Nano.gov
U.S. National Nanotechnology Initiative

Nanotechnology 101: The Biggest Thing You've Never Seen

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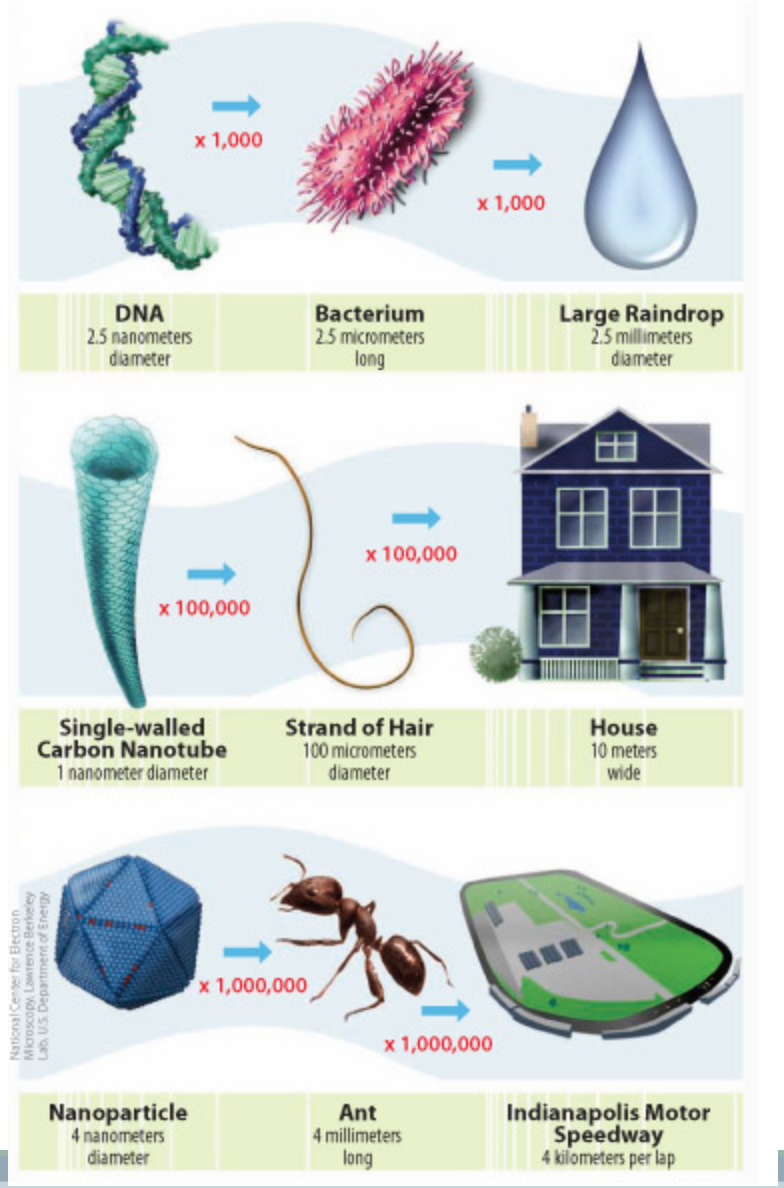
www.Nano.gov

Outline

- Just what is the nanoscale?
- What is unique about nanotechnology?
- Some examples of nanotechnology based products currently available
- What will nanotechnology do in the future?
- Wrap-up

What is Nanotechnology?

- Control of matter and processes at the atomic and molecular level
  - Typically 100 nanometers in two dimensions
    - Nanometer is one billionth of a millimeter
      - Single sheet of paper is about 100,000 nm thick
- Conventional physics often breaks down at the nano-level
  - Affects electrical, optical, thermal and mechanical properties



Source: National Nanotechnology Initiative (www.nano.gov)

NNI Vision

A future in which the ability to understand and control matter at the nanoscale leads to *a revolution in technology and industry that benefits society.*

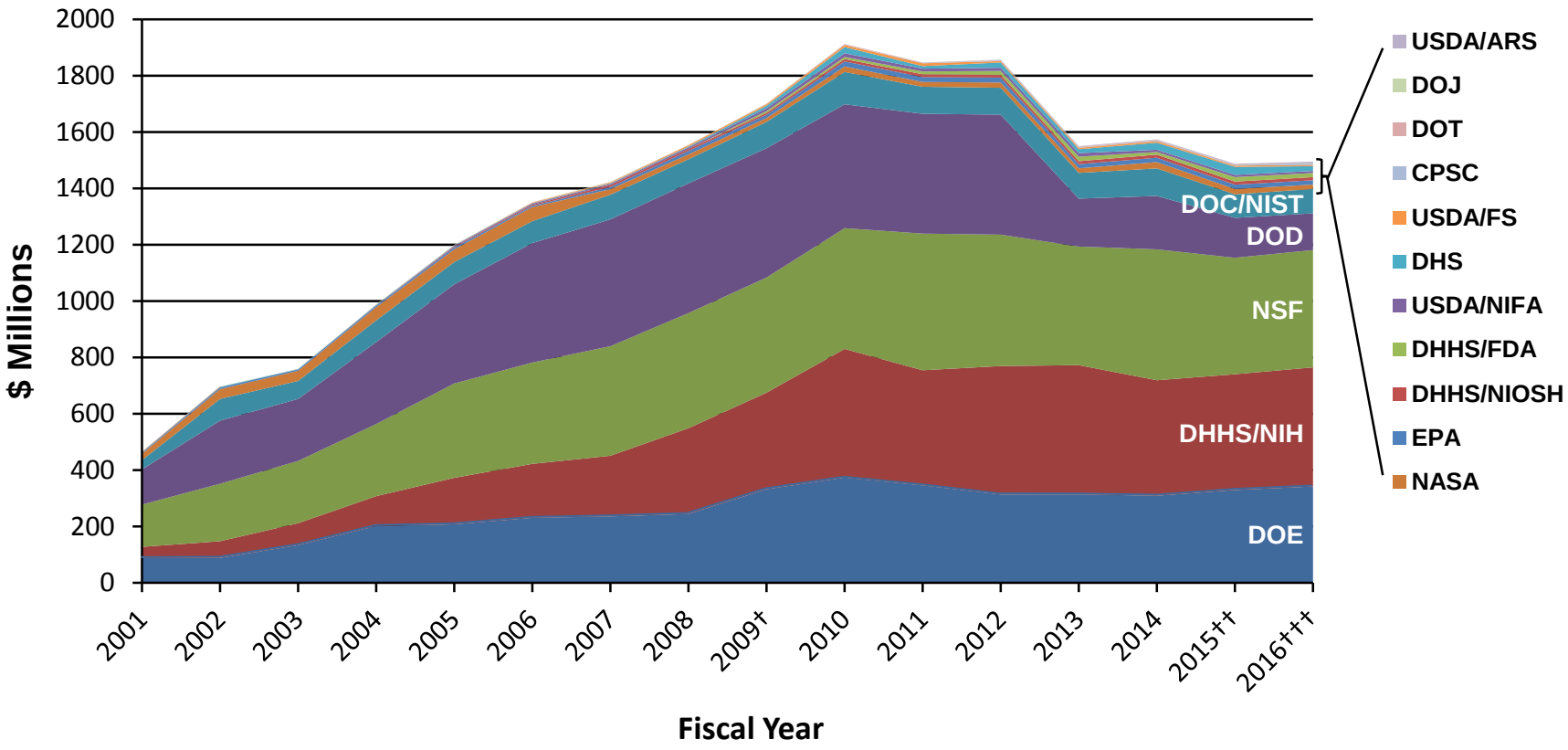
The National Nanotechnology Initiative (NNI)

- Established in 2000 by President Bill Clinton
- Intent of the NNI is to provide a framework for member agencies to work together to:
  - Advance world-class nanotechnology research
  - Foster the transfer of technologies into products for commercial and public benefit
  - Develop and sustain educational resources, a skilled workforce and the supporting infrastructure and tools to advance nanotechnology
  - Support the responsible development of nanotechnology
- The NNI is a coordinated initiative not a distinct funding program

Signature Initiatives

- Sustainable Nanomanufacturing
- Nanoelectronics for 2020 and Beyond
- Nanotechnology Enhanced Solar Energy Capture and Conversion
- Nanotechnology for Sensing
- Nanotechnology Knowledge Infrastructure

Funding by NNI Agency, 2001-2016

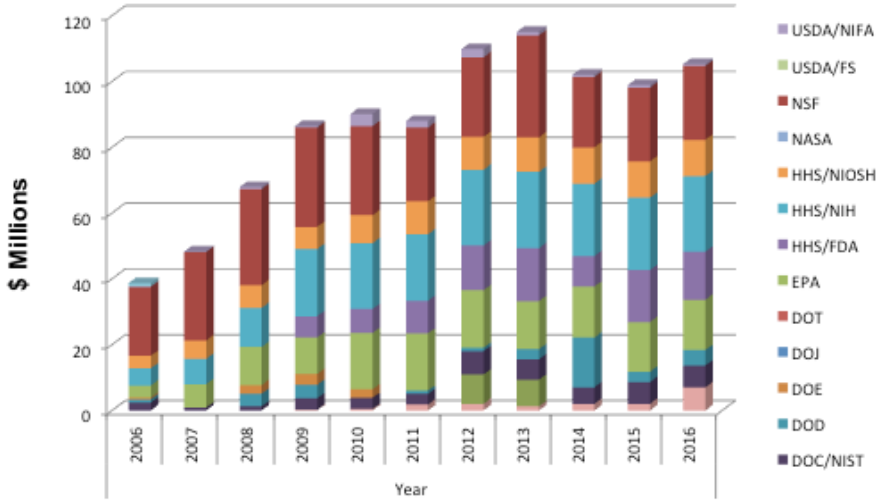


† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE ($293 million), NSF ($101 million), NIST ($43 million), and NIH ($73 million).
†† 2015 estimated based on 2015 enacted levels and may shift as operating plans are finalized.
††† 2016 Budget.

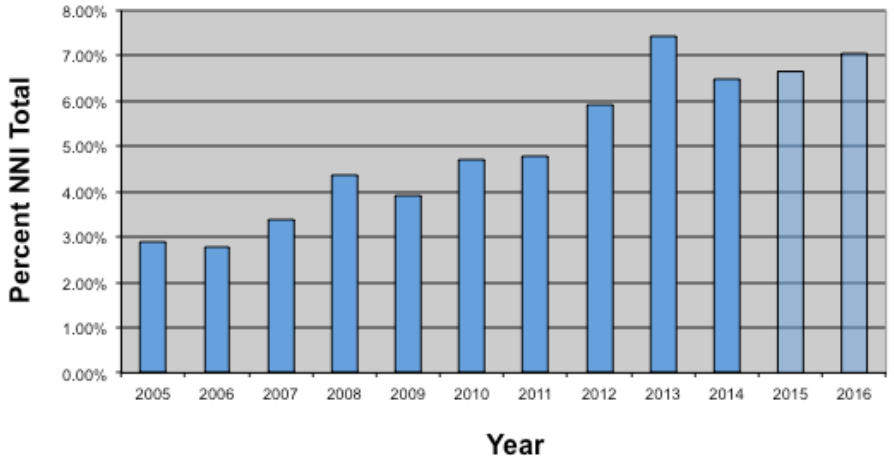
NNI EHS Priorities

- Federal agencies continue to target and accelerate nanoEHS research by
  - Prioritizing nanomaterials
  - Establishing standard measurements, terminology, nomenclature, and assay methods
  - Developing informatics and predictive modeling tools
  - Stratifying knowledge for risk assessment
  - Partnering to achieve the NNI EHS research goals, both domestically and internationally

EH&S Investments by Agency



Percentage of NNI Budget Invested in EH&S

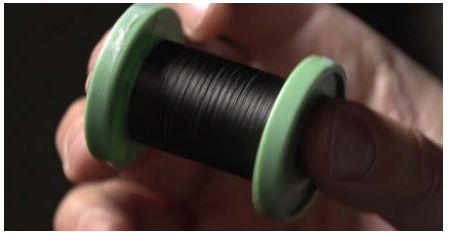


Some Nano-Factoids

Lux Research, February 2014

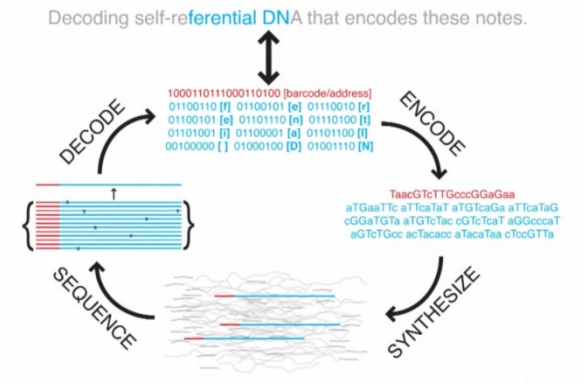
- Worldwide governments, corporations and VCs invested **$18.5 billion in 2012** (8% increase over 2010)
  - The **U.S. contributed 36%** of this amount – leads in government and corporate spending
  - Corporations expanded spending by 21%, governments by 5% and private investors by 10% (2012 compared to 2010)
- **Global value of nano-enabled products, nano-intermediates and nanomaterials predicted to reach $4.4 trillion by 2018.**
  - The **revenue** from nano-enabled products grew from $339 billion in 2010 to **$731 billion in 2012**.

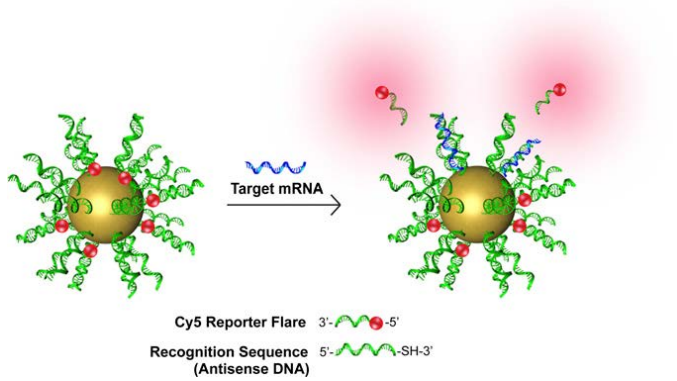
President Clinton's Vision



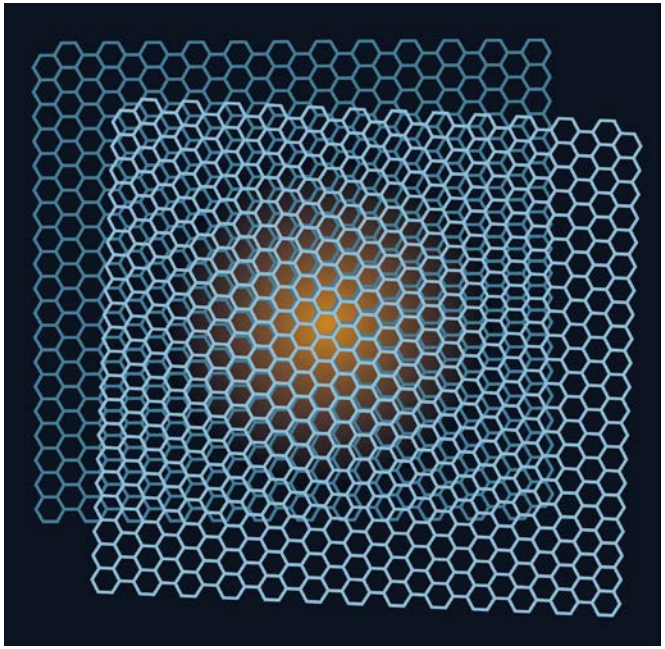
" Just imagine, materials with 10 times the strength of steel and only a fraction of the weight; shrinking all the information at the Library of Congress into a device the size of a sugar cube; detecting cancerous tumors that are only a few cells in size. Some of these research goals will take 20 or more years to achieve. But that is why—precisely why there is such a critical role for the Federal Government."

President Clinton, California Institute of Technology, January 21, 2000





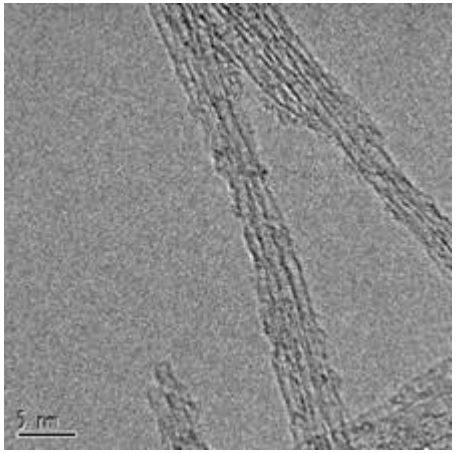
Graphene



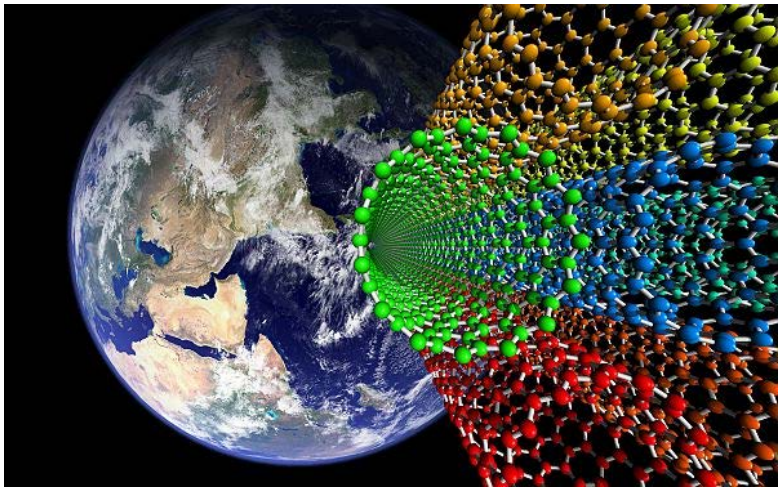
2010 Nobel Prize in Physics
Andre Geim and Kostya Novoselov
University of Manchester

- Lightweight – one football field of graphene would weigh less than 1 gram
- Over 300 times stronger than steel
- Ballistic electrical conductor

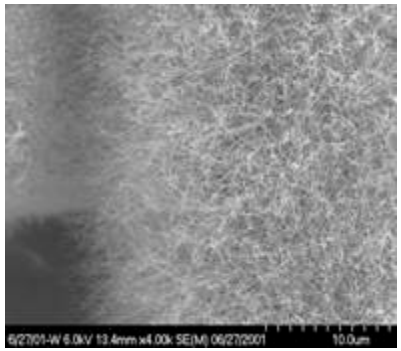
Carbon Nanotube Based Materials



Purified Single Wall Carbon Nanotubes



Carbon Nanotube Space Elevator



Nanotube Modified Substrates

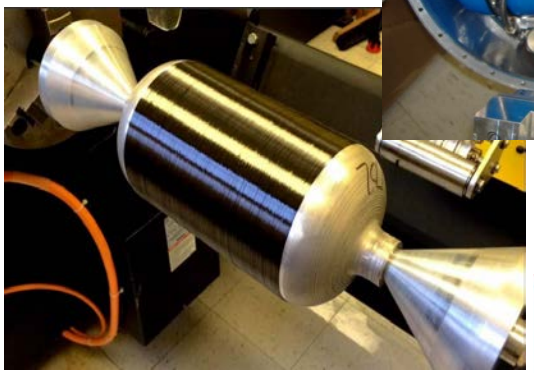
Nanotubes have remarkable properties-

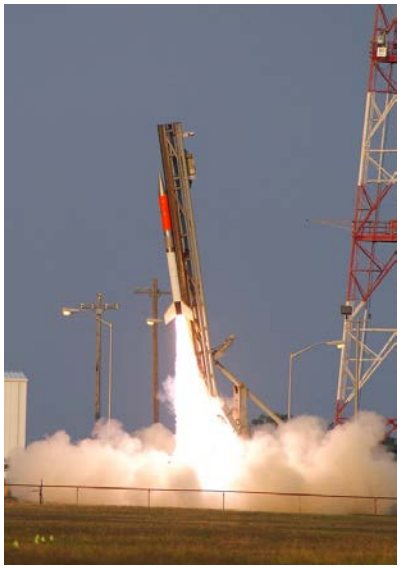
- Specific strength 150X that of conventional carbon fibers, 100X aluminum
- Elongation 10X that of conventional carbon fibers
- Electrical and thermal conductivities ~10X that of high conductivity carbon fibers

Because of these properties, carbon nanotubes have been proposed for disruptive applications such as a space elevator cable

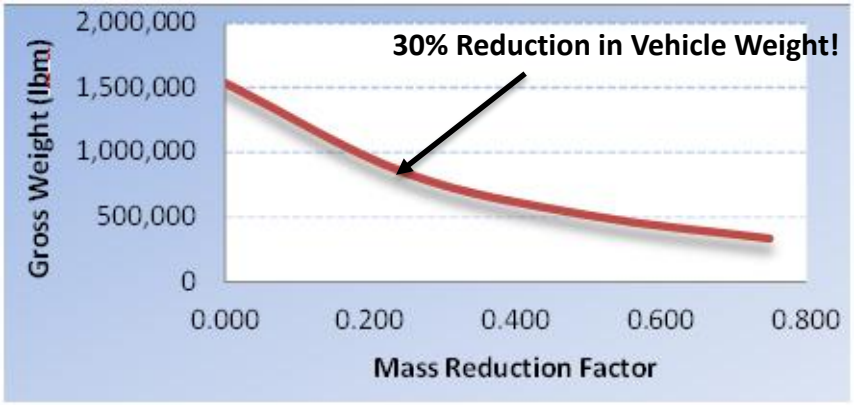
Carbon Nanotube Yarns in Production

CNT Reinforced Composites to be Demonstrated in a Structural Component



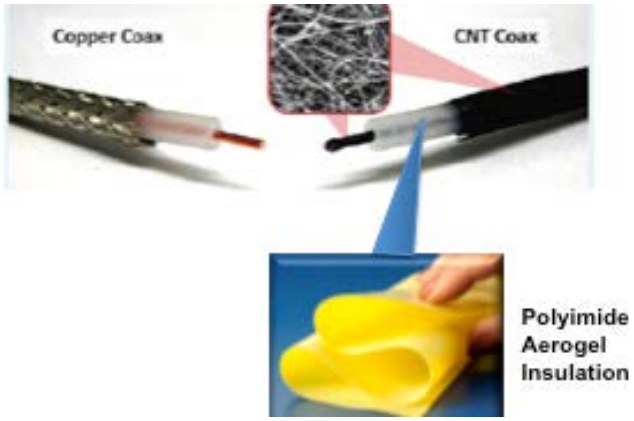


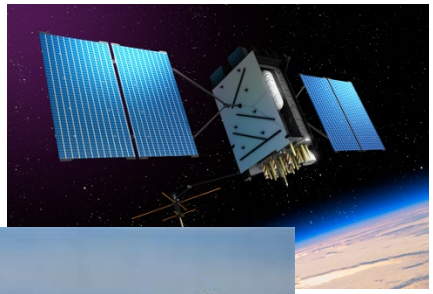
Flight Test 2016



nanocomp TECHNOLOGIES, INC.

Replacement of Metallic Conductors with CNTs Can Reduce Data Cable Weight by 30-70%





NORTHROP GRUMMAN

LOCKHEED MARTIN

BOEING

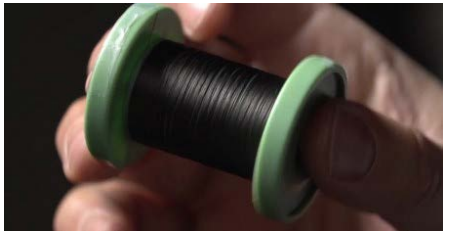
TE connectivity

nanocomp TECHNOLOGIES, INC.

MINNESOTA WIRE Life Saving Connections

MICRO-COAX Leading the way in transmission line solutions.

President Clinton's Vision



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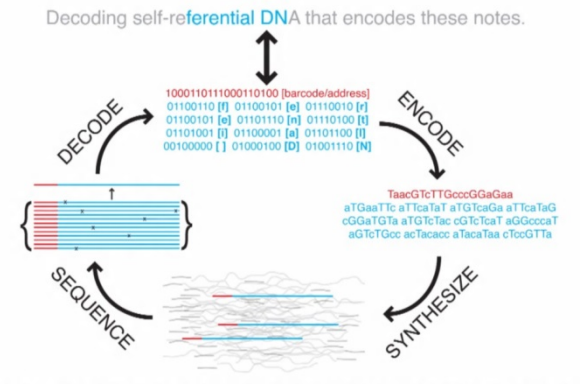
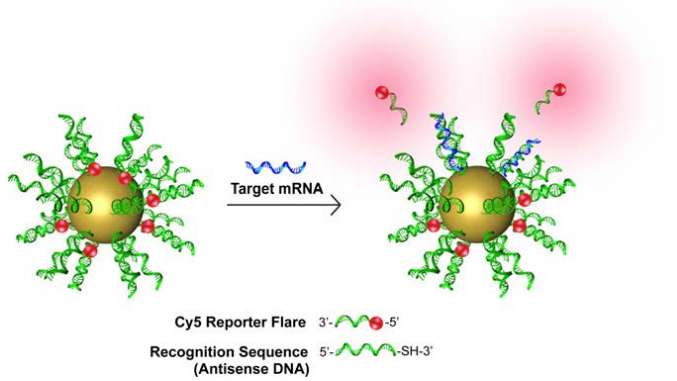
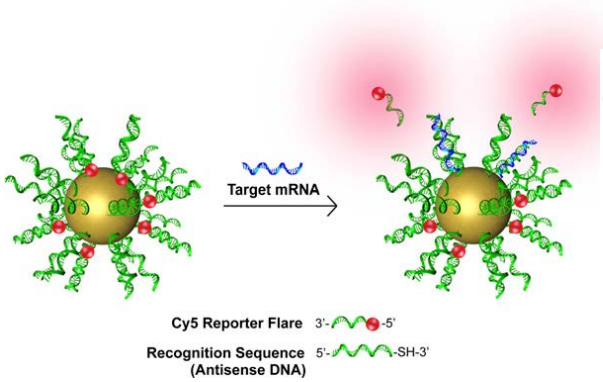
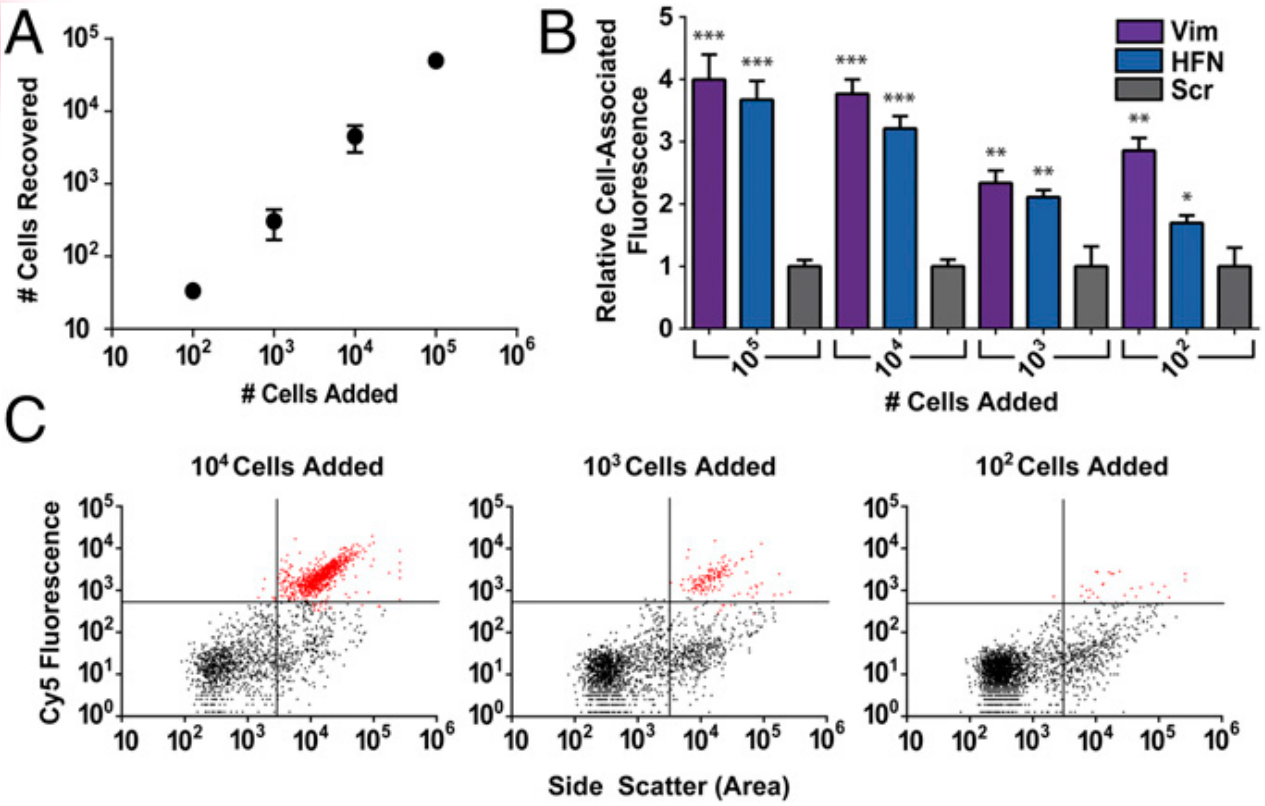




NanoFlares Can Detect as Few as 100 Cancer Cells per mL of Blood

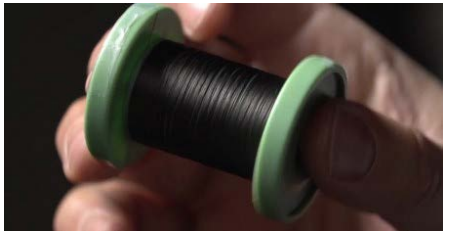




- Gold NPs decorated with a monolayer of antisense DNA and fluorophore containing reporter flare
- Binding of target mRNA releases fluorophore

T.L. Halo et al *PNAS* **2014**, *111*, 17104-17106

President Clinton's Vision



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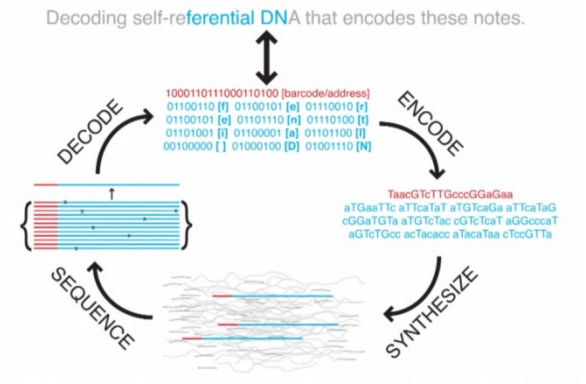
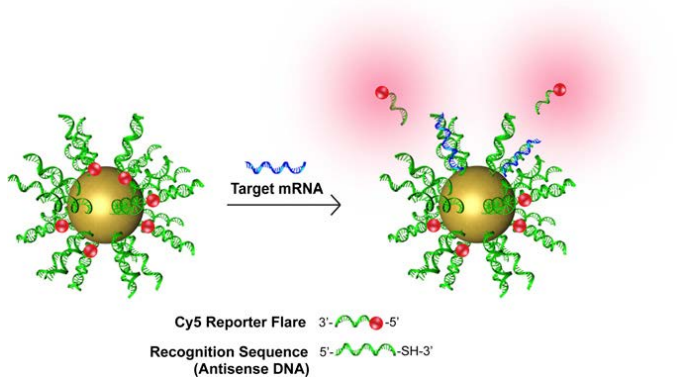
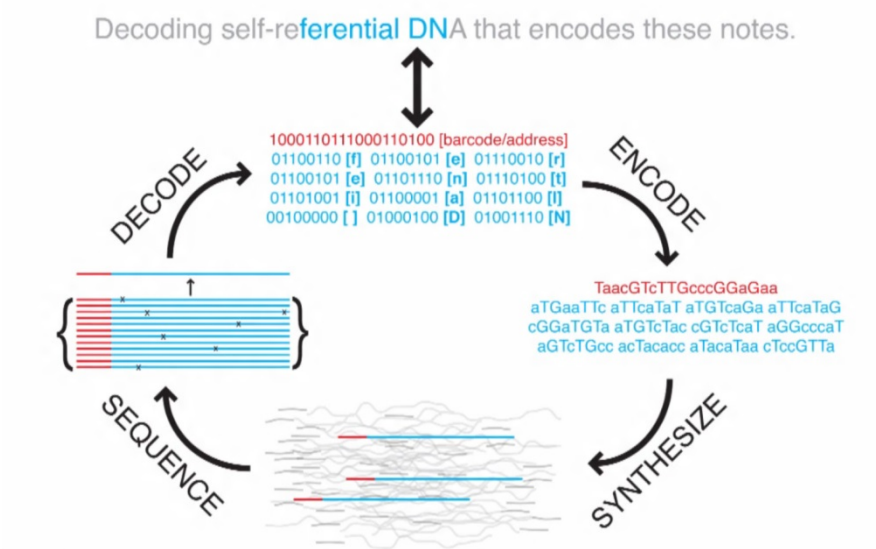
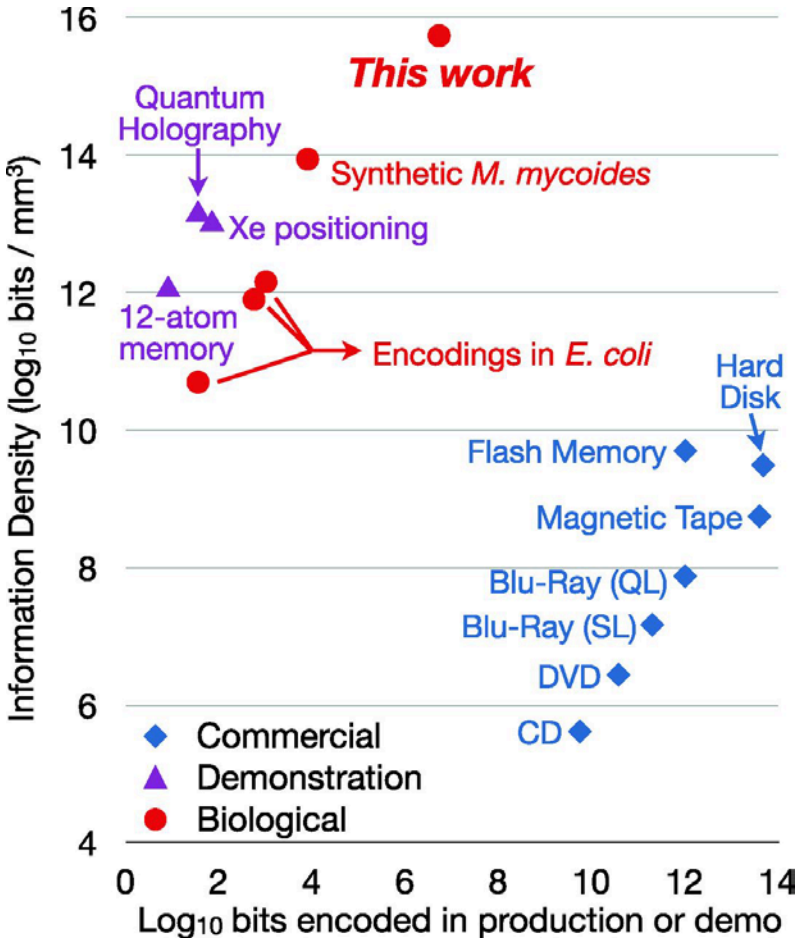




DNA Encoding Provides a Route to High Density Data Storage





G.M. Church, Y. Gao, S. Kosuri *Science* **2012**, *337*, 1628

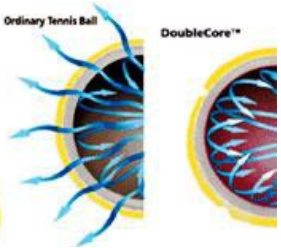
Nanotechnology is Nothing New

Lycurgus Cup
(*British Museum)*

Damascus Steel

Nanotechnology is Now

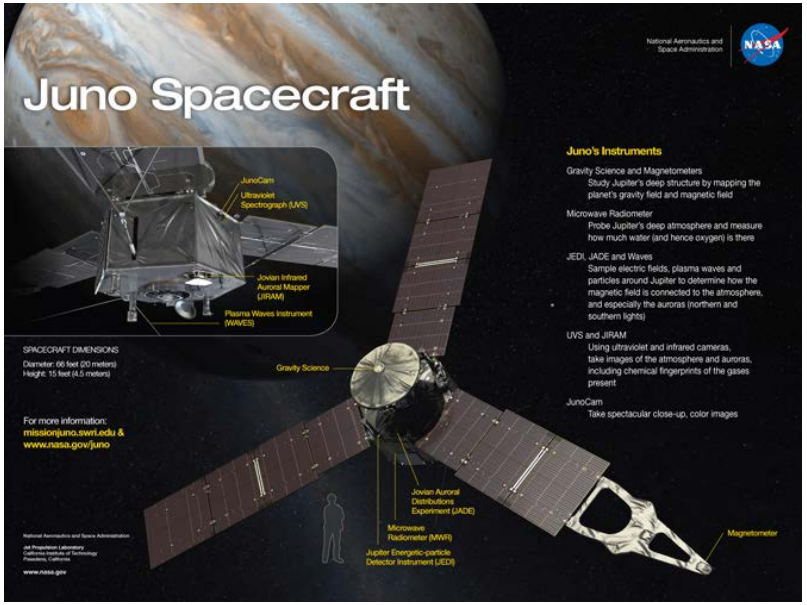
http://www.smt.sandvik.com/nanoflex



Eddie Bauer with NanoTex

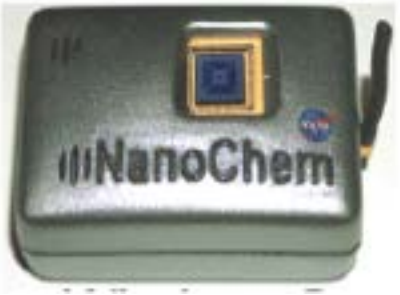
http://www.bmc-racing.com

Nanotechnology Has Made it into Space

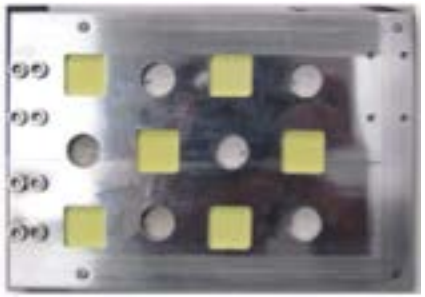


Silica Aerogels

CNT Nanocomposites for Charge Dissipation



CNT “Electronic Nose”



Polyimide Aerogels

What's So Special About Nanotechnology?

- Once things get really small (less than 100 nm):
  - conventional physics breaks down
  - New physical phenomena arise
- Properties (mechanical, optical, electrical, thermal) of materials can change at the nanoscale. These changes are influenced by:
- Surface Area
- Size
- Porosity
- Surface Roughness
- Multifunctionality

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Large Surface Areas Cause Higher Chemical Reactivity

AlICE Propellant

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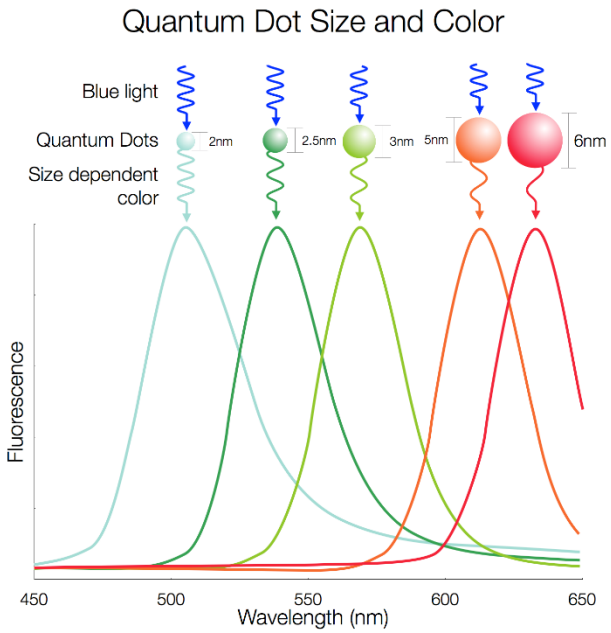
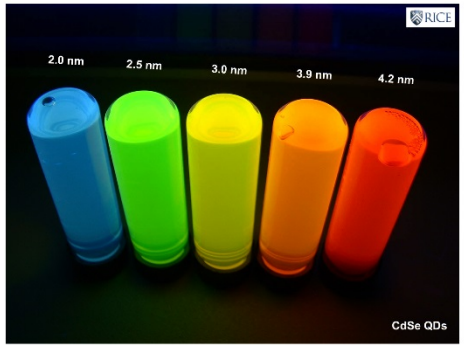
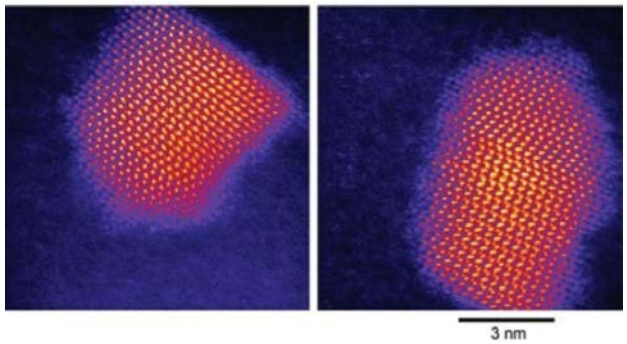
Size Can Influence Optical Properties



Source: Nanosys, Inc



Source: Rice University

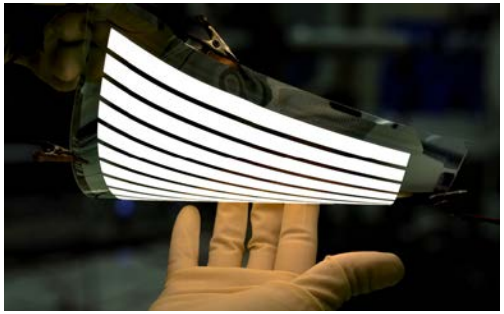


Electron Microscope Image of Quantum Dots Shows Individual Atoms
Source: Rosenthal Lab, Vanderbilty University

Applications in:

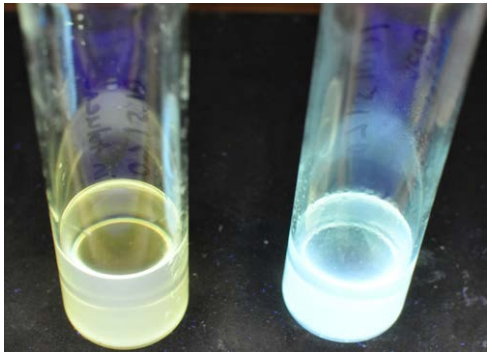
- Solid state lighting
- Displays
- Improved efficiency solar cells
- Medical diagnostics

Quantum Dots in Solid State Lighting



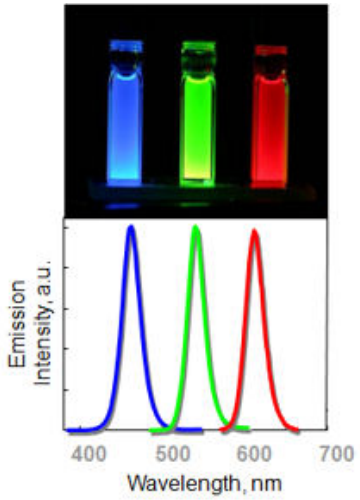
Source: United Display Corporation

- Global market for Solid State Lighting (LED and OLED) projected to be $22B by 2020, with a CAGR of 7.3% (*Source: MarketsandMarkets*)
- Replacement of all lighting in US with SSL would reduce power consumption by 70% (4296 out of 7000 trillion Btu) – *Source: US DOE*
- Major challenge has been to produce lighting with pleasing white tones - using LEDs of multiple colors or quantum dots



Surface Treated Quantum Dots Glow White
(*S. Rosenthall, Vanderbilt U.)*

QD Vision's Color IQ Technology



- QD Vision developed CdSe quantum dots for use in solid state lighting and displays (Color IQ)
- Color IQ incorporated into Bravia LED televisions in 2013
  - "Best of 2013 CES" – *Tech Radar*
  - Reduces power consumption by 20% - less pollution
- QD Vision received U.S. EPA's Green Chemistry Challenge Award in 2014 for reducing use of hazardous materials in their manufacturing processes

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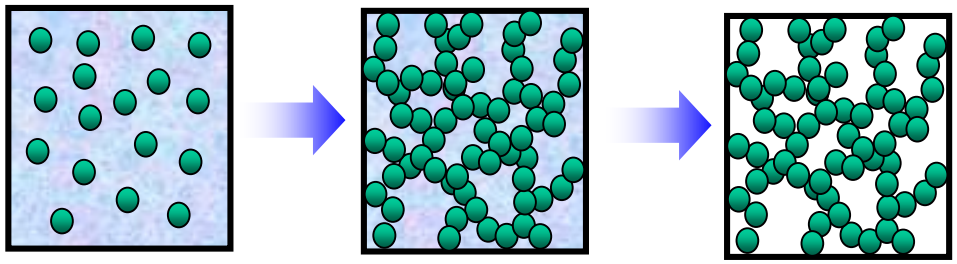
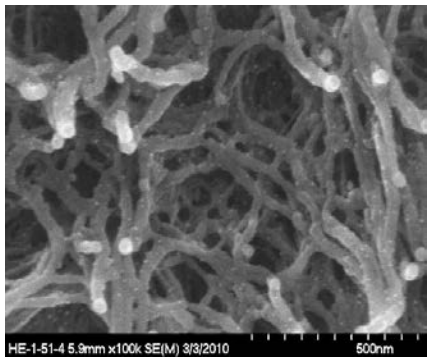
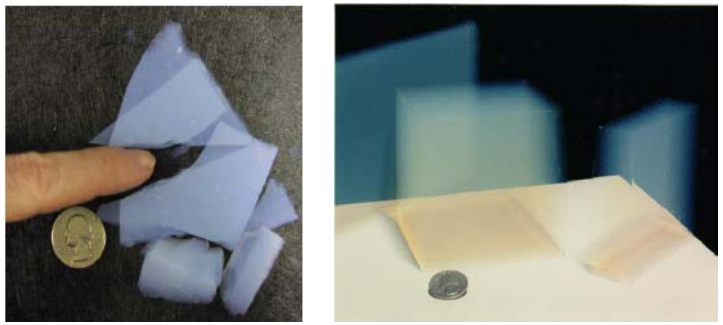
What are aerogels?





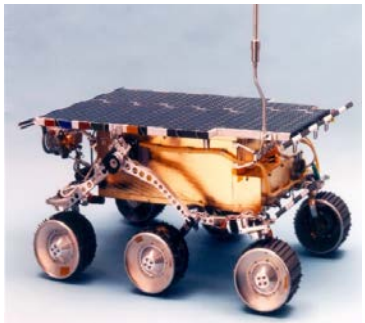
Aerogel under a Scanning Electron Microscope

- Highly porous solids made by drying a wet gel without shrinking
- Pore sizes extremely small (typically 10-40 nm)—makes for very good insulation
- 2-4 times better insulator than fiberglass under ambient pressure, 10-15 times better in light vacuum



Typical monolithic silica aerogels

Cosmic dust collector Stardust Program



Insulation on rovers

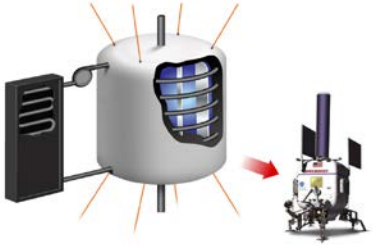
Aerogels are an Important Component of Advanced Insulation

- Global market for advanced insulation is expected to grow from $894M in 2015 to $1.9B in 2019 (*Source: Lux Research)*
- Applications include:
  - Commercial and residential buildings
  - Oil and gas
  - Refrigerators
  - Shipping
  - Aerospace

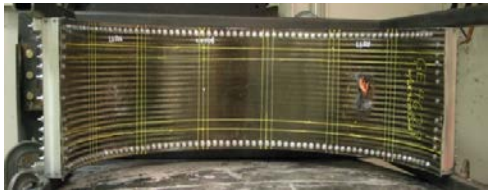
Expansion Pack™

Particle Pack™

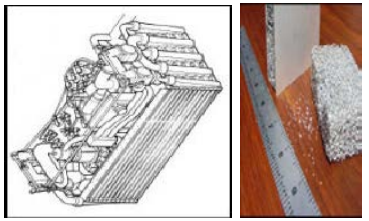
Potential applications for durable aerogels in aeronautics and space exploration



Cryotank Insulation



Fan engine containment (Ballistic protection)



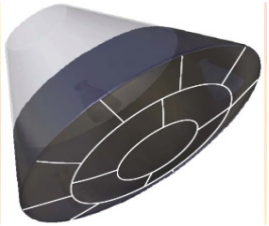
Air revitalization

Ultra-lightweight, multifunctional structures for habitats, rovers

Inflatable aerodynamic decelerators

Sandwich structures

Propellant tanks



Heat shielding

Insulation for EVA suits, habitats and rovers

New Aerogels are Flexible and Durable

Silica aerogel is easily broken by light finger press while PI aerogel easily supports the weight of a car

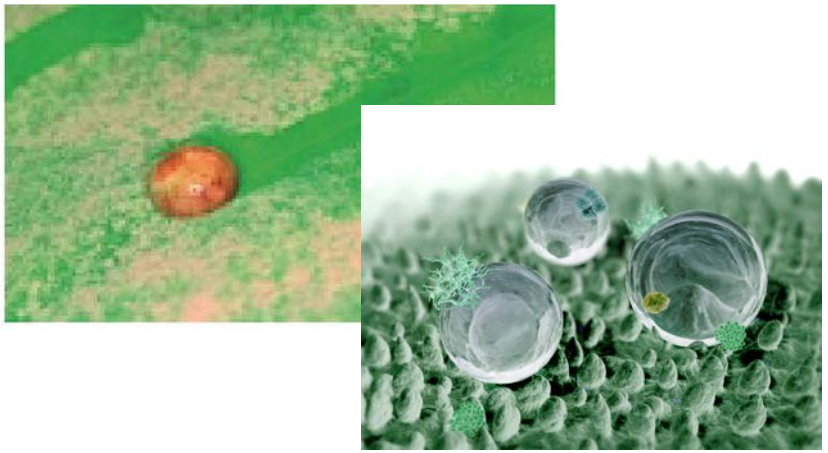
Source: M.A. Meador, NASA

What's So Special About Nanotechnology?

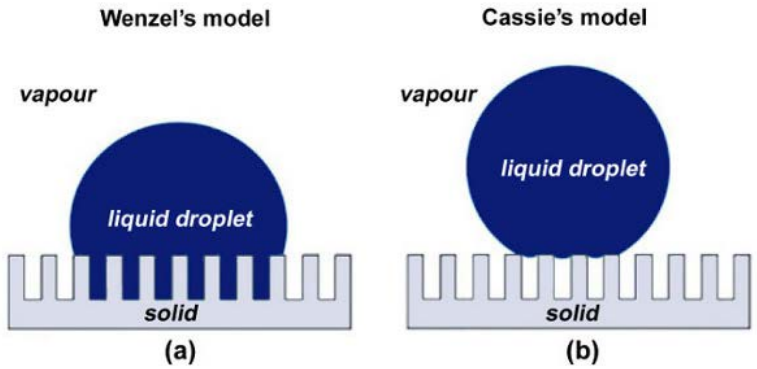
- Once things get really small (less than 100 nm):
  - conventional physics breaks down
  - New physical phenomena arise
- Properties (mechanical, optical, electrical, thermal) of materials can change at the nanoscale. These changes are influenced by:
- Surface Area
- Size
- Porosity
- Surface Roughness
- Multifunctionality

Controlled Wetting

- Mimic biological systems to design surfaces that are highly water repellant (superhydrophobic) or oil repellant (superoleophobic) and self-cleaning
- Wetting characteristics follow two models:
  - ✓ Wenzel – liquid fills the spaces between pillars
  - ✓ Cassie – air fills the spaces between pillars
- Can change surface properties by changing both the material used and the type of nanotexturing
- Potential applications include:
  - ✓ Biomedical
  - ✓ Coatings for pipes to reduce pumping energy
  - ✓ Antimicrobial surfaces
  - ✓ Self-cleaning surfaces

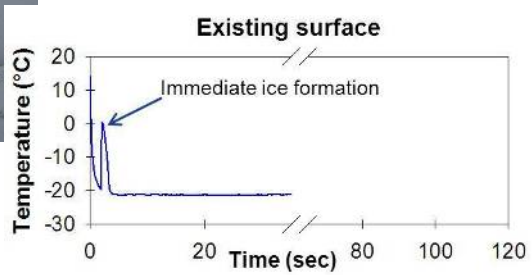


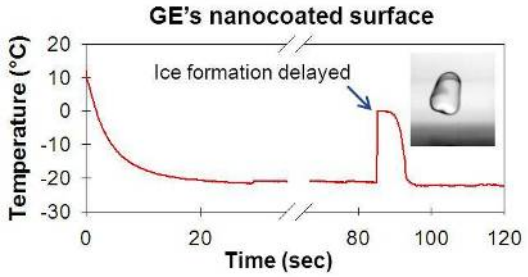
Self-cleaning, superhydrophobic character of lotus leaf due to nanopillared surface



Nanotextured Coatings Prevent Ice Buildup

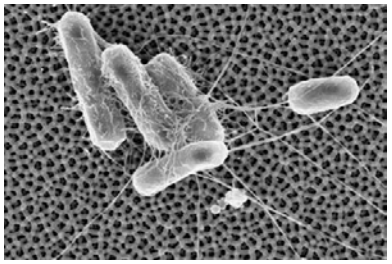
- Ice formation is a major problem for wind turbines and aircraft
  - ✓ Reduces the efficiency of wind turbines and can lead to damage
  - ✓ 25 million gallons of de-icing agents are used annually in the US at commercial airports
- Nanotextured surfaces can prevent ice buildup and:
  - ✓ Allow longer term operation of wind turbines
  - ✓ Reduce or eliminate the need for deicing fluids for aircraft



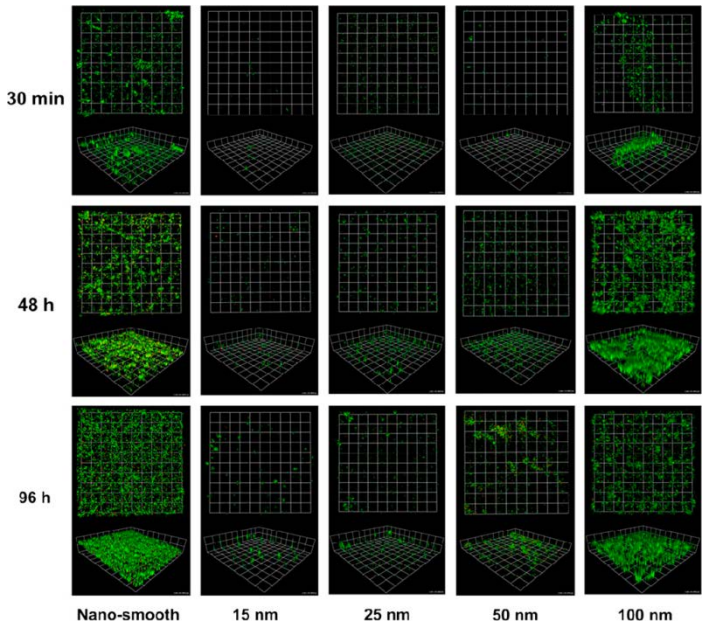


Nanotextured Surfaces for Antimicrobial Protection

- Nanotextured surfaces can inhibit adhesion of bacteria onto surfaces
- Application of a nanoporous alumina surface (anodized alumina) onto metals inhibits cell adhesion and growth of biofilms
  - ✓ *E coli* O157:H7
  - ✓ *Listeria monocytogenes*
- Smaller pore sizes (15 and 25 nm) are the most effective



SEM images of live *E coli* cells attached to a nanoporous alumina surface



Confocal light microscopy images of attachment and biofilm formation by live *E coli*

Source: Feng et al *Biofouling* **2014**, *30*, 1253-1268
Joint effort between Cornell and RPI

What's So Special About Nanotechnology?

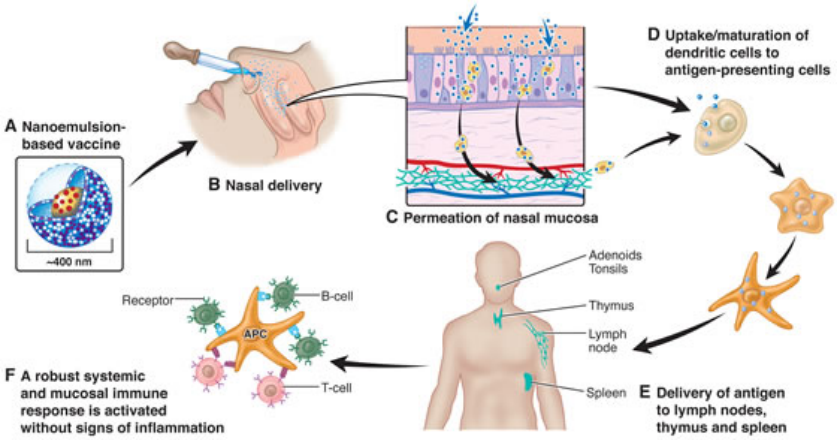
Properties (mechanical, optical, electrical, thermal) of materials can change at the nanoscale, typically less than 100 nm. These changes are influenced by:

- Surface Area
- Size
- Porosity
- Surface Roughness
- Multifunctionality

What will nanotechnology do in the future?

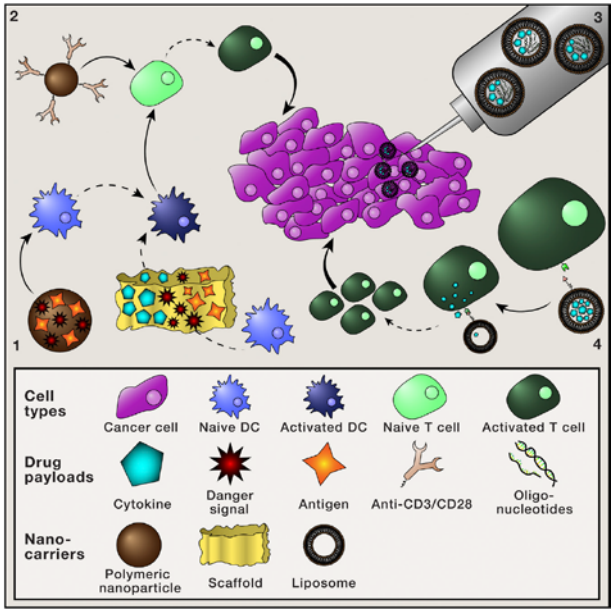
Nanotechnology in the Treatment of Cancer and Infectious Diseases

Nanoemulsion Vaccines for Infectious Diseases

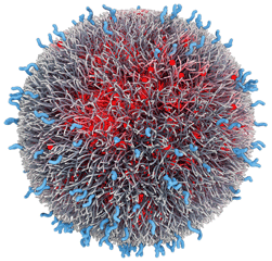


Source: NanoBio Corporation

Nanoparticle Drugs for Cancer Immunotherapy



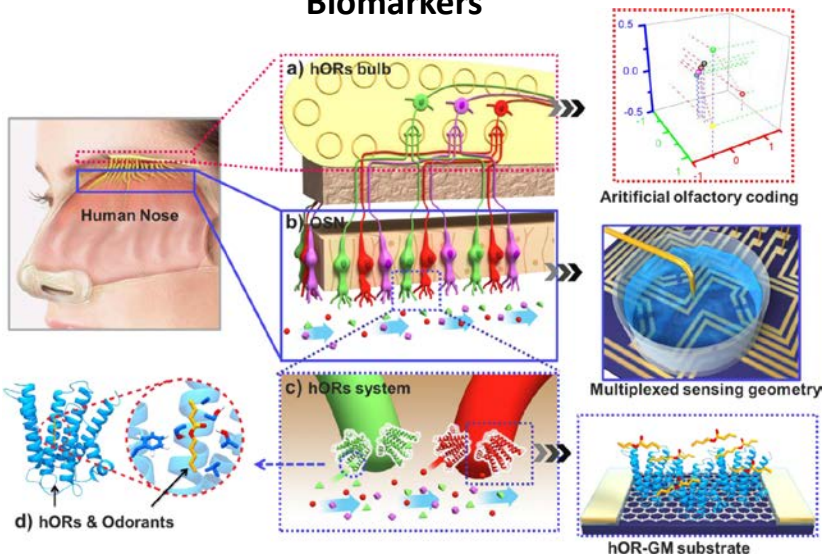
M.S. Goldberg *Cell* ***2015****, 161*, 201



BIND Nanoparticle Cancer Drug has Passed Phase I Human Clinical Trials in the US

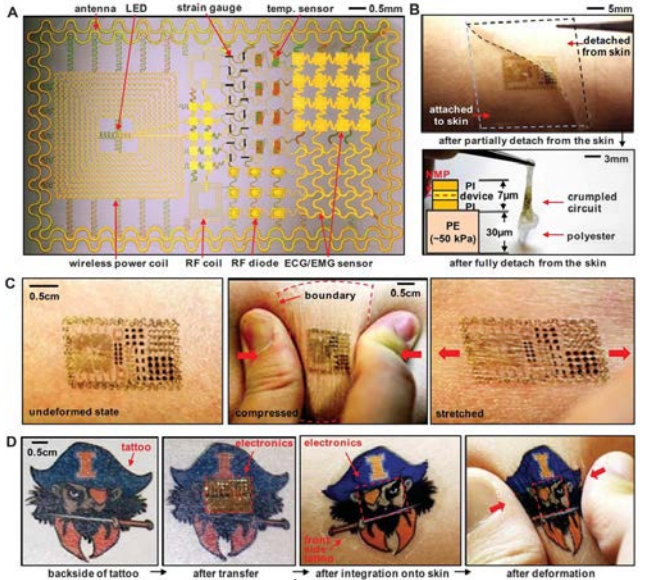
Nanotechnology in Medical Diagnostics and Health Care

Graphene Electronic Nose Can Detect Cancer Biomarkers



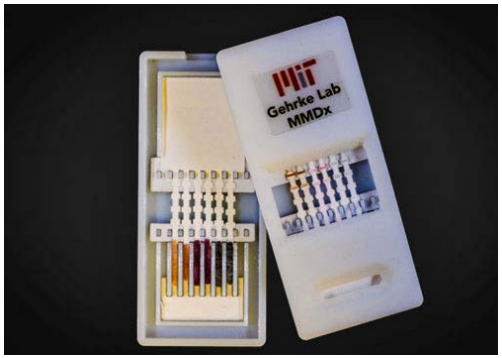
O.S. Kwon, et al *Nano Letters* ASAP

Epidermal Sensors to Measure Skin Properties



D.-H. Kim, et al *Science* **2011**, *333*, 838-843

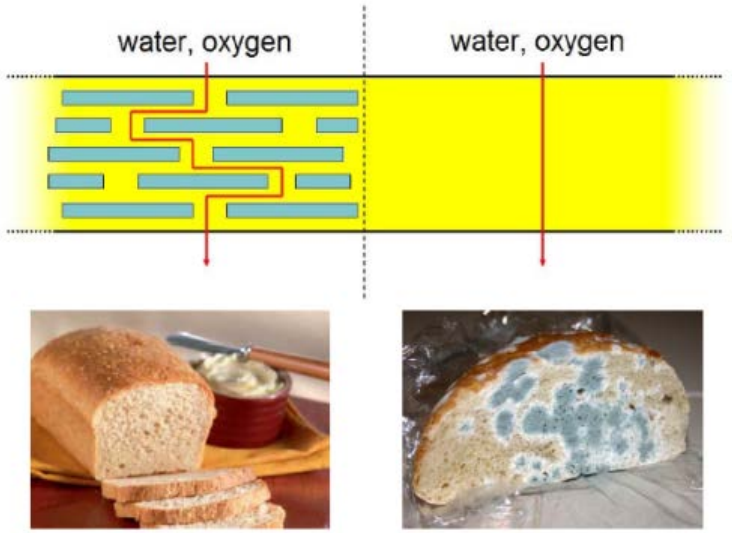
Nanosilver Based Sensor for Rapid Detection of *Ebola*



C.-H. Wan et al *Lab on a Chip* **2015**, *7*, 1638-41

Nanotechnology in Food Packaging

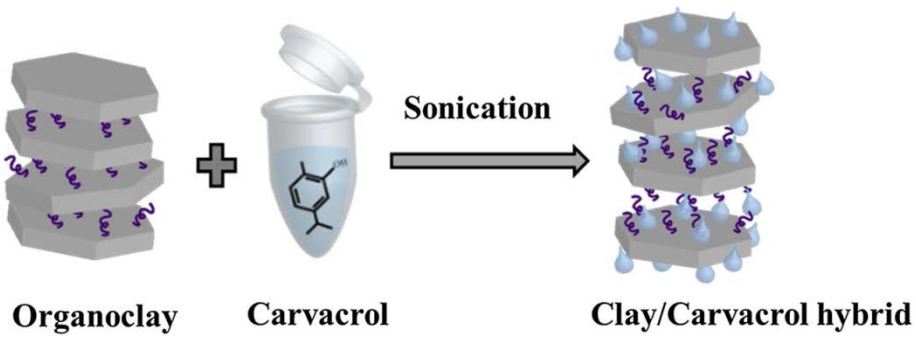
- 40% of all food grown in US is never eaten
- Nanotechnology can reduce/eliminate food waste due to spoilage
  - Reduce spoilage by eliminating oxygen and pathogens
  - Detect spoilage

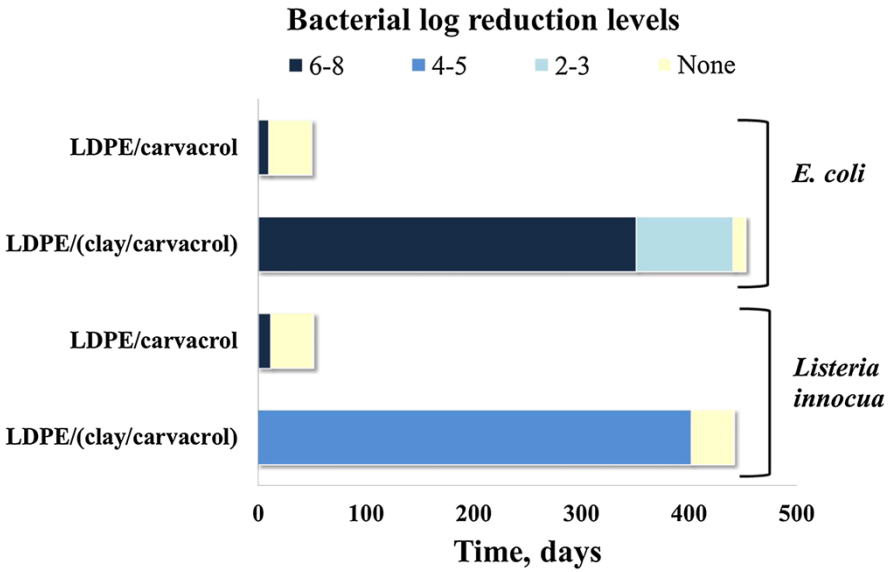


Duncan, *J. Colloid Interf. Sci.* 363 (2011) 1-24.

Active Packaging

- Active packaging can be made with nanoscale additives to inhibit oxygen infiltration and natural antimicrobial agents (essential oils)
- Example at the right involves an essential oil model (carvacol) intercalated clay nanocomposite in poly(ethylene)
  - ✓ Films containing clay are more effective at suppressing bacterial growth because they starve the bacteria for oxygen
  - ✓ Essential oils may be more attractive for packaging since they don't have potential EH&S issues

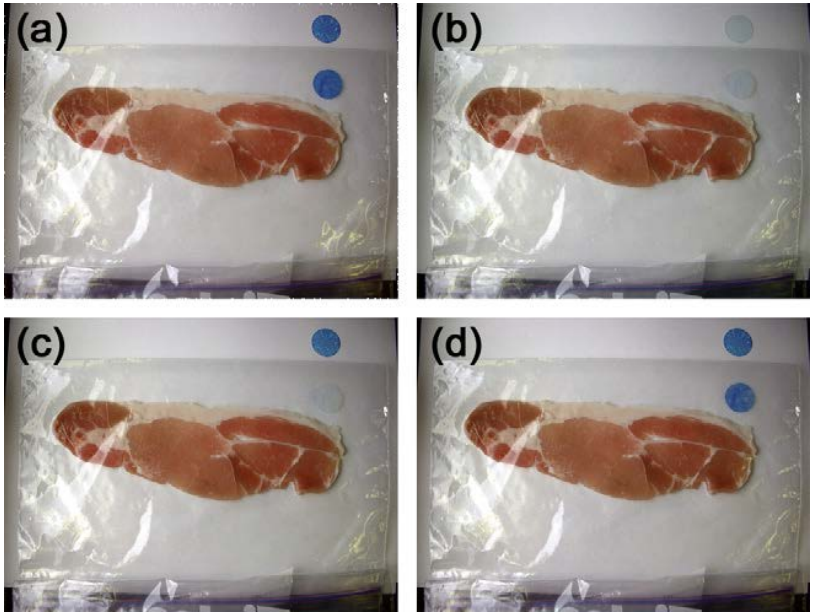




Source: Shemesh et al *Polymer Advanced Technologies* **2014**, 26, *110-116.*

Smart Packaging

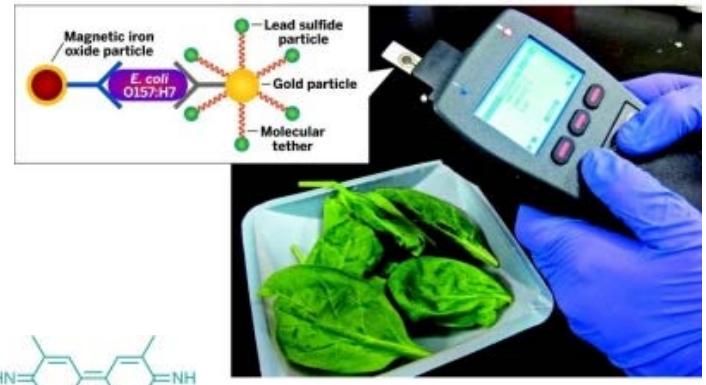
- Sensors incorporated into polymer packaging can detect:
  - ✓ Pathogens
  - ✓ Spoilage
  - ✓ Presence of oxygen or other gaseous species
  - ✓ Tampering
- Example at the right is an optical sensor to detect presence of oxygen due to leaks in packaging
  - ✓ Difficult to quantify the amount of oxygen in the package
  - ✓ Easy way for consumers and vendors to see that oxygen has leaked into the product



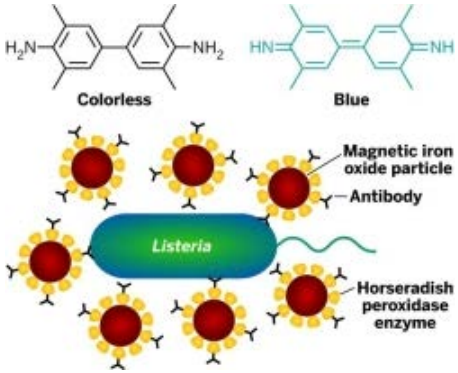
Blue dot is sensor comprised of titanium dioxide and Methylene Blue (indicator dye) which will turn blue in the presence of oxygen. Pictures show two dots; top one is outside package, bottom is inside: (a) freshly sealed sample, (b) after activation of sensor with uv light, (c) after standing for a few minutes, (d) package is opened

Sensors for Detection of Food-borne Pathogens

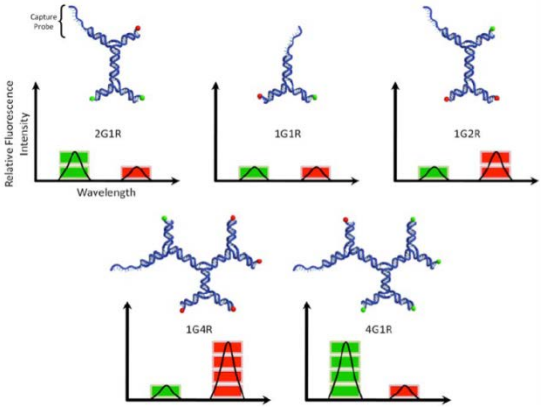
- Functionalized metal nanoparticles and nanostructures have been used in detection of pathogens
  - Functional groups designed to attach to specific pathogens
  - Optical or electrochemical properties of the nanoparticles change when they bind with the pathogen
- Many groups are working on the development of handheld sensors, such as the one on the right, for pathogen detection



A.C. Alocoilja, Michigan State University



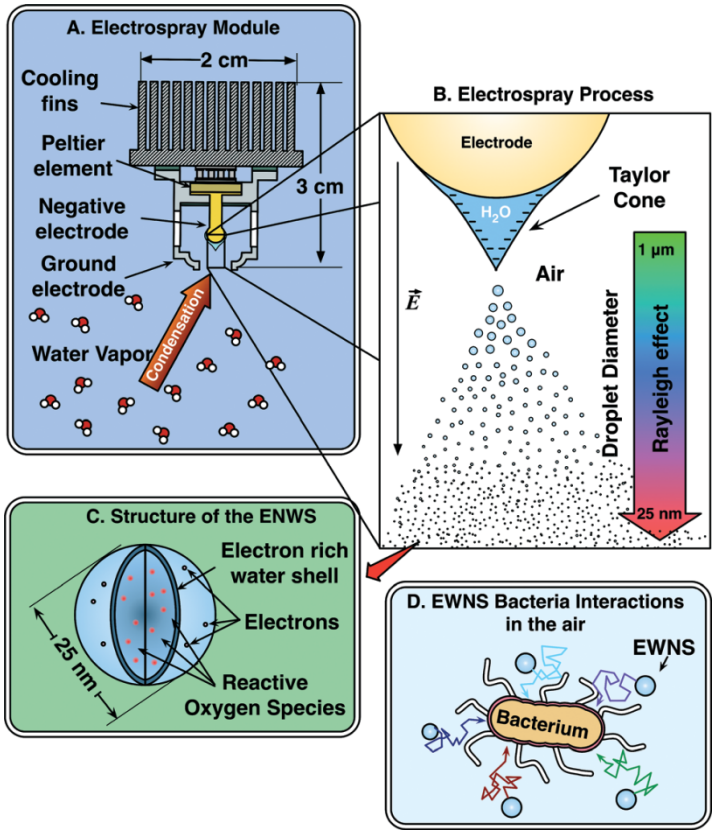
J. Inudayaraj, Purdue



D. Luo, Cornell

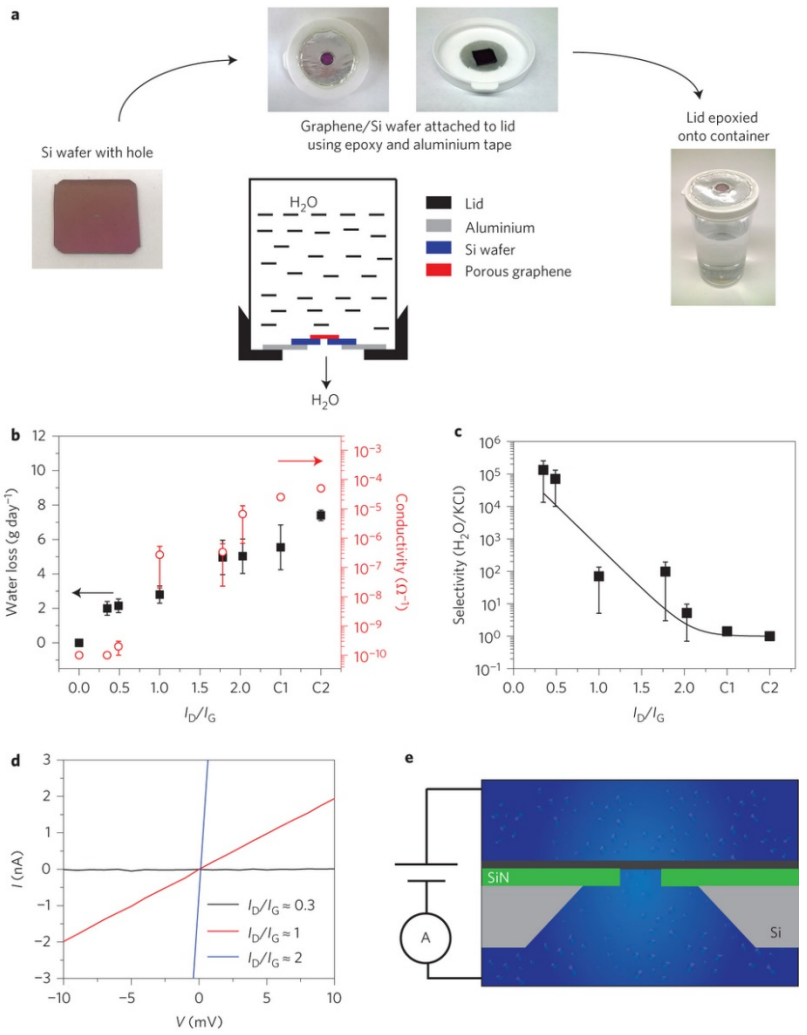
Engineered Nanowater for Disinfecting Surfaces

- Electrospray process involves building up a large electric charge on water drop
  - ✓ Water droplets condense on the electrode (Petier cooling element), become charged
  - ✓ Charged droplets break up into smaller droplets and accelerate away from the electrospray module
  - ✓ High charge also breaks down water into reactive species (radicals) which attack and damage bacterial cell walls
  - ✓ Studies reveal little or no damage to the product being decontaminated



Nanoporous Graphene for Water Desalination

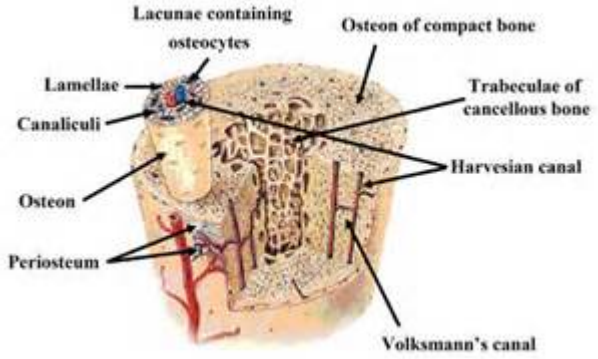
- Single layer of graphene treated with oxygen plasma
  - ✓ Produces nanoscale pores within the graphene
  - ✓ Pore size can be controlled by varying reaction time
- Membranes show high water molecule selectivity over dissolved ions
  - ✓ ~100% salt reject rate
  - ✓ Water fluxes as high as high as 10^6 $gm^{-2}s^{-1}$ at 40°C
- Porous graphene water purification membranes were also developed by Lockheed-Martin – "Perforenes" – 100 times better flow through than reverse osmosis systems



Source: Surwade et al *Nature Nanotechnology* **2015**, *10*, 459-464

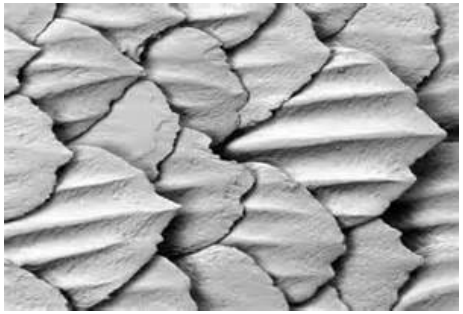
Hierarchical Structures – Mimicking Nature

- Nature is adept at creating highly ordered (hierarchical structures)
- Structures are tailored to provide a specific function
- Can we use nanotechnology to mimic nature?



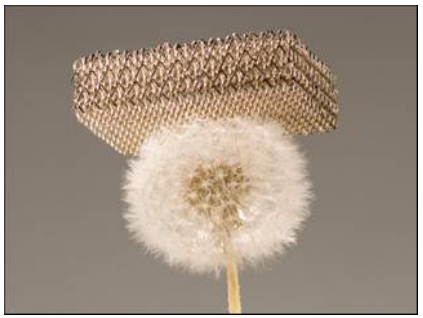
Structure of Bone

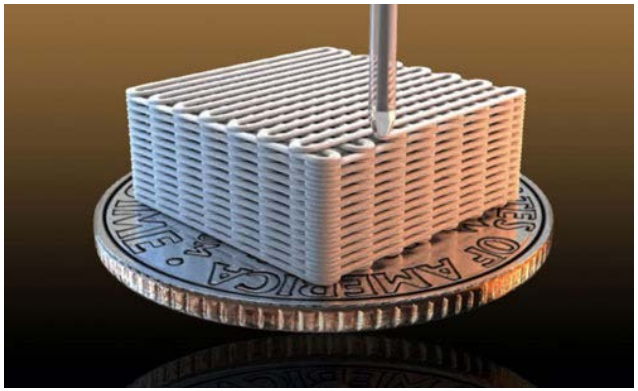
Gecko Feet



Great White Shark Skin

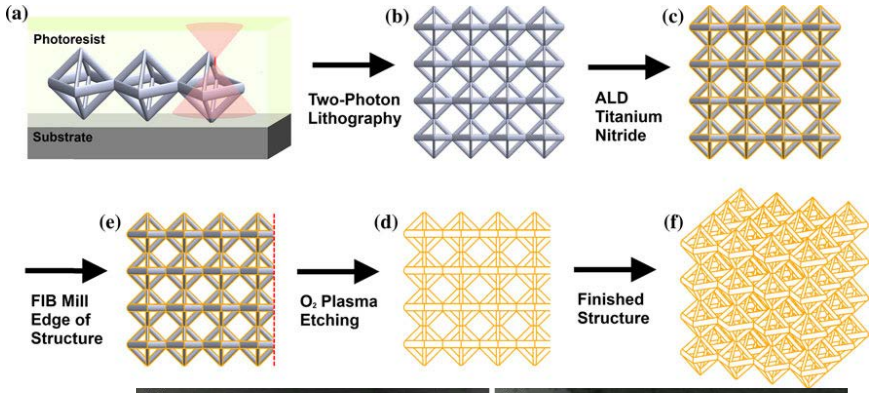
Engineered Hierarchical Structures – Marrying Nano and Biotechnology and Manufacturing

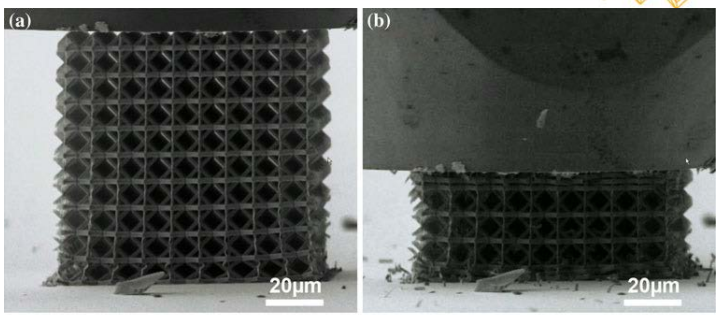


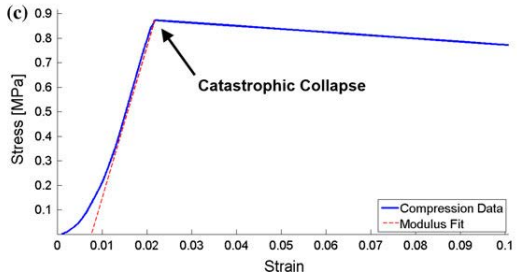


Source: Lawrence Livermore National Laboratory

Zhu, et al *Nature Comm.* **2015**, *DOI:10.1038*





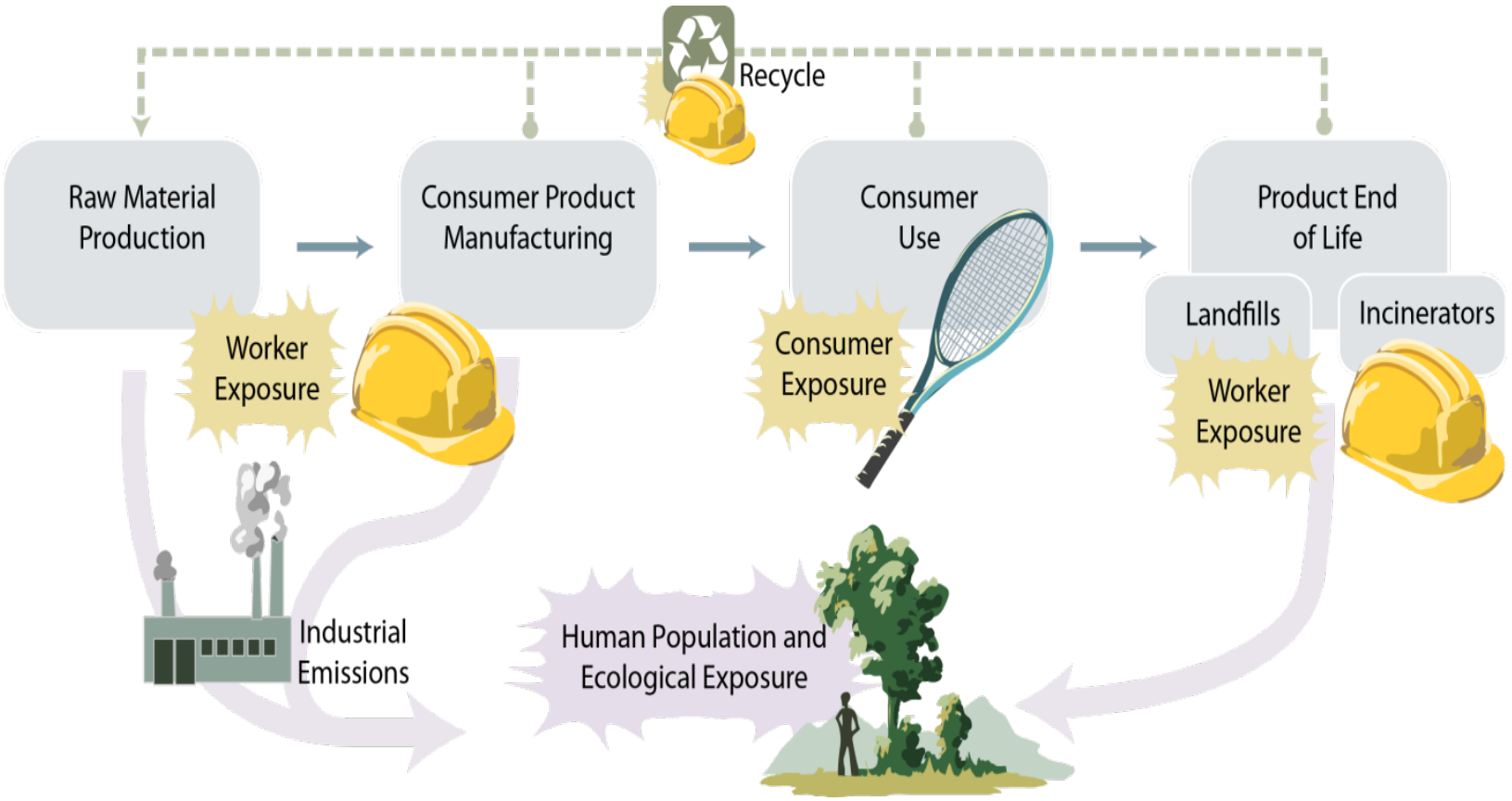


L.R. Meza and J.R. Greer *J. Mater. Sci.* **2014**, *49*, 2496

Environmental, Health and Safety Aspects of Nanotechnology

- EH&S risks associated with nanomaterials are a function of two factors
  - ✓ Toxicological effects of nanomaterial
  - ✓ Risk of exposure
- Significant amount of toxicological studies have been done on a variety of nanomaterials
  - ✓ Study conditions should closely mimic those that would likely occur during exposure
- Not as much work has been done to understand exposure
  - ✓ Agencies funding work in EHS under the NNI are looking at assessing the knowledge gaps with respect to exposure
  - ✓ Joint workshop with the NNI and Consumer Product Safety Commission : Quantifying Exposure to Engineered Nanomaterials from Manufactured Products, July 7-8, Arlington, VA

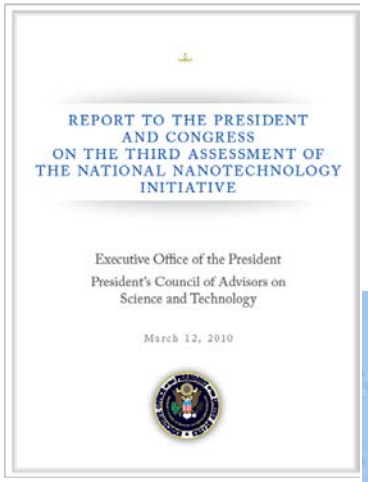
Life Cycle Stages

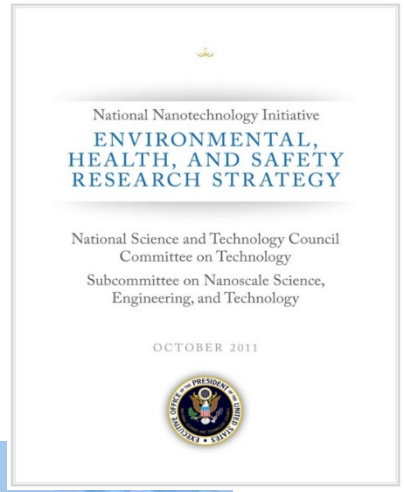


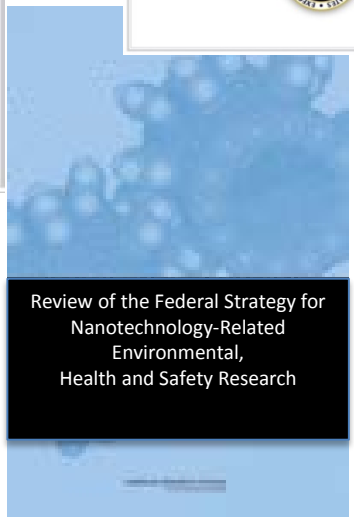
The NNI EHS Research Strategy

Process

- Assessment of strengths and weaknesses
- Four public workshops
- Writing Teams
- Public Comment Period
- Input from NRC and PCAST→





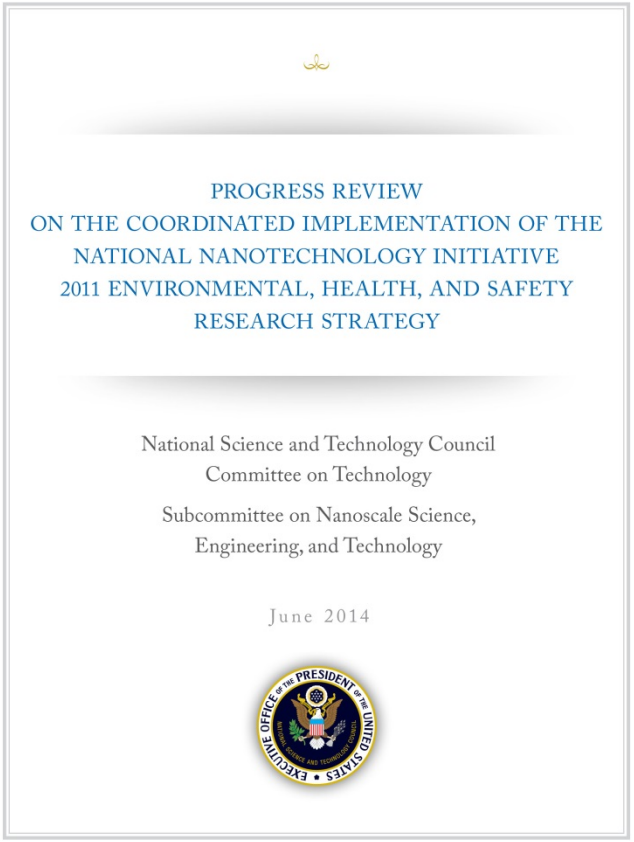


Key Elements

- Informatics and predictive modeling
- Concepts for targeting and accelerating research
- Best practices for coordination and implementation of research

Progress on the NNI EHS Research Strategy

- **Progress review published June 2014**
- **Examples of progress provided for each of the EHS research needs categories**
- **Not intended to be comprehensive, but rather illustrative**
- **Extensive documentation (references)**
- **Includes section on implementation and coordination**



PROGRESS REVIEW
ON THE COORDINATED IMPLEMENTATION OF THE
NATIONAL NANOTECHNOLOGY INITIATIVE
2011 ENVIRONMENTAL, HEALTH, AND SAFETY
RESEARCH STRATEGY

National Science and Technology Council
Committee on Technology

Subcommittee on Nanoscale Science,
Engineering, and Technology

June 2014

Key Concepts in the 2011 EHS Research Strategy

Risk Assessment

Identify Hazard

Characterize Risk

Targeting and Accelerating Research

Critical Elements:

- Prioritize nanomaterials for research
- Establish standard measurements, terminology, nomenclature, and assay methods
- Develop informatics and predictive modeling tools
- Stratify knowledge for risk assessment
- Partner to achieve the NNI EHS research goals, including globally

Informatics and Modeling for NanoEHS Research

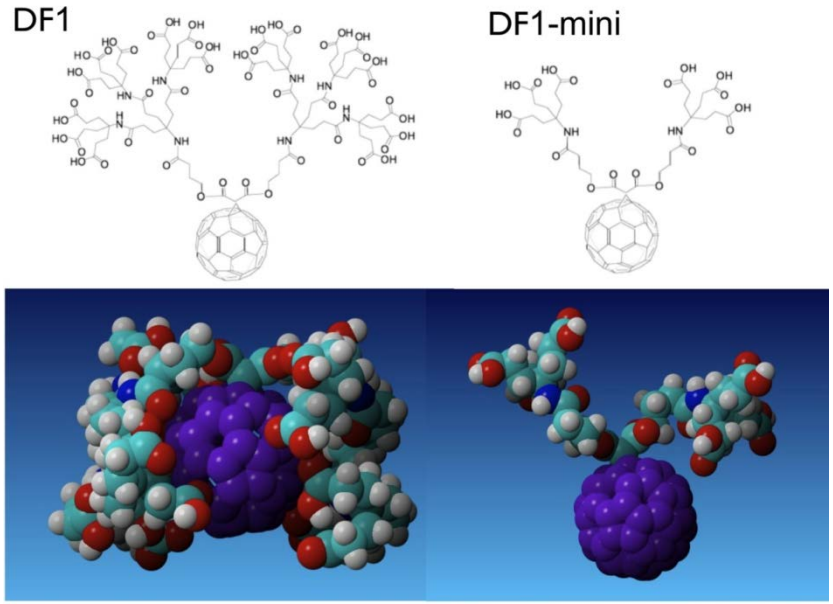
Outcomes:

- Aid development, analysis, organization, archiving, sharing, and use of data that are acquired in nanoEHS research projects in the core research.
- Effectively manage reliable, high-quality data to support advanced modeling and simulation.

Components:

- Data acquisition, analysis, sharing
- Structural models
- Predictive models and simulations
- Collaborative informatics infrastructure

New research needs

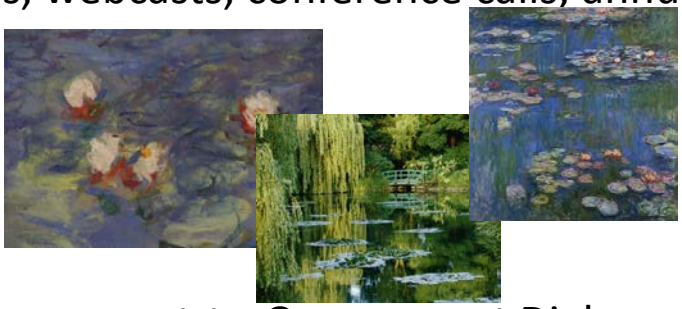


NNI Multilateral Engagement

- Organisation for Economic Co-operation and Development (OECD)
  - Working Party on Bio-, Nano-, and Converging Technologies (BNCT)
  - Working Party on the Safety of Manufactured Nanomaterials (WPMN)
- Standards Organizations
  - International Organization for Standardization (ISO) – especially Technical Committee 229 (Nanotechnologies)
  - International Electrotechnical Commission (IEC) – especially Technical Committee 113 (Nanotechnology Standardization for Electrical and Electronics Products and Systems)
  - ASTM International – especially Committee E56 on Nanotechnology
- United Nations Environment Program (UNEP) Strategic Approach to International Chemicals Management (SAICM)
- Safe Implementation of Innovative Nanoscience and Technology (SIINN) joint call
- U.S.-EU: Bridging NanoEHS Research Efforts

us – eu
bridging nanoEHS research efforts

- Bottom-up collaboration – Communities of Research (CORs)
  - groups of **people**: American and European scientists
  - share a **significant interest**: nanoEHS
  - develop a **shared repertoire of resources**: experiences, tools, ways of addressing recurring questions and challenges
  - **regular contact**: use wikis, webcasts, conference calls, annual U.S.-EU nanoEHS meeting.

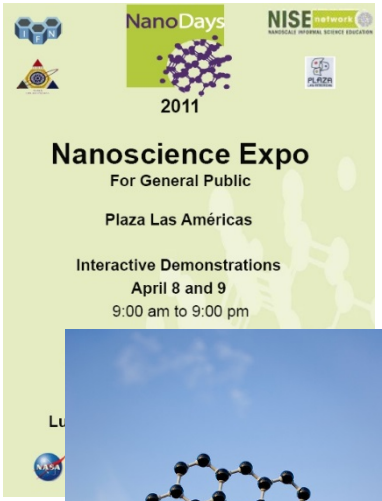


- Top-down collaboration – Government-to-Government Dialogue
  - Monthly teleconferences
  - Joint Call in 2015: SIINN ERA-NET
  - U.S.-EU:Bridging NanoEHS Research Efforts workshop (every 12-18 months)
  - Exploring future parallel solicitations

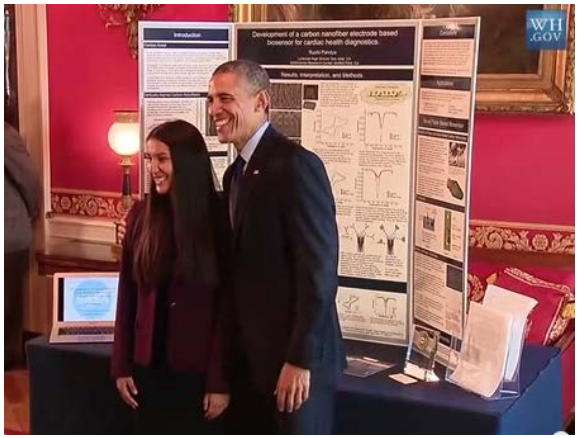
Nanotechnology can Inspire Students

NNI Booth at the USA Science and Engineering Festival

NNI Video Contest Winners Jennifer Gil and Carlos Acevedo (U of Puerto Rico)

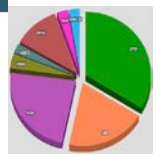


NISENet



Ruchi Pandya, student intern at NASA Ames from Lynbrook High School, with President Obama at the 2015 White House Science Fair.

Improving Communications with Stakeholders

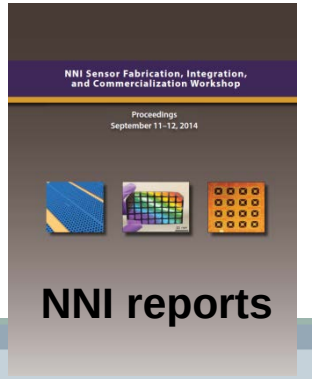


NNI Dashboard @ http://nanodashboard.nano.gov

Webinars

YouTube

EnvisioNano



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Grand Challenges

- Recommended by PCAST in their 2014 review of the NNI
- Definition derived from Administration's Innovation Policy
- Attributes of Grand Challenges are:
  - ✓ Require advances in fundamental scientific knowledge, tools, and infrastructure for successful completion.
  - ✓ Drive the need for collaboration between multiple disciplines, some of which do not normally interact, to come together, collaborate and share resources and information to solve the challenge .
  - ✓ Span efforts from discovery and fundamental science to engineering demonstration and commercialization, i.e., catalyze the transition of technologies from lab to market.
  - ✓ Be too big to be undertaken by one or even a few organizations.
  - ✓ Be exciting enough to motivate decision makers to provide funding and resources and multiple organizations to collaborate, share resources, and information to solve the challenge.
  - ✓ Have a measurable end-point and clear intermediate milestones that are measurable and valuable in their own right
- RFI released in June to solicit public input on potential Nanotechnology Inspired Grand Challenges – over 100 responses
- Expect to announce 1 Grand Challenge later this year – more to follow

A Nanotechnology-Inspired Grand Challenge for Future Computing:

Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.

While it continues to be a national priority to advance conventional digital computing—which has been the engine of the information technology revolution—current technology falls far short of the human brain in terms of both the brain's sensing and problem-solving abilities and its low power consumption. Many experts predict that fundamental physical limitations will prevent transistor technology from ever matching these twin characteristics. This grand challenge will bring together scientists and engineers from many disciplines to look beyond the decades-old approach to computing based on the Von Neumann architecture as implemented with transistor-based processors, and chart a new path that will continue the rapid pace of innovation beyond the next decade. **Read more**

This challenge will look beyond conventional computing based on the Von Neumann architecture.

Read more about:

- Statements of support for this challenge from Federal agencies (DoD, DOE, IARPA, NIST, NSF)
- Statements of support for this challenge from other organizations (CCC, Moore Foundation, IBM, IEEE, Kavli Foundation, SRC)
- Workshop reports and white papers relevant to this challenge
- Meetings and workshops relevant to this challenge
- Frequently asked programmatic and technical questions about this challenge

Summary

- Nanotechnology is at a cross-roads
  - Significant investments have been and continue to be made in nanotechnology research, development and commercialization
  - Remarkable advances have been made in nanoscale science and engineering
  - Nanotechnology is moving from an area of focused attention to an enabling technology, i.e., an important tool in the toolkit to make better materials, devices, …
- What's next?
  - Continue to make break-through advances, e.g., convergence of nanotechnology with biotechnology and other emerging technologies, Grand Challenges
  - Increase emphasis on nanotechnology enabled systems
  - Continue to make progress on commercialization
    - EH&S is a critical part of this
  - Develop global partnerships to tackle the hard problems