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Nanotechnology: From Laboratories to Commercial Products

Summary: Testimony is provided on the current state of nanotechnology research and development (R&D), as well as, its future opportunities and challenges. The National Nanotechnology Initiative (NNI) is discussed; and its successes on many levels (new knowledge generation, patents, technological innovations, infrastructure investments, and workforce training) are highlighted. The impact of federal funding in nanotechnology and the need for future investments are summarized. Additionally, forthcoming prospects of nanotechnology are envisioned to impact several sectors (Energy, Environment, Health, Medicine, Information Technology). Finally, the testimony will detail how the University of Texas at Austin, specifically the Center for Nano- and Molecular Science and Technology, has significantly impacted STEM education, and the nations nanotechnology workforce via establishment of focused research, educational and training programs, dedicated user-facilities, and grant-assistance programs.

Chairman, Rep. Lamar Smith (R-TX) of the Committee on Space, Science and Technology; and Chairman, Rep. Larry Bucshon (R-IN) of the Research and Technology Subcommittee, my name is Keith J. Stevenson, and I am a Professor of Chemistry and the Director of the Center for Nano- and Molecular Science and Technology (CNM) at The University of Texas at Austin. I appreciate the opportunity to appear before you today to provide my insight into the current state of nanotechnology research and development (R&D), as well as, its future opportunities and challenges. You have also asked me to address the National Nanotechnology Initiative (NNI) and the ways my University is addressing STEM and workforce needs.

In a relatively short interval for an emerging technology, nanoscience and nanotechnology research has provided significant economic impact in numerous sectors including semiconductor manufacturing, electronics, catalysts, medicine, agriculture, and energy production. Since 2001, the National Nanotechnology Initiative (NNI) has served as the vehicle for coordinating and reporting on activities in this dynamic field across the Federal Government. At least twenty departments, independent agencies, and independent commissions have participated in the NNI, representing a wide variety of missions, responsibilities, interests, and expertise. By many measures, the NNI has been assessed, evaluated and reviewed for impact on scientific production, commercialization, technology transfer, STEM and workforce development (see www.nano.gov for publications). Several reports now strongly document that NNI has been a tremendous success on many levels including scientific and technological merits and broader societal and environmental impacts. Yet, the current federal deficit is the result of significant cuts to the federal investments in fundamental research and higher education at a time when other nations (Europe, China, Korea, Saudi Arabia, Singapore, Russia), having learned from the unprecedented success of US technological innovation, have dramatically increased their investments in nanoscience and nanotechnology. As a result, the US risks losing its competitive advantage in advancing fundamental knowledge; in the discovery of breakthrough materials; in the commercialization of innovative technologies, and in the scale-up and manufacturing of new products. It is abundantly clear that continued and increased investments in research and education in nanoscience and nanotechnology are required for the US to maintain a strategic advantage in nanotechnology and related sectors (e.g. Communications, Electronics, Energy, Health, and Environment).

You have asked me to address the following questions:

1. What is the importance of federal funding to fundamental advances in the area of nanotechnology?
2. What fundamental questions in nano-science are fruitful to further investigation, and why are these questions appropriate for federal funding?
3. What and where is the future of applications of nanotechnology research?
4. What potential areas will most benefit from fundamental advances in nanotechnology? Please explain.
5. What additional ways could the federal government be supportive of nanotechnology initiatives and research?
6. How is your University working to address the relevant STEM and workforce needs in nanotechnology.

1. Importance of federal funding on fundamental advances in nanotechnology.

Since the launch of the National Nanotechnology Initiative (NNI) in 2001 the US has established itself as a foremost leader in nanoscience and technology and continues to maintain prominence in a variety of important science, engineering and technology areas. In particular, federal support has allowed us to learn a great deal about the unique and important properties of matter that emerge when confined to the nanoscale. A tremendous amount of new knowledge has arisen from federal support of nanoscale science and engineering evidenced by the establishment of at least 50 new scientific journals (e.g. Nature Nanotechnology, Nano Letters, ACS Nano, Nano Today, Small, Nanomedicine, Nanotoxicology) dedicated to nano-related topics with high scientific impact factors. The nano community is now well positioned to address more complex issues of how the functionality of these properties can be tuned and exploited in real world materials and devices, and more importantly how we can predict, design and control the functionality of new materials. For instance, the launch of several new research initiatives (Materials Genome, Mesoscale Science, Brain Initiative) are inextricably intertwined with the advances and breakthroughs made in nanoscience and nanotechnology. In many respects, these initiatives have sprung out of and build upon the fundamental advances made in the support of nanotechnology research.

2. Fundamental questions worthy of further investigation for fruitful outcomes.

There remain a multitude of fundamental questions that are worthy of further investigation whose pursuit for their answers will produce new scientific knowledge and advances. For example, five "grand challenges" adapted from DOE BESAC workshop reports that involve nanoscale science and engineering could include:

- *"How do we perfect cheap, efficient and scalable ways for the synthesis and fabrication of nanomaterials and nanostructures with tailored properties?"*
- *"How do we characterize and control nanoscale materials and phenomena?"*
- *"How do we study and evaluate the environmental, health, safety, economic and societal impacts of nanomaterials and nanotechnology?"*
- *"How can we predict and design new properties of nanomaterials?"*
- *"How do we foster the safe and ethical development of nanomaterials and technologies?*

These grand challenges in nanotechnology raise even more explicit fundamental questions that if answered in detail could enable tremendous scientific and technological advances. For instance, not only do we want to increase the efficiency of nanosynthesis and nanofabrication methods, can we develop methods with precise enough control to facilitate the assembly of elaborate multifunctional architectures, atom by atom, from the bottom up. Put another way: can we engineer functional systems at the atomic and molecular scale? The attempt to answer these questions provides the basis of nanotechnology. If we could do so, we could achieve several so-called "holy grails" in several areas including artificial photosynthesis (energy), single molecule cancer detection (disease diagnostics, health), and quantum computing (information technology). Yet it is important to emphasize that the pursuit is more important than achieving a specific outcome. "Use-inspired" and goal driven research has great value for steering and producing rewarding outcomes, but fundamentally the scientific process involves many diversions, explorations, and unexpected observations that produce fortunate discoveries not previously imagined or conceived.

3. Future applications of nanotechnology research.

It is almost impossible to forecast everything that nanotechnology will bring to the world considering that it is still a relatively underdeveloped field. However, in our journey to understand, to think, to envision, to innovate there will be many new significant scientific discoveries and breakthroughs that produce new applications. Several future applications of nanotechnology will be realized and will be evidenced by the continual growth of the number of relevant patents and scientific publications. One newly emerging theme is idea of guided self-assembly of multifunctional nanocomponents into three-dimensional circuits and fully-integrated devices. For instance, the nano-bio-medical subfield could design such systems to improve the tissue compatibility of implants, or to create scaffolds for tissue regeneration, and even construct three-dimensional "printed" artificial organs. Other applications will possibly emerge that involve molecular nanosystems and heterogeneous networks in which molecules and supramolecular structures serve as distinct multifunctional devices (nanobots) or self-powered, autonomous biosensors. The idea of "edible electronics" is emerging where medical devices could be taken orally or implanted in the body to measure biomarkers or monitor health problems. The edible battery also could be used to stimulate the targeted release of drugs for the treatment of cancer. Other bio-nano systems will also enable the direct interfacing of humans with wearable electronic devices for telecommunications and for continuous health and environmental monitoring.

4. Beneficial outcomes from fundamental advances in nanotechnology.

There are many beneficial outcomes that will result from fundamental advances in nanotechnology. I provide a few case examples where there will be broad impact.

Electronics and Computers. We will continue to see the improvement of flexible, light weight display screens on wearable electronics devices as well as the increase in the density of memory chips. Memory chips are now being developed for future information storage applications with feature sizes below 20 nm such as terabyte memory arrays and ultra-fast gigabyte nonvolatile memories. There will be a continued reduction in the size of transistors with lower power demands used in integrated circuits which will lead to faster, more powerful lightweight computers with a much smaller footprint.

Telecom and Datacom. The ability to engineer and integrate both optical and electrical nanomaterials will bring about tremendous advances in telecommunication and data communication sectors by providing low power, high speed, interference-free devices such as electrooptic and all-optical switches integrated on computer chips. These developments will lead to the further integration of related components such as the massive storage of data on compact storage devices with high-performance computing features. This in turn will enable new high speed communications and high performance information processing that will impact several sectors (Information Technology, Energy, Health, Medicine, Environment).

Energy. Nanoscience and technology will significantly impact the renewable energy sector. For instance, the incorporation of low-cost, earth abundant nanomaterials in energy conversion and storage device architectures will improve the efficiency, energy and power densities of fuel cells, capacitors, and batteries for portable applications, transportation, and large scale grid storage. These energy storage and conversion devices are important to many areas of technology, including portable electronics, medical devices, power tools, transportation and the storage of electricity produced by intermittent renewable sources (wind and solar). Advances in this area will accelerate the design and implementation of on-site energy generation and decentralized energy generation systems. These systems will change how we generate, deliver and use electricity. The development of decentralized generation networks enables collection of energy from many sources which offer the promise of reducing environmental impacts and improving our security of supply.

Environment. Nanotechnology will play a heavy role in addressing critical environmental problems for water purification and remediation. For instance, new nanomembrane technologies will enable efficient water purification processes, and facilitate the development of improved remediation strategies for clean-up of hazardous waste streams. Nanomaterials in various shapes/morphologies (particles, tubes, wires, fibers) with be made to function as adsorbents and catalysts for the detection and removal of toxic gases (SO_2, CO, NO_x, H_2S), inorganics contaminants (arsenic, nitrate, heavy metals), organic pollutants (polyaromatic hydrocarbons, Bisphenol A) and biological substances (spores, viruses, bacteria). Nanotechnology will also create new 'green' synthesis and processing technologies that can minimize the generation of undesirable by-products in effluents and emissions streams.

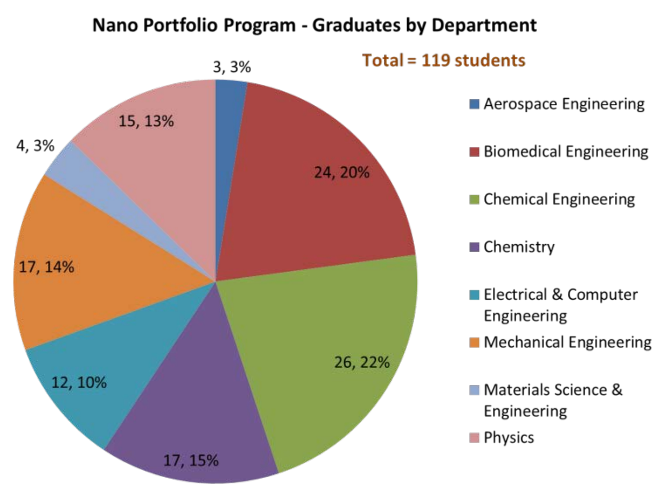
Health Care, Medicine, Biodiagnostics. There will be rapid advancement of the development of biological nanosensors for fast and accurate monitoring of health and biological functions at the point of care level. Nanotechnology is now facilitating the creation of 'lab on a chip' technologies involving the assembly of artificial organs to enable organ-based screens for drug development and treatment.

5. Needs for federal government support in nanotechnology.

There remains a critical need for the continued investment in basic research and in small- and intermediate-scale instrumentation for characterization and study of nanomaterials. The continued support of established larger-scale NNI facilities and networks is crucial, as well as, increased investments of multi-disciplinary research activities that integrate both theorists and experimentalists. The recent federal focus on the materials genome and mesoscale science initiatives are inextricably intertwined with advances in nanoscience and nanotechnology so support of nanotechnology will aid in advancing new research initiatives. Existing nanotechnology facilities should be leveraged to attract grant funding in other emerging areas. New investments for the training of a nanotechnology workforce (undergraduates, graduate students, postdoctoral fellows, and early stage scientists) is still vital for maintaining a competitive scientific and technological advantage. While the most recent focus on nanotechnology funding includes support of environmental, health and safety (EHS) areas, solar energy conversion, sustainable nanomanufacturing, and nanoelectronics, the support for work in newly emerging areas (nanophotonics, nanobiotechnology, energy, health and medicine) should be increased. While NNI and other mechanisms have facilitated the establishment of an extensive nanotechnology infrastructure for nanofabrication and characterization capabilities, increased and continued investments need to be made for evolving nanotechnology discoveries from the research laboratory into innovative technologies. Both new facilities and networks should be established and the existing capabilities and user facilities should be supported as they broadly support R&D on many levels including nanoscale characterization, synthesis, simulation and nanomanufacturing.

6. How is your University working to address the relevant STEM and workforce needs in nanotechnology.

Since its founding in the 2002 by Professor Paul Barbara, UT-Austin's Center for Nano- and Molecular Science and Technology (CNM) (www.nano.utexas.edu) has proven to be a great mechanism for the recruitment, retention, education and training of a nanotechnology workforce. The CNM early on established a new certification program in interdisciplinary nanoscience and technology fields for graduate students enrolled in department-level science and engineering programs. Now, nearly 120 graduate students have obtained their nanotechnology certification. These well-trained graduates are now working in academics, national laboratories, nanotech industries and small businesses.



The CNM also sustains grant-initiated educational outreach programs focusing on nanoscience by helping faculty PIs develop and host educational and outreach activities such as summer science camps, building tours of nanotechnology user facilities, and in conducting nanoscience demonstrations. Over this time, the CNM has produced several publications for communicating and educating the general public on nanotechnology. These activities help communicate how nanotechnology is relevant and engaging and acceptable by involving them in nanoscience experiments they can do themselves. Examples, include: "New Nanotech from an Ancient Material: Chemistry Demonstrations involving Carbon-based Soot," *J. Chem. Ed.* **2012**, *89*(10), 1280; and, "A Simple Method for Production of Nanoscale Metal Oxide Films from Household Sources," *J. Chem. Ed.* **2013**, *90*(5), 629.

The CNM has also worked with the College of Natural Sciences (CNS) at UT-Austin to achieve a large scale reinvention of its undergraduate research paradigm that was faculty initiated. This program was originally conceived in the Departments of Chemistry and Biochemistry and Molecular Biology (Stevenson, Ellington, Stephens) in response to a 2005 NSF Undergraduate Research Center solicitation. This program has now morphed into what is known as the "Freshman Research Initiative" (FRI) (www.cns.utexas.edu/fri) that addresses the following goals: 1) attract and retain students in STEM, 2) engage large numbers of students with diverse backgrounds in authentic research, 3) improve undergraduate retention and academic success (g.p.a. and graduation rates), 4) bridge the gap between education and research by using research as a vehicle for teaching, 5) create an environment in which the effects of research training can be assessed, 6) drive STEM curriculum reform, and 7) enhance interdisciplinary collaborations that promote education through undergraduate research.

This newly integrated research and teaching model has now been proven to increase the number and diversity of students participating in undergraduate research experiences by involving a large number of incoming freshmen in an intimate research experience over the course of their first two years on campus. Students are recruited during freshman summer orientation and are encouraged to participate because FRI program offers a research-based, smaller-class alternative to required freshman courses, is linked with other high-demand courses, and offers closer interaction with research faculty. Students begin by enrolling in Research Methods, then choose one of >25 Research Streams, and participate in research as part of their Stream through the subsequent Spring, Summer and Fall. Selected sophomores may remain in the program through the following Spring to mentor incoming freshmen. For example, as a founding faculty member of the FRI program, I have run a research stream since 2005 on "Nanomaterials for Chemical Catalysis" (https://sites.google.com/site/frinanostream), which now has trained and educated over 400 undergraduates of diversity (35% minority, 50% female) in the area of nanoscience and technology. This program has significantly improved retention (70% on track to graduate within 4-years) and graduation rates (a doubling) of at-risk, underrepresented students enrolled in CNS majors. This program has also expanded interactions with corporations, industry researchers, and local small businesses and provided new opportunities such as internships and jobs after graduation.

Photo of undergraduate students participating in the 2014 Nano-Stream at UT-Austin.

The CNM has also supported several large scale research centers funded by the NSF and DOE. For instance, currently the CNM provides administrative support, facilities training and management, and educational resources to support a $15M DOE funded Energy Frontier Research Center (EFRC) based on solar energy and electrochemical energy storage (www.efrc.nano.utexas.edu). Since 2009 this DOE program has trained and educated over 72 graduate students and postdocs that now have entered the energy workforce. This program is currently pending a five-year renewal.

Specific Examples of the Value Added to STEM and Workforce Needs:

CNM sponsored programs integrate education, research and training to increase students' competitiveness for fellowships, national awards, graduate school, postdoctoral fellowships and industrial positions

- Educational outreach increases the public's appreciation of scientific and engineering excellence in nanotechnology at UT-Austin
- Secondary school students are recruited to UT-Austin as science and engineering majors

- Undergraduates at other campuses are recruited to UT-Austin as graduate students
- CNM resources and programs are leveraged by CNM-affiliated faculty to initiate and sustain their own education and teaching efforts for federal grants
- CNM supports mechanisms for modernization of undergraduate education and training programs to increase students' competitiveness in the workforce
- CNM runs the Doctoral Portfolio Program in Nanoscience and Nanotechnology
    - 119 graduate students have earned credentials to date
    - Current enrollment of >60 students representing >10 disciplines
- CNM supported the Summer Nanoscience Academy aimed at educating HS students and Teachers
    - Originated as a NSF IGERT-funded educational outreach activity
    - More than 100 HS students and teachers have participated in the program since its inception in 2007
- CNM established a UT Pan Am Materials Partnership to increase minority participation
    - Funded UTPA undergraduates' trips to UT-Austin for training and data acquisition on CNM equipment
    - Pairs UTPA undergraduates with UT-Austin graduate students and faculty to consult on nanotechnology research
    - This program was leveraged in a past $1.5M NSF CCI Phase 1 proposal
- Supported the Partner University Fund (PUF) international student/faculty exchange
    - Funded student and faculty exchanges between CNM And Universite Joseph Fourier, Grenoble, France
    - Supports fellowships to attend Summer European School on Nanosciences and Nanotechnologies (ESONN) in Grenoble, France

The CNM also provides training, management and maintenance of a suite of $28M in nanofabrication and analysis tools to a user base of more than 300 students, postdocs and faculty, annually. The CNM works with UT-Austin faculty and other Centers to identify instrumentation needs and acquire new instrumentation capabilities via federal and private funding. CNM staff technicians and facility managers consult with faculty to develop customized tools and techniques for their research needs. Other investments associated with the Microelectronics Research Center (former host of a National Nanotechnology Initiative Network site) and the Texas Materials Institute complement CNM's nanotechnology resources and infrastructure investments.

Specific Examples of the Value Added to STEM and Workforce Needs:

- Increased research productivity and training of students through well-managed and maintained nanotechnology facilities with minimal downtime

- Access to of state-of-the-art nanotechnology facilities on campus improves recruitment and retention of undergraduates and graduate students.
- Hands-on, state-of-the-art training provided to increase competitiveness in the STEM workforce

I would like to close by restating my sincere appreciation to this committee, Congress, and the American people for the continual support of fundamental core science areas that have facilitated tremendous advancement of nanoscience and nanotechnology in this country.