in silico methods), and to develop and/or adapt risk assessment frameworks for nanomaterials. Since there are so many different types of materials and applications, another approach rather than doing case-by-case assessments is needed. The importance of understanding the EHS implications of nanomaterials is essential to ultimately guaranteeing the success of nanotechnology as a whole. In addition, continued research is needed to understand the ethical, legal, and societal implications (ELSI) of nanotech and nanomaterials, especially advancements are made in sectors such as food and agriculture. Among other topics, to be able to understand and communicate the ELSI aspects of nano also requires that EHS information and data are obtained in order to have meaningful dialogues and informed decisions. Further, I also support more work on the responsible innovation of nanotechnology used in diverse sectors, that integrate EHS and ELSI considerations within nanotech and nanomaterial innovation cycles, starting from early innovation stages and iteratively reviewing life cycle stages in light of EHS and ELSI considerations.

Topic Area: What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

- **Response**: Some of the main challenges to nanotech in the US and worldwide is our inability to understand potential EHS (and ELSI to some extent) aspects, even though nano-enabled products are on the market. So we do not have proper mechanisms in innovation, research, and regulation/policies that can be flexible and adaptive to this emerging technology while at the same time promoting commercialization and successful applications. In other words, since we do not yet have nano-specific testing protocols and guidelines, it is very challenging to ensure the safety of many nano-enabled products on the market or soon to be. There needs to be a paradigm shift in incorporating mechanisms like safe-by-design early in innovation cycles in order to design and develop safe/safer materials from the earliest innovation stages. We also need better tools and protocols for detecting nanomaterials in diverse matrices and for conducting monitoring.

Topic Area: As concepts surrounding responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?

- **Response**: Improved mechanisms to share data and information between different stakeholders involved in nano R&D, for example between researchers, industry, and regulatory officials. Data provisions schemes have typically not worked when they have been initiated by e.g. voluntary information sharing schemes, therefore another mechanism that could be anonymous and provide confidential data sharing is needed. This data/information-sharing mechanism(s) would help diverse stakeholders better understand evolving data (of nano-EHS or nano-safety), although some work should be conducted to understand how best to incentivize such processes. For example, some data providers could also have access to others' data, or have access to confidential discussions with regulators (?) in terms of nano-specific EHS studies that may be needed. Overall, it will be important to share data/information among stakeholders in a transparent mechanism that also allows for data security, privacy, and confidentiality.

Mechanisms

How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization?

Government can develop funding opportunities that incentivize federal grantees to interact with industry·

It can provide opportunities that would enable new startup companies the ability to economically work with academia providing a clear path to commercialization.

NIH already announces initiatives that focus on technology development rather than fundamental insights; such mechanisms lead to new ideas/products for industrial implementation in the long run (NIH: IMAT program, Cancer nanotechology, Physical Sciences Oncology Network)

This effort could also focus on the important problems of quantum science, heterointegration challenges, additive methods for 3D fabrication as well as non-destructive methods for 3D characterization while engaging students in workforce training in cooperation with industry (see below)

What are some best practices for this kind of engagement?

Initiation of such interaction with pilot grants; intellectual property issues need to be resolved

Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?

In the sciences examples are the SBIR and STTR programs of the NSF, NIH, DOD; the NYSTAR program is an example in NY State along with the URI500 Southern Tier Capital money program.

Communication

What are effective strategies for improving communication of desired nanotechnology workforce skills and capabilities between industry and academia?

The best way to improve communication is to establish programs where industry and academia work together to a well-defined goal. In such a partnership, industry works towards commercialization and academia trains students and carries out fundamental research. Quantum science, heterointegration (taking advantage of organizations like X-fab), life science topics all provide common opportunities. Large industry and small industry can engage but separate programs would be useful since startups have quite different capabilities and needs than established large companies. Working with state economic incubators would also enable creation of startup communities.

How can the NNI participating agencies or NNCO best raise awareness among teachers regarding the educational resources that have been developed over the past 20 years and help get these resources into their classrooms?

The NNCI already provides excellent programs for outreach and creation of educational programs as part of its NCF supported mission. 4H through its partnership with NNCI offers a national mechanism for reaching out to the country with their STEM mission. They are located in every country and every state and are also situated in large urban areas. Efforts in one country get shared across the state and nation.

Topics

What are the high priority open scientific questions in nanoscience and nanotechnology?

Life Sciences: Precision Medicine, high resolution imaging, biomanufacturing, model systems for drug development and discovery

Quantum device fabrication

Machine learning applied to questions of device manufacture and process improvement in nanofabrication

Emerging research areas related to NNI include 2D materials, 3D fabrication and characterization, and heterointegrated systems.

What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

The US is facing lagging economic growth, it has fallen behind in supply chain capabilities, its suppliers are overseas and it is increasingly difficult to attract the world's best talent and the world is dealing with increasing numbers of infectious diseases, the need to feed the world's population while energy supply continues to be scarce.

While some of the challenges relate to science and technology policy, nanoscience itself will have a beneficial impact on food supply, dealing with diseases and energy management, production and use reduction.

What nanotechnology-enabled "moonshots" should be considered?

Areas such as nanorobotics, precision medicine, machine learning and its impact on nanofabrication and digital agriculture will alter technology and life as we know it.

How does nanotechnology support other foundational fields/initiatives?

Quantum devices all depend on nanofabrication capabilities but bring additional demands for high purity, uniform materials and levels of characterization beyond that already practiced for semiconductors.

Digital agriculture is about to take off and nanotechnology provides the internet of things, sensors, computational resources and the tools for communicating with plants.

What future technical topics are likely to emerge from advancements in nanotechnology?

Rapid developments in the life sciences, defense systems, telecommunications, information management, healthcare, digital agriculture, and new energy technologies will continue to emerge. Convergent technologies combining topics such as quantum science and life science will develop over the long term.

· **What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)?**

Life sciences approaches often need less sophistication at the fab level, but higher throughput. This may also be the situation with the coming quantum effort and other developing, high impact technologies outside semiconductor manufacture.

For startup industry, there is a major gap in going from research to medium scale production. A mechanism where there are scaleup partnerships would be tremendously useful.

The scale of tools in research facilities are smaller than those used in manufacturing and this divergence will continue. As a result the useful toolset may become scarce unless tool manufacturers cater to research facilities. Workhorse tools remain vitally important but difficult to purchase because the government funding agencies have not followed the recommendations of the periodic NNI reviews and provide funding mechanisms for this class of infrastructures.

What other tools are necessary to conduct nanotechnology R&D?

It can't be emphasized enough that baseline tools and a broad toolset are needed. In addition, complete sets of tools and support facilities that provide start to finish processing, testing and characterization.

What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?

Topics related to 2D materials, additive manufacturing, heterointegration, life sciences, and quantum information science could benefit from public-private partnerships.

The United States invests ~$2B in nano research
AND
lots of software and data are generated.
BUT
the broader audience cannot learn from these artifacts,
because they are not accessible
THEREFORE
we created nanoHUB that
converts these resources into usable apps
that now have a global user base

nanoHUB now serves over 21,000 simulation tool users and nearly 2 million lecture and tutorial users annually. nanoHUB has accumulated over 7,000 research and education-focused content items. nanoHUB can boast about a systemic change in academic curricula with about ½ of the simulation users using nanoHUB in formalized education settings at over 180 institutions. Nearly 2,500 citations to nanoHUB in the literature point to use in research.

We have been on the forefront of publishing user friendly apps wrapped around fundamental scientific simulation tools. These apps broaden the participation dramatically and are now new publications listed in the Web of Science and Google Scholar. Going forward we are working the same broadening by creating apps around data repositories, that make data sets usable.

nanoHUB is currently funded by the NSF Engineering Research Center division and is beginning its final 3 years of funding. The ERC division informed us that nanoHUB will no longer be funded through them.

We are intensely working on sustainability models including individual as well as institutional subscription models. It is possible that these sustainability efforts may not succeed, or that sustainability will require significant changes in how we interact with the NNI community. As a result, the resources and cyberinfrastructure available to the NNI community today may not be available in the future, may take a different form, or may not be as freely accessible as today.

We believe nanoHUB has become part of the National Infrastructure Portfolio and as such should be considered a cyberinfracture facility of national importance with a significant operational component in addition to a cyberinfrastructure research and development component to keep pace with and support this important national investment.

We request that nanoHUB becomes a formal part of the NNI Cyberinfrastructure investment.

Kind Regards
Gerhard Klimeck

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RFI: NNI Strategic Planning

The responses are a compilation of input from several NNCI sites, including Cornell University, Stanford University, and Georgia Tech.

Mechanisms

- **What is your understanding of how the Federal Government has supported the nanotechnology community since the launch of the NNI?**
- **How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?**

  The recent *Quadrennial Review of the NNI* highlights how the NNI could evolve:

  1. Investing into activities/programs that are more driven by **using nanotechnology approaches to solve grand challenges** (e.g., clean energy, safe food and water, secure computing and communication, health, to name a few); in a way, nanotechnology would be the enabling part of technologies and solutions (the area of MEMS has undergone a similar process: from MEMS-focused research to solutions enabled by MEMS).
  2. Emphasizing programs that **promote collaborations/partnerships between industry and academia** including strong translational components/programs; develop funding opportunities that force federal grantees to interact with industry.
  3. Looking at worldwide competition, provide academia and industry an "unfair advantage" by providing the **best infrastructure and workforce development programs**, including a nanotechnology innovation ecosystem and academic foundries in strategic areas (e.g., GaN, SiC, diamond, 2D materials).
- **What key elements and intersections are necessary to form an agile framework that will enable response to new developments along the nanotechnology continuum, from discovery and design to development and deployment?**
  - Research Infrastructure: a world-class research infrastructure remains of key importance to provide broad access to nanotechnology capabilities and support nanotechnology research and development. A state-of-the-art research infrastructure must procure the newest, state-of-the-art tools but also replace aging workhorse equipment. World-class infrastructure will continue to attract world class talent at all levels.
  - Workforce Development: multidisciplinary training at all levels (from 2-year degrees to PhD) will remain critical to develop the necessary workforce.
  - Formation of Innovation Ecosystem: a nanotechnology innovation ecosystem needs to be developed to better connect academic discovery, industrial R&D and production/manufacturing. Existing components, such as iCorps-like programs, university-based incubators, research infrastructure networks, prototyping and scale-up facilities need to be connected to make it easier for nanotechnology innovators to translate their ideas into products.

- **How can the government engage effectively with stakeholders in industry and academia to advance nanotechnology research, development, and eventual commercialization? What are some best practices for this kind of engagement?**

    - Partnerships between the Semiconductor Research Corporation (SRC) and funding agencies such as DARPA and NSF to develop joint research programs seem to be a successful engagement in the micro/nanoelectronics space, with the NRI and JUMP programs as examples. Could a nanotechnology industry consortium play a similar role in other nanotechnology areas?
    - Encourage industry to participate in workshops and program review meetings and have industry serve on extremal advisory boards of funded programs/centers.
    - Work with academia to address intellectual property issues that more often than not are a stumbling block for successful collaborations.
- **How could public-private partnerships contribute to progress towards the NNI goals? Are there any examples (domestic or international) of productive partnership mechanisms that should be considered as a model?**
    - International examples for productive public-private partnerships include IMEC in Belgium and LETI in France, both in the nanoelectronics space as well as C2MI in Canada in the MEMS space. IMEC is an example of a hub that allows for successful mingling and cooperation between industry, government, and academic researchers.
    - Switzerland has successful programs to accelerate the conversion of research results to marketable products where the private sector is expected to cover 50% of the project cost. Typically, federal funds cover the activities at the academic partner, whereas the industry partner covers its expenses.
    - SBIR and STTR programs continue to be excellent programs by NSF, NIH and DoD supporting the translational goals of the NNI.
    - Adjust educational programming and curriculum development based on industry needs.
- **What are exemplary models (domestic or international) for accessing NNI resources, including user facilities and laboratories?**
    - Infrastructure programs like NNCI and the DoE Nanolabs continue to be "role models" for international nanotechnology networks. However, more coordination among national infrastructure resources would be beneficial, including relevant MRSEC and ERC resources, as well as manufacturing institutes.
    - Examples of international infrastructure networks include EuroNanoLab, NanotechJapan and CMC Microsystems in Canada.

Communication

The NNCO serves as the public-facing entity of the NNI in addition to and in support of NNI agency communication efforts. NNCO maintains *Nano.gov* and shares information through numerous communication means. However, the NNI community is complex and multifaceted, and diverse stakeholder groups consume information in different ways.

- **How can the NNCO facilitate communication and collaboration throughout the nanotechnology R&D ecosystem to enhance research and ultimately commercialization? How can the NNI/NNCO best communicate opportunities, resources, and advancements to the community? How can the NNI/NNCO best engage with the stakeholder community to understand their advancements and needs?**
    - Continue to build the NNI Community through attendance and talks at conferences. NNI member agencies should make their relevant PIs aware of the NNI and associated resources,

and encourage participation in NNI activities, town halls, networks, etc. Interviewing NNI members through the podcast series gives them an opportunity to share their successes and resources, helping to strengthen the community.
    - For community formation and engagement, there must be a value proposition. Right now, PIs get funding from NNI agencies and may not even know that their award is considered to be in support of the NNI. Does the NNCO get a list of such awardees? If yes, there could be targeted outreach, highlighting funding opportunities, translational activities, infrastructure resources, student engagement programs etc. Alternatively, member companies could do such targeted outreach to their NNI PIs.
    - The NNCO should establish more interactive communication formats, such as discussion forums and listservs, in addition to the more passive delivery options currently used (podcasts and newsletters).
- **Beyond the media platforms used by NNCO, what additional means should be considered to better reach the public and various stakeholder groups?**
    - Each group has its own source for information and the NNCO should engage on those platforms. More multimedia content designed for a lay audience, especially centered around careers and themes, will be helpful. Creating some sort of ambassador for the relevant stakeholders could also be a useful tool. An NNI Teacher Ambassador who can speak to fellow teachers at the NSTA, for example, with the NNI covering their travel. An Entrepreneur Ambassador could do something similar. Researchers active in the networks or signature initiatives could be asked to share information at conferences, too. These efforts could tie in with existing network activities, which should continue to be supported and strengthened.
    - The NNCO should better use social media platforms as communication and dissemination vehicles.
- **What are effective strategies for improving communication of desired nanotechnology workforce skills and capabilities between industry and academia?**
    - Continue to encourage and support collaboration between industry and academia (including K12, community/technical colleges, through to R1 universities) with respect to education and training. The SEMI Works efforts may be a good example. NNI agencies can encourage training programs that include ties to local industry and entrepreneurship for students/teachers/embedded within research grants.
    - Key stakeholders can be engaged through focused workshops or working groups that are charged with producing white papers or short reports.

- **How can the NNI participating agencies or NNCO best raise awareness among teachers regarding the educational resources that have been developed over the past 20 years and help get these resources into their classrooms?**
    - The NNI should continue to meet teachers where they are – conferences, workshops, classrooms – and extend to the educational platforms teachers use. NNI member agencies can also continue to support teacher training programs such as the RET or other programs (with stipends for teacher participation). Continue to assist the NSEE community with maintaining searchable databases that are easy to access, provide guidance on media that can be used in the classroom, and encourage NNI agencies to use their social media channels to promote resources tied to current events and celebrations (i.e., Women's History Month and #WomeninNano). The NNI should work to tie existing resources to career

opportunities for students. Providing information on nanotechnology without giving it this context makes it more difficult for teachers, student, and parents to understand the importance of it. MNT-EC plans to produce podcasts about people working in the MNT industry, these will be a useful tool.
    - While the NNCO has developed some innovative teacher resources such as annual contests, distribution could be accelerated through partners such as the NNCI and NACK network which reach large numbers of teachers. Likewise, the NNCI and NACK resources should be shared by NNCO.
    - 4H, through its partnership with NNCI, offers a national mechanism for reaching out to the country with their STEM mission. They are located in every country and every state and are also situated in large urban areas. Efforts in one country get shared across the state and nation.

Topics

- **What are the high priority open scientific questions in nanoscience and nanotechnology?**
    - The basic methodologies of fabrication and characterization of nanoscale materials and devices have been pretty well established over the past 30+ years. The goals now are to use this foundation as the basis for advancements in key disciplines such as life sciences/medicine, energy research, advanced computing, and others.
    - In addition, a fuller understanding of the environmental impact of nanoscale materials, scaled-up production, and sustainable manufacturing technologies are still in development and require national investment and attention.
- **What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?**
    - Examples of areas that can benefit from nanotechnology:
        - Health: Rapid diagnostics (see COVID-19 pandemic); technologies for the aging population; precision medicine; biomanufacturing; efficient and fast drug development and discovery.
        - Computing: next-generation computing; secure computing and communication; quantum information sciences
        - Energy: high-performance batteries; renewable energy sources
        - Food and water: water treatment; food safety; smart agriculture.
        - Manufacturing: machine learning and AI applied to improve nanomanufacturing
    - Challenges for advancing nanotechnology and nanotechnology-enabled solutions:
        - Difficulties to recruit overseas talent, including students, researchers and faculty.
        - Limitations on international cooperation and collaboration.
        - Other countries having caught up or even overtaken the US in terms of infrastructure investment and research output (publications and patents).
        - Infectious diseases as we have seen over the past 10 months.
- **What nanotechnology-enabled "moonshots" should be considered?**
    - A variety of high-risk, high-reward research areas may be assisted by involvement of nanotechnology materials or approaches. These areas include the following:
        - Healthcare: personalized medicine (therapies) and rapid, point-of-care diagnostics.
        - Computing: implementation of quantum information science; rapid advancement of internet-of-things and distributed computing; next-generation computing; secure communication.

        - Electronics: nanofabrication enhanced with artificial intelligence techniques; nanosensors for the internet of things; precision agriculture.
        - Climate change/energy: new materials, energy sources, and manufacturing methods to reduce anthropogenic sources of greenhouse gases.

- **How does nanotechnology support other foundational fields/initiatives? What future technical topics are likely to emerge from advancements in nanotechnology?**
    - Quantum devices all depend on nanofabrication but bring needs for high purity, uniform materials and levels of characterization beyond that already practiced for semiconductors.
    - Artificial intelligence and machine learning rely on high-performance computing platforms that ultimately are the result of nanotechnology, in particular nanoelectronics advances.
    - Environmental concerns and nanotechnology recycling: Nano-based devices and electronics utilize a variety of rare elements and are often obsolete in a matter of a few years. If those are mass-produced (ex. mobile phones), recovery of these elements should be considered to avoid toxic pollution.
- **What are the gaps in the fabrication, characterization, and modeling and simulation tools available through the NNI user facilities (listed on Nano.gov)? What other tools are necessary to conduct nanotechnology R&D?**
    - Based on input from NNCI user facilities (and its 13,000+ global users), the biggest gap in current infrastructure is the ability for these facilities to replace workhorse tools. Of the 2200+ tools available in the NNCI, the vast majority are standard deposition, etch, and patterning tools that are used by a majority of researchers but are difficult to update or replace with current funding mechanisms which favor advanced, state-of-the-art equipment.
    - Another gap is in tools and facilities to scale nanomanufacturing technologies, ranging from 2D vs 3D processing, role-to-role manufacturing, heterogeneous integration, etc.
- **What specific nanotechnology topics could be accelerated to commercialization by public-private partnerships?**
    - Examples include: reliability and scale-up of 2D materials; energy-efficient and environmentally-friendly batteries; data-driven/AI-enhanced (nano)manufacturing; large-area “next-generation” photovoltaics; biomanufacturing.

- **As concepts surrounding responsible development have evolved over the past twenty years, what factors may contribute to the responsible development of nanotechnology going forward?**

Submission to the Request for Information: National Nanotechnology Initiative Strategic Planning

Authors: Tarek R. Fadel, PhD. & Tahoura S. Samad, PhD.

The Marble Center for Cancer Nanomedicine brings together leading faculty from the Koch Institute for Integrative Cancer Research—Drs. Sangeeta Bhatia (Director), Robert Langer, Angela Belcher, Paula Hammond, Darrell Irvine, and Daniel Anderson—to focus on grand challenges in cancer detection, treatment, and monitoring that could benefit from the emerging biology and physics of the nanoscale. Marble Center members are collaborating on a wide variety of efforts, from detecting cancer earlier than existing methods allow, to harnessing the immune system to fight cancer as it evolves, to exploiting therapeutic insights from cancer genomics in order to design therapies for previously undruggable targets, to combining existing drugs for synergistic action, to creating tools for better surgical intervention. A central mission of the Center is to tackle these grand challenges through **miniaturization** and **convergence**—the blending of the life and physical sciences with engineering.

The contributions below represent the personal views and positions of the authors ONLY and do not constitute an official response from the Koch Institute community or the Massachusetts Institute of Technology.

Mechanisms:

How should this support evolve into 2030 and beyond? What mechanisms and programs are necessary to support the broad NNI R&D portfolio?

Historically, there has been a special focus on nanotechnology funding by member agencies, which has helped elevate the field as a national priority. The dilemma faced by the federal government is whether the evolution of the field warrants **a continued prioritization on a-per-agency basis** or declaring that the field has matured enough to be integrated into new priority areas.

We believe that the impact of nanotechnology has been felt economically and that the investments are paying off. For example, if there is anything 2020 has taught us, it is that the sustained Federal investments in nanotechnology have ultimately opened the door for the rapid deployment of impactful technologies that are helping us fight the COVID-19 pandemic; from breakthroughs in PPE, diagnostic (E25Bio) to vaccines (non-viral formulations to deliver mRNA). Investments in nanotechnology have redefined the way we think about technology translation and deployment as a whole. The NNI should continue to track how years of funding have finally culminated in these breakthroughs and are ultimately saving millions of lives. This can be illustrated by tracking specific cases of technology deployment, vs. a general assessment of the field.

Another important lesson of 2020 is that basic research investments in nanoscience need to remain a priority and that the field has a long way to go before hitting "main street." Breakthroughs in the biological and physical sciences continue to rely on nanoscale approaches to uncover mechanisms and new applications. Small-scale technologies drive our progress towards a new age of information technology as much as they enable the discovery of new basic science mechanisms, for example through advances in microscopy, genome editing, or synthetic chemistry, which have enabled an entirely new field of nucleic acid delivery. Advances made by Alnylam and Moderna took years before bearing fruit. Now an entirely new field is evolving from these investments. Importantly, these focused investments often evolve into unexpected benefits in a competitive landscape (Moderna's investments in proprietary delivery technology and subsequent benefits of mRNA-1273 when it comes to cold chain management of the vaccine).

We suggest that member agencies work via the NSET Subcommittee towards new collective priorities inspired by grand challenges in the **basic sciences** (rather than downstream, translational goals; reference here: https://mbio.asm.org/content/7/4/e01381-16), to guide the incoming Administration on new goals and priorities. Each basic science goal would be structured under a program joined by Federal agencies/departments/commissions investing in this research area. These basic science goals may enable advances in other strategic programs and priorities within the member agencies (for example: a theme around "vaccine materials of the future," i.e. do not require refrigeration, would not only intersect with agency programs dealing with global health, but material science programs in various agencies).

Another important challenge is connecting the various research centers and institutes around the country to help foster new collaborations and broad impact in the field. Many communities have grown out of government investments in nanoscience and have achieved tangible progress in the field; for example, the CCNE model. Are these communities still interacting? At what level? We think it is essential to maintain a level of interactions between these communities even though these programs have sunset. We suggest that the NNCO look into various mechanisms to reinvigorate these various networks and maintain these interactions to foster impactful collaborations.

Finally, the challenge the NNI is facing at this stage of its evolution is certainly not specific to nanoscience. We would encourage reaching out to members from other similar initiatives to help join the strategic planning committee(s). This will provide a frame of reference for planning the next phase of the initiative.

Topics

What are the high priority open scientific questions in nanoscience and nanotechnology?

- The post-Moore's law era and how miniaturization would evolve in that phase (and how it will impact the future of computing).
- Novel materials with dynamic properties (malleable, or responsive to a local stimulus, whether it is a biological or environmental trigger; also a renewed focus on cooperative material mechanisms in biology.)
- The future of sensing and communication powered by miniaturization, whether it is for national security, biomedical, communication, or space applications,

What are challenges facing the United States and the world where nanotechnology is poised to make significant contributions?

- Cancer detection
- Infectious Disease (Diagnosis and treatments)

- Rapid vaccine deployment
- Novel drug delivery technologies
- Protective materials for defense and biosecurity applications
- Novel computing architecture and device integration
- Broad sensing networks and novel communication technologies (example: personalized health labs at home that rely on biosensors and help monitor a panel of health markers).

What nanotechnology-enabled "moonshots" should be considered?

- Can we create biomaterials that have inherent homing properties to specific tissues (targeting-free)?
- Can we engineer a "living" cell and program it for a specific function? (Inspired by Dr. Paul McEuen's work on cell-sized sensors and robots)
- Home-based health: can we engineer personalized health check systems that can operate from our own home and better guide our visits to the doctor's office (Inspired by Dr. Gambhir's work with the smart toilet; intersections with other initiatives like NITRD).

Response to OSTP RFI: National Nanotechnology Initiative Strategic Planning

Submitted on January 19, 2021 by:

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Thank you for this late opportunity to submit comments, which I am pleased to do following the excellent NNI Strategic Planning Stakeholder Workshop, held January 11-13, 2021.

My comments on a few specific topics mentioned in the RFI:

Mechanisms

How should support (of the nanotechnology community) evolve into 2030 and beyond?

The NNI community today consists primarily of researchers/technologists and educators (nothing wrong with that), while the "nano business community" consists more of non-academic founders and CEOs, many without PhDs. Meaningful involvement of established industry (which prioritizes revenue opportunities and talent sourcing, but is willing to assign lower level personnel to public service committees, etc.) is challenging and not impressive, but perhaps not necessary if effective startup/spinout generation and support mechanisms are in place. But even here bridging the gap between the academic/research and business/commercialization communities still needs work. The solution is not always more research, education or training, which are the primary things NNI – conceived narrowly – can currently do. There needs to be more in the program that is attractive to businesses and entrepreneurs – especially the spinouts and startups that do the early development on the most leading edge ideas. What that "more" could be will be the subject of my remaining comments.

What key elements and intersections are necessary to form an agile framework….

There are two things I have significant experience with that could be very powerful. One should be fairly easy, while the other will be considered by many to be farfetched or out of scope. However, in view of the existential threat or economy faces from China, we should be willing to do the (ethical, of course) things required to win. Just doing the same things over again will lead to the same results we have been getting – not bad, but not nearly as impactful as they could be in terms of job opportunitiess and tax base growth.

1. The easy one: Internships in startups for students (at all post-secondary levels) in nanotechnology-related disciplines. NSF funds an ASEE program to place postdocs in Phase II SBIR companies. Not bad, but too limited, and the funded interns are ASEE fellows/"visiting scientists"rather than startup employees. A better program would focus on students having a definitive and open-ended (i.e. may become permanent employee) startup experience where

they make essential contribution to the company (not just the technology) and experience first hand what startup management teams have to do to succeed. They would be company employees, and the government agency would make a grant (covering, say, $25/hr) to the company. The grant would require regular reporting, a mid-term go/no-go review and a final presentation by the intern. The eligible pool of companies could be SBIR recipients, but perhaps not limited to that. The main thing to be vetted is that the company will properly supervise the intern and provide the quality of experience required. In our experience, this was not hard to achieve and almost always went very well.

2. The hard one: there is not enough early stage capital and domain-competent fund management in the US for commercialization of NNI (and other) research. Even though the VC industry cut its teeth on hard tech (Intel, Genentech, etc.), it does not favor it now, except for pharma (special well defined path) and some high-impact biotech – and even then someone else has to fund the early stages. This problem is deep (see Venture Investing in Science by Jamison and Waite, and other works) and won't be solved without bold changes that will sound like "industrial policy" or "picking winners" to some. To come right out with it, I think the government should find ways to invest – not just grant – more funding to the best companies, as determined by fund managers/contractors with both venture finance and science commercialization 'chops'. Possible mechanisms (all with thorny problems to solve):
    a. Make some or all Phase II SBIR awards dilutive (this will encourage business seriousness) and allow agencies to hold equity, at reasonably generous valuations and on company-friendly terms (as long as company is in US), but with follow-on funding available (to the best companies) at market rates and terms. Returns can be reinvested by the agency. Existing PDs may not be qualified to do the investment management (though many/most of the NSF SBIR PDs are), but contractors who are can be found.
    b. Distribute investment funds to state and local initiatives – with appropriate state/local match - for investment in promising nanotechnology companies. A little like SBICs, but rather than expect private capital to come in right away, both USG and states/regions would take pre-seed/seed stage equity (through contractors managing LLC funds) and have a goal for commercial/VC funding to come in one or two rounds later – when the technology and business model are largely de-risked and more 'conventional' fund managers (who understand SaaA and consumer products & services) can model risks and returns.

In sum: success for NNI must be much more than patents and papers, and more of it must occur in the US rather than travel back to countries sending graduate students (another problem – more top-notch US citizen/permanent resident graduate students....). I am trying not to sound like an alarmist, but I do think US S&T leadership and prosperity are at significant risk, particularly from China - which is not averse to implementing things such as I have described.

(I could comment on specific technical topics, shared facilities and other matters – but the above items seem most important to me, and are within my areas of experience and expertise.)

Response to RFI: National Nanotechnology Initiative Strategic Planning

A Notice by the Science and Technology Policy Office on 10/13/2020

Semiconductor Nanotechnology Research – a National Imperative

Submitted by

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H.-S. Philip Wong	Professor, Dept. Electrical Engineering, and Willard R. and Inez Kerr Bell Professor in the School of Engineering	Stanford University

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Executive Summary

Semiconductor technology[1], a nanoscale science and engineering practice that includes micro/nano-electronics, spintronics, and photonics, is a foundational technology that without its *continued* advancement, the promises of artificial intelligence (AI), 5G/6G, and quantum computing will never be realized in practice. Our nation's economic competitiveness, sustainable development, and national security, depend on our staying at the forefront of semiconductor nanotechnology. Beyond economic impact and security, semiconductor technology plays a major role in enabling R&D solutions toward many societal challenges, such as digital transformation of health care, climate change, and protecting the environment – from supercomputers to massive deployment of internet of things with extreme energy efficiency and diverse functionalities.

Over the past two decades, the National Nanotechnology Initiative (NNI) has developed critical research infrastructures such as the NSF-funded NNIN/NNCI user facilities and seeded many basic science advances. Many of these basic advances are ready for translation into new technologies that will catapult semiconductor technology into a new era of heterogeneous materials, devices, and system integration beyond the two-dimensional down-scaling of silicon CMOS technology that had dominated progress over the past five decades.

While it is critically important that the US make efforts to incentivize and nurture domestic manufacturing of semiconductor chips, we must also recognize that semiconductor technology requires sustained, rapid innovations to meet application demands. We must not be lured into complacency that just because there has been a new generation of semiconductor technology every two years in the past few decades, that we can expect to ride the same trend for the next few decades. Today, the historical rate of progress, following the predictable path of down-scaling, is no longer guaranteed as it had been in the past. Yet, there are many plausible paths to move forward, and the potential for further advances is immense. Take computing energy efficiency as an example: there are at least 1,000 times improvement to be gained going forward.

We must accelerate the pace of exploration and translation, broaden the set of researchers, and equip them with capability to do research across the full spectrum of nanoscience enabled technology, from nanomaterials to nanoscale devices, circuit and system design, to system architectures that utilize unique nanoscale and quantum phenomena. There is a bright future in materials, devices, and system integration that require end-to-end co-design and innovation. Isolated programs staying in traditional silos will be inadequate. That is where large-scale efforts, best coordinated across multiple federal agencies, can make a

[1] Semiconductor technology broadly refers to all forms of micro- and nano-electronics, spintronics, photonics, sensors and actuators, as well as the circuit and system architecture design, manufacturing, and packaging technologies. For simplicity, we use "semiconductor technology" and micro-/nano-electronics synonymously.

substantial difference. The technology edge of the US is to stay at the forefront, ahead of our competition[2].

We recommend

1. The establishment of a *Subcommittee on Semiconductor Research, Development, and Manufacturing*, reporting to the National Science and Technology Council (NSTC) and the Office of Science and Technology Policy (OSTP) of the White House. This subcommittee will be assisted by a national office that coordinates activities across agencies.
2. A redoubled effort across agencies to focus nanotechnology research on advancing "*semiconductor devices, design, architecture, and manufacturing technology beyond conventional silicon CMOS*."
3. The establishment of a *National Network for Microelectronics Research and Development*, to bridge the gap between laboratory discoveries and manufacturing fabrication (lab-to-fab and lab-to-new-fab translations), and compress the time between technology invention and broad societal adoption. Ensure relevance to the existing industry and provide methods and funding to support the initial growth of startups.
4. That the National Science Foundation help develop ways to lower the entry barrier and shorten the learning curve for students to participate and receive training in the field of micro/nano-electronics.

[2] Rafael Reif (President, MIT), House Ways and Means Committee hearing, February 26, 2020. https://waysandmeans.house.gov/sites/democrats.waysandmeans.house.gov/files/documents/Reif%20Testimony.pdf

1. Semiconductor Technology is a Foundational Technology

"*Semiconductors are essential to modern life. Progress in semiconductors has opened up new frontiers for devices and services that use them, creating new businesses and industries, and bringing massive benefits to American workers and consumers as well as to the global economy. Cutting-edge semiconductor technology is also critical to defense systems and U.S. military strength, and the pervasiveness of semiconductors makes their integrity important to mitigating cybersecurity risk*."[3]

The opening statement of the 2017 PCAST report to the President is prescient. Today, the importance of semiconductor technology is unquestioned. From supplying the auto industry to enabling e-commerce in a pandemic, ensuring military superiority and cyber-security, semiconductor technology is essential. Twelve out of seventeen of the United Nations Sustainable Development goals rely on ***continued advances*** of information and communication technologies (ICT) that are based on semiconductors. Every day, more than half the world's population use the internet. Beyond direct impacts on the economy and national security, semiconductor technology plays a major role in enabling R&D solutions toward many societal challenges, such as digital transformation of health care, climate change, and protecting the environment – from supercomputers to massive deployment of internet of things with extreme energy efficiency and diverse functionalities. Semiconductor technology is a foundational technology[4] and the demand going forward is insatiable.

It is widely recognized that the US must lead in artificial intelligence (AI) and 5G communication. The AI revolution has been made possible by advances in three areas: first, the availability of large data sets for machine learning; second, computers sufficiently powerful to process this large volume of data; finally, the development of new AI algorithms. Out of these three, the first two were made possible with semiconductor technologies. Large sets of data are made possible with sensors (such as cameras and GPS) on mobile devices such as cell phones, and the internet of things (IoT) to collect them. These are all products of semiconductor technologies. Going forward, the low-latency, high-speed connectivity of 5G is essential to collecting vast amounts of high-quality data; 5G is also based on semiconductor technology. Powerful computing is, of course, not possible without chips made with advanced semiconductor technology. Simply put, we cannot run today's ICT systems on 90s technologies. Voice recognition simply won't work on flip phones. More powerful software applications require more powerful hardware technologies. If hardware technology fails to progress, then software applications will soon stall.

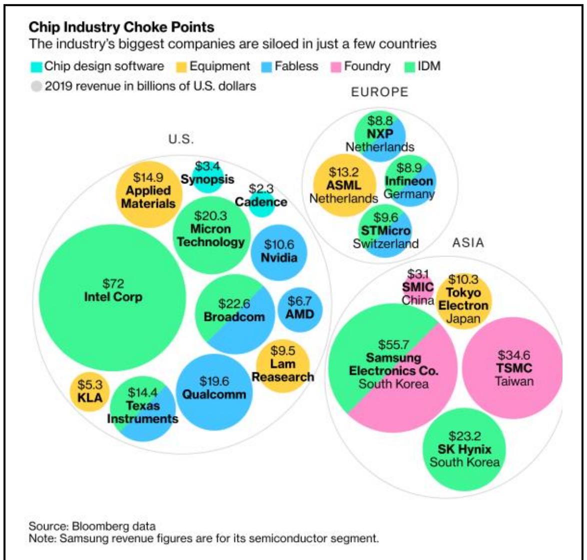
[3] PCAST report to the President, "Ensuring Long-Term U.S. Leadership in Semiconductors," January 2017. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_ensuring_long-term_us_leadership_in_semiconductors.pdf

[4] PCAST report to the President, "Networking and Information Technology Research and Development Program Review, January 2021. https://science.osti.gov/-/media/_/pdf/about/pcast/202012/FINAL_PCAST-NITRD-Report_2021.pdf?la=en&hash=6855ECA97C8C8C27F2727B2DF617758B54F7F1C3

Over the past five decades, semiconductor technology has continually advanced to provide faster, more energy-efficient computing and communication technologies with such regular paces that it seems like a certainty that newer and better generations of semiconductor technologies will always arrive like clockwork. Businesses have built in assumptions of ICT advances into their business models without questioning the assumptions.

However, after five decades of advancing on a single, predictable path – the two-dimensional scaling-down of device sizes – that path has gradually become less effective, and future progress is no longer guaranteed. Yet, there are many plausible paths to move forward, and the potential for further technology advances is immense. Take computing energy efficiency as an example: there are at least 1,000 times improvement to be gained going forward.

Semiconductor device technology and manufacturing are increasingly being advanced by semiconductor foundries outside the US. While the US is currently still leading in chip design and system applications, fabless companies and system companies are beginning to deplete the pipeline of available technologies. Future economic growth based on chip design activities may stagnate because future ICT advances require a very intimate co-design of device technology and system architecture. Rather than facing stagnation, our country must find ways to break out from our competition and take the lead in semiconductor technology advances.



Major semiconductor companies worldwide. Source: Bloomberg ("*EU Weighs Deal with TSMC, Samsung for Semiconductor Foundry*", February 10, 2021.)

It may be argued that the breakthroughs are best left to individual companies to pursue and the federal government has no role in supporting specific industries. However, simply relying on industry R&D will put the US at a clear disadvantage versus national efforts elsewhere. For a foundational technology as important as semiconductor technology, our country cannot afford to be in second place. Besides, this foundational technology is essential for achieving many other broader societal goals: protecting the environment, sustainable development, affordable and clean energy, and more accessible, higher quality education, which could reduce inequality.

2. Path Forward

Semiconductor technology[5] broadly refers to all forms of micro- and nano-electronics, spintronics, photonics, sensors and actuators, as well as the circuit and system architecture

[5] For simplicity, we use "semiconductor technology" and micro-/nano-electronics synonymously.

design, manufacturing, and packaging technologies. It encompasses the entire food chain from materials, process technology, devices, to circuits, architecture, and systems that are the engines that run the software and user applications. While innovations are needed across this entire food chain, inspirations for what is needed often come from the top – the user application. End-user applications, such as a self-driving car and language translation on a wearable device, inspire innovations down the food chain and set the targets for research and development. At the same time, basic science discoveries may lead to opportunities for new applications and open up a completely different vista. This closely coupled research and development ecosystem requires us to advance research in all areas, rather than some selected silos.

Over the past five decades, semiconductor technology has provided increasing speed, energy-efficiency, and reduced cost per function, generation after generation on a regular cadence. The reduced cost per function not only gives rise to a burgeoning industry, it also broadens the access of technology and opens up economic opportunity to a broader cross-section of society. These phenomenal technology advances have largely been achieved through two-dimensional scaling down of the transistor size. Today, the features of a transistor have reached the single-digit nanometer scale, and will eventually reach the atomic scale, after which further reductions are impossible.

It is important to point out that two-dimensional scaling of transistors is not the only way to keep moving forward. And transistor down-scaling is only a subset of technology advances across the broad spectrum of micro-/nano-electronics. Research has shown that it is fruitful to increase device density at the system level, in addition to increasing the density of the individual transistor. Advanced packaging and system integration solutions can connect individual chips together on a package or directly stack them together in three dimensions. This kind of integration reduces system cost per function by allowing chips of different technologies (such as logic, memory, sensors, power, spintronic, and photonic devices) to be connected together at high density, and thereby increases density and functionality at the system level. Going forward, system integration can extend to monolithic integration of heterogeneous materials and devices on the same chip, possibly providing orders of magnitude improvement in energy efficiency and diverse functionality[6].

These different paths forward are not straightforward problems. They are much more challenging than what we have seen in the past; and solving them will require a broad and coordinated research effort. We will need to look for new materials at the nanoscale, and use new physics that manifest at the nanoscale to broaden the possibilities – quantum physics, topological states, many-body and collective behaviors are just some examples. An enormous effort is needed to search for and characterize new nano-materials with detailed measurements, not to mention the modeling of device physics at the atomic scale in three

[6] Mark Liu (Chairman, TSMC), "*Unleashing the Future of Innovation*," plenary paper, *IEEE International Solid-State Circuits Conference*, February 2021.

dimensions. These are not simple extrapolations from current practices; they require deep understanding through fundamental research to develop new technologies. And because engineering efficient systems requires an end-to-end approach, research on design, architecture, and design methodology must be an integral part of the solution.

3. Critical Needs – Role of the National Nanotechnology Initiative (NNI)

Microelectronics is a field that requires sustained and rapid innovations to meet societal expectations. There is a future in system integration of heterogeneous technologies that requires end-to-end co-design from materials to system architecture. Isolated efforts in silos, such as miniaturization of components, will be inadequate. It is in this context that large-scale efforts, best coordinated across federal funding agencies, can make a substantial difference.

Because end-to-end co-design innovation is essential, there is a strong need from academia and also companies, large and small, to build demonstrators of new devices with new materials and new physics with more than a few devices in order to bridge the lab-to-fab gap. One approach is to use foundry wafers as the starting material and add on layers of new devices. By contrast, the typical academic research project seldom demonstrates more than a handful of devices, which is insufficient for system demonstrations. Enabling the building of system prototypes is essential for research that spans the hardware-software and system architecture boundary in microelectronics research.

3.1 *Public-private-academic partnership for lab-to-fab translation*

The US government-initiated (DARPA and NSF) MOSIS program[7] that started around 1981 unleashed innovation in circuit designs and enabled integrated circuit research and education to proceed in parallel by way of using abstractions that decoupled circuits research from device technology research. Fast forwarding 40 years, the needs of today are drastically different. End-user design innovations are now strongly coupled with chip-/system-architecture innovations. Circuit/architecture innovations often derive from the use of new device nanotechnologies and their integration; conversely, device nanotechnology innovations are driven by application needs and require circuit/architecture level co-design and system-level demonstrations to be relevant. In short, co-design across the technology stack is the future of tomorrow's systems; and innovations and investments are needed to push beyond the traditional approaches.

University cleanrooms (such as those supported by the NSF NNCI[8]) today are missioned to facilitate basic science discoveries and engineering research at the single- or few-devices level. These facilities, while they are successful in fulfilling their stated missions, do not have the capability to fabricate state-of-the-art transistors that are relevant to practical applications, nor do they have the capability to yield large enough number of devices for meaningful circuit demonstrations. The ability to demonstrate circuit and system-level functionality and benefits,

[7] https://www.mosis.com/, accessed January 27, 2021.
[8] https://www.nnci.net/, accessed February 26, 2021

using advanced technology nodes, or using emerging, but not-yet-commercialized technology, or using lab-scale technology developed at universities, is the essential paradigm for breaking down abstraction boundaries to effect co-design and co-optimization from materials to system applications – a technical direction that is highlighted by earlier studies on the subject[9].

The time-cycle for hardware explorations are currently much longer than software experimentation and computer modeling. The pace of progress in hardware is not keeping up with the pace of advances in software and applications. Yet, we know that the software and the hardware must go hand-in-hand. We cannot run today's software on hardware that are 20 years old.

3.2 *Value proposition – NNI, the source of the pipeline*

As much as science likes a simple story, the history of semiconductor technology advancement has never been a straight line of two-dimensional (2D) scaling down of the device size, and it is certainly not simply about developing the next-generation lithography. New physics (quantum mechanical tunneling, strained silicon), new materials (copper, low-k dielectric isolation, high-k gate dielectrics, metal gate electrodes), new fabrication methods enabled by chemistry and materials fundamentals (chemical-mechanical polishing, atomic layer deposition), new design methodologies (TCAD and EDA tools, design-technology co-optimization that relies on accurate and fast models and simulation methods), all contribute to the phenomenal growth in energy efficiency, speed, and functionality of information and communication technology over the past 50 years.

Yet, microelectronics is at a crossroads today. The maturation of 2D scaling has driven the development of microelectronics in qualitatively different directions that promise dramatically enhanced performance and energy efficiency. In particular, there is an acceleration in adopting new nanomaterials and new devices at the nanoscale into the broad microelectronics ecosystem. *This is prefaced by two decades of investments in nanotechnology by the NNI at the national scale, and sustained investments in basic sciences by federal agencies such as the NSF and the DOE that have created a long and broad research pipeline ready for translation into practical technologies based on new materials, new physics, new fabrication methods, and new system architectures using new device technologies.* The recent resurgence of microelectronics (*e.g.*, the DARPA ERI program) as a focused area of research is indicative of the vast opportunity in front of us.

The highest impact will come from end-to-end, hybrid integration of heterogeneous technologies (logic, memory, interconnect, photonics, spintronics, nanomechanical sensors/actuators, RF/mm-wave, communication) through all forms of 3D integration. Heterogeneous on-chip integration is facilitated by acquiring Si CMOS wafers from foundries and integrating beyond-CMOS devices on to these wafers. An early example is shown by the

[9] DoE report: "Basic Research Needs for Microelectronics," Oct 2018. https://www.osti.gov/biblio/1545772-basic-research-needs-microelectronics, accessed January 27, 2021.

IARPA project on Trusted Integrated Circuits (TIC)[10] in which a variety of beyond-CMOS devices are integrated onto foundry CMOS wafers using facilities at universities (NSF NNCI nodes). These include reconfigurable photonic networks, wavelength tunable hybrid III-V/silicon laser, nanomechanics, piezoelectrics, AlN MEMS, resistive switching memory, SAR ADC, wideband RF receiver, neurocomputing associative memory – integrated onto foundry silicon CMOS, analogous to a "sauce plus pasta" menu that is extremely rich in functionality[11]. The CMOS circuits from the foundry wafer provide the control, sense, amplification, and computation for system-level functionality required for lab-to-fab translation demonstrations. Similarly, the DARPA 3DSoC program is pursuing dense monolithic 3D integration of a variety of heterogeneous nanotechnologies (silicon CMOS, carbon nanotube FETs, Resisitive RAM) at SkyWater Technology Foundry in Minnesota.

University cleanrooms (*e.g.,* NSF NNCI facilities) excel in discovery and they are not missioned for larger scale circuit/macro level demonstrations, let alone complete systems that show system-level benefits. For a truly new technology, foundry access is impossible because until the industry itself decides to do internal research, nothing is available. Currently, the value of these discoveries is largely unrealized because there is no means to integrate them into system scale demonstrations to prove their value and to de-risk their adoption by industry. In general, commercial foundries are unable and unwilling to pursue such transformative work, which is incompatible with their business models. Also, historically, even when industry does decide to invest in such transitions via internal research, they keep the new capabilities as proprietary trade secrets. Industrial fabs are further inhibited in these new domains by their strict contamination controls and regimented process flows, and operate with costly 300 mm tools. Hence, introducing new materials and new devices require extensive initial proof of efficacy before the risk and efforts can be justified. A foundry is not going to create a new device recipe to facilitate creation of a new technology that relies on system demonstration to show potential benefits. Yet, the history of academic research includes many examples of successful systems that were not only designed, but actually built, at universities. This has essentially ended. Therefore it is necessary to create new capabilities that bridge this "innovation lab-to-fab gap" by connecting academic research labs and commercial fabs with new prototyping facilities and new kinds of partnerships

The challenge today is in demonstrating the benefits of these innovations beyond the laboratory scale of 1 to 1000 devices. Innovation at system and architecture level are meaningful (that is solving meaningful problems) only when demonstrated at scale. For example, array-level characterization is critical for 3-sigma statistics including variations, disturbances, and aging – issues that require understanding of fundamental physics for solutions. Often, it is possible to mitigate some of the device weaknesses at the circuit level.

[10] https://www.iarpa.gov/index.php/research-programs/tic, accessed January 27, 2021.
[11] https://scholar.google.com/scholar?start=0&q=N66001-12-C-2008+OR+N66001-12-C-2013+OR+N66001-12-C-2009+OR+N66001-12-C-2011+OR+N66001-12-C-2010+OR+N66001-12-C-2012&hl=en&as_sdt=0,47, accessed January 27, 2021.

While one can explore the circuit/system design space using simulation tools (e.g. NeuroSim[12]), the underlying models used in these tools must be validated by actual experimental data.

3.3 *Present solutions*

A small subset of university researchers have access to wafers from foundries through ad hoc personal connections (along with lengthy legal processes) and post-process these wafers above the back-end-of-the-line (BEOL) layers to add the "sauce on the pasta" in the university cleanrooms. At university cleanrooms, demonstrations at the 1,000 device scale are generally the limit of such experimental settings. This limit is due in part to the impossible dual tasks of maintaining stable processes while at the same time allowing maximum flexibility for exploratory research.

In a very small number of cases where new devices are emerging from commercialization (*e.g.,* RRAM, MRAM), university researchers with special agreements may tape out circuits using those emerging device technologies at foundries. However, even in those cases, foundries only provide macro cells as a black box. A designer neither can try new circuit topologies using individual transistors and memories, nor can she simulate the device using a SPICE model of the unique devices because the device models are not available.

3.4 *Proposal for a National Facility*

We propose to establish a National Facility to facilitate demonstration of realistic systems of emerging technologies. Having such lab-to-fab translation of systems technologies makes academic research relevant and will go far toward advancing device/process technology as well as architecture innovations in US universities.

The mission of such a National Facility would be (a) fast turn-around experimentation of chip-scale and package-scale systems, (b) achieve flexibility at scale, and (c) facilitate lab-to-fab translation of systems technology, thereby making academic research relevant for advancing foundational microelectronics technology for the country. This national facility will be analogous to a "MOSIS for technologists and system designers". This National Facility will focus on system-level demonstrations and address technology questions related to scale-up of materials/device innovations, and its mission will be distinct from existing user facilities such as the NSF NNCI and user facilities in national laboratories which focus on discoveries and basic science.

The National Facility[13] will consist of well-equipped facility/facilities along with a network of regional hubs across the US. The hubs will take as starting material completed wafers with CMOS circuits from foundries. They will be user facilities that integrate various materials and devices on the foundry wafers or baseline technologies developed locally. These will be wafer

[12] https://shimeng.ece.gatech.edu/downloads/

[13] In one estimate, a National Facility such as the one described here would require funding for US$ 1.6B over the course of 4 years.

scale fabrication (albeit smaller diameter wafers ≤ 200 mm) aimed at systems demonstration. There will be permanent staff who work with visiting researchers to translate the new processes developed at universities into capabilities for system prototypes. There will also be protocol in place to transfer the successful technology developed at the university hubs to the central core for large scale integration. There is a general agreement now that semiconductor technology in the next decade and beyond will look very different from what we have today. These hubs will play a critically role for US leadership in that exciting future.

To make this system prototyping capability broadly available to academic researchers, there will be a design ecosystem that consists of a wafer brokerage and well-defined design interfaces that specify the process technology level interfaces (*e.g.*, alignment marks, materials and planarity of the top surfaces) as well as the circuit design protocols. Some level of standardization of the fabrication and design methodology is needed. Design enablement such as PDKs, foundational IPs, parametric test structures and device models should be made available. There will be a one-stop shop for handling legal processes and non-disclosure agreements, collecting and composing multiple design projects into mask sets, distribution of foundry wafers to users, and serve as the interface to foundries.

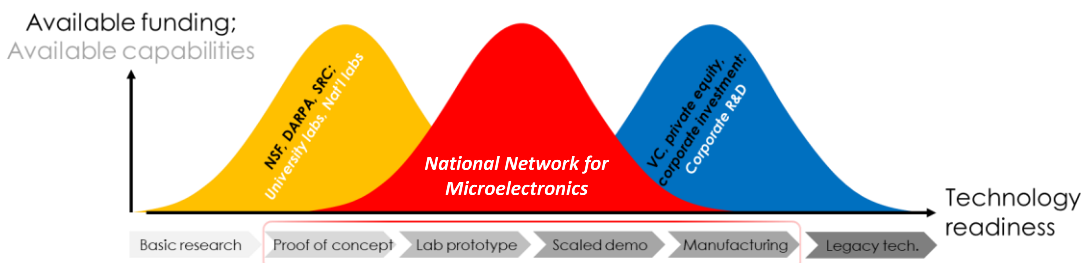


Fig. 1 Lab-to-fab translation fills a much needed gap in advancing innovations along the technology readiness timeline.

Elements of such a National Facility exist in other parts of the world, but not here in the US. The TSRI in Taiwan[14] provides foundry shuttle wafers for Taiwan university researchers working at the memory array level. TSRI can do post-processing on such shuttle wafers to fabricate and integrate new devices such as MRAM, RRAM, ferroelectrics, and gas sensors. In France, CEA-LETI worked with a US university and offered 130-nm CMOS+RRAM/PCM technology for system demonstrations[15]. Device fabrication at national facilities at foreign countries (such as TSRI and CEA-LETI) require the researcher to have a collaboration project with the foreign party and is not a simple fee-for-service arrangement. IMEC (Belgium)[16] has the capability to prototype

[14] https://www.tsri.org.tw/en/index.html, accessed January 27, 2021.
[15] T.F. Wu, B.Q. Le, R. Radway, A. Bartolo, W. Hwang, S. Jeong, H. Li, P. Tandon, E. Vianello, P. Vivet, E. Nowak, M.K. Wootters, H.-S. P. Wong, M.M. Sabry Aly, E. Beigne, S. Mitra, "A 43pJ/Cycle Non-Volatile Microcontroller with 4.7µs Shutdown/Wake-up Integrating 2.3-bit/Cell Resistive RAM and Resilience Techniques," *International Solid State Circuits Conference (ISSCC)*, paper 14.3, San Francisco, CA, February 17 – 21, 2019.
[16] https://www.imec-int.com/en/ic-link, accessed January 27, 2021.

beyond-CMOS devices at 200-mm and 300-mm wafers, but US universities can participate only through joint projects.

4. Broader Societal Impacts and Workforce Development

We have come a long way from having a handful of computers in government laboratories to billions of mobile computing devices that enabled nations to leapfrog to the internet-connected world. To ensure progress, we must lower the barrier for ***all*** US researchers to build and demonstrate nanosystems at a scale that is sufficient to convince industry that a new technology has a chance of success. This will unleash innovation and ensure US supremacy in end-user product design.

To remain competitive, the US must run faster than our competitors. We must have a robust semiconductor supply chain not only for manufacturing, but also for research and development. Semiconductor technology and manufacturing are “high know-how” activities. Thus, manufacturing and R&D must go hand-in-hand. Incentivizing companies to build semiconductor manufacturing plants in the US is only a stop-gap solution. A state-of-the-art semiconductor fab will be obsolete as soon as the first chip rolls out of the manufacturing plant. There must be consistent, constant renewal and development of newer generations of technology to maintain competitiveness. Investing in R&D is essential to protect government investments in semiconductor manufacturing. Toward this end, we must have a knowledgeable workforce that supports an industry with expanding societal impact.

Electrical engineering undergraduate student enrollment has been declining across most US universities. STEM students have flocked to related fields with higher compensation or with the cachet for addressing large societal challenges. We have a duty to inform students the importance of semiconductor technology as a foundational technology for advancing broad societal goals. From protecting the environment, sustainable development, affordable and clean energy, to quality education and reduced inequality, semiconductor technology is foundational for solving these societal challenges.

While we are not aware of studies of why electrical engineering enrollment is declining, anecdotal information from current students inform us that long learning curve and high barrier for technology access are two of the key factors depressing interest in the broad fields of microelectronics and nanosystems. To address these issues will require a rethinking of pedagogical methods as well as new research that may shorten the learning cycle for students. Examples of such new research include open-source designs and design methodologies, AI-enabled semiconductor process equipment, and high throughput nano-materials engineering and nano-characterization methods.

Channeling nanoscience and nanotechnology research toward advancing semiconductor technology will not only enable the entire semiconductor industry to thrive and prosper, but also to help realize a human-centric, intelligence-embedded, equitable society.