Nanotechnology: Thinking Big About Small Things

Lloyd Whitman, *Deputy Director, CNST*

Interim Director, National Nanotechnology Coordination Office
National Science and Technology Council

CNST Center for Nanoscale Science & Technology

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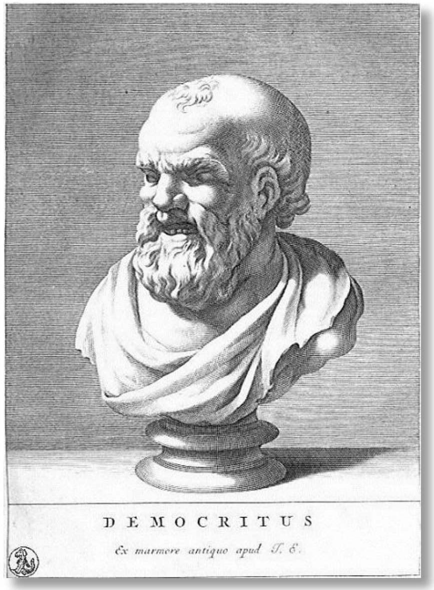
Democritus and the Atomic Theory

- Ancient Greek philosopher Democritus (ca. 460 – 370 BC)
  - There must be a point where you can no longer cut something up any smaller.
  - He called it the “atom”, after the Greek word *atomos*, which means “that which can't be split”
- With his teacher, Leucippus, formulated an atomic theory for the universe
  - Everything is composed of "atoms“
  - Between atoms lies empty space
  - Atoms are indestructible
  - Atoms have always been, and always will be, in motion
  - There are an infinite number of atoms, and kinds of atoms, which differ in shape, and size

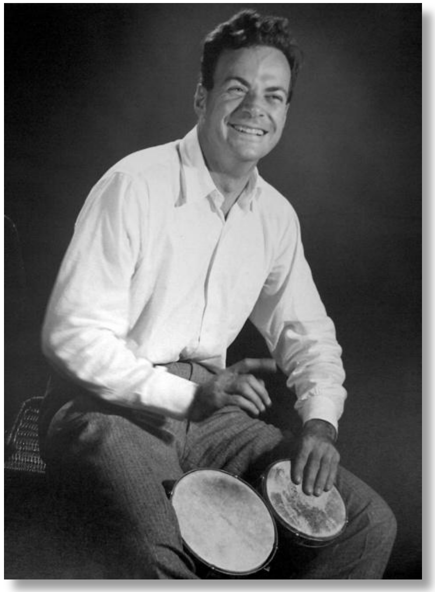


www.phil-fak.uni-duesseldorf.de/philo/galerie/antike/demokrit.html

Nanotechnology: The Beginning

From "*There's Plenty of Room at the Bottom, An Invitation to Enter a New Field of Physics*," by Richard Feynman, December 29, **1959** (!)

"What I want to talk about is the problem of manipulating and controlling things on a small scale…I am not afraid to consider the final question as to whether, ultimately---in the great future---we can arrange the atoms the way we want; the very *atoms*, all the way down! What would happen if we could arrange the atoms one by one the way we want them…? …When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc.…"



R. Feynman (1918-1988)

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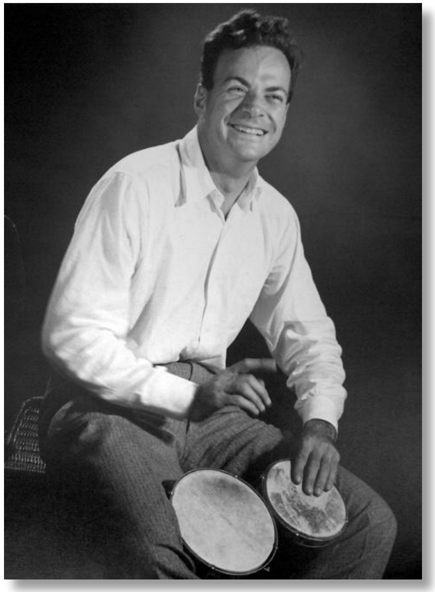

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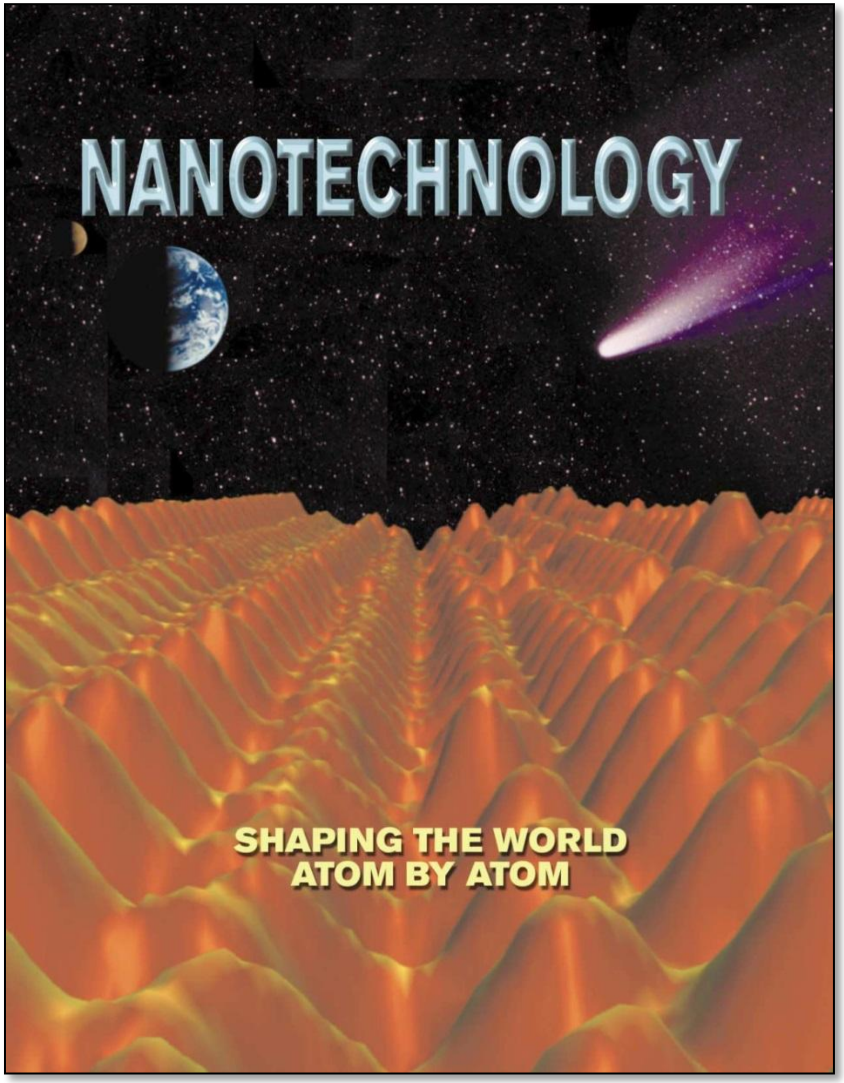
Nanotechnology Defined

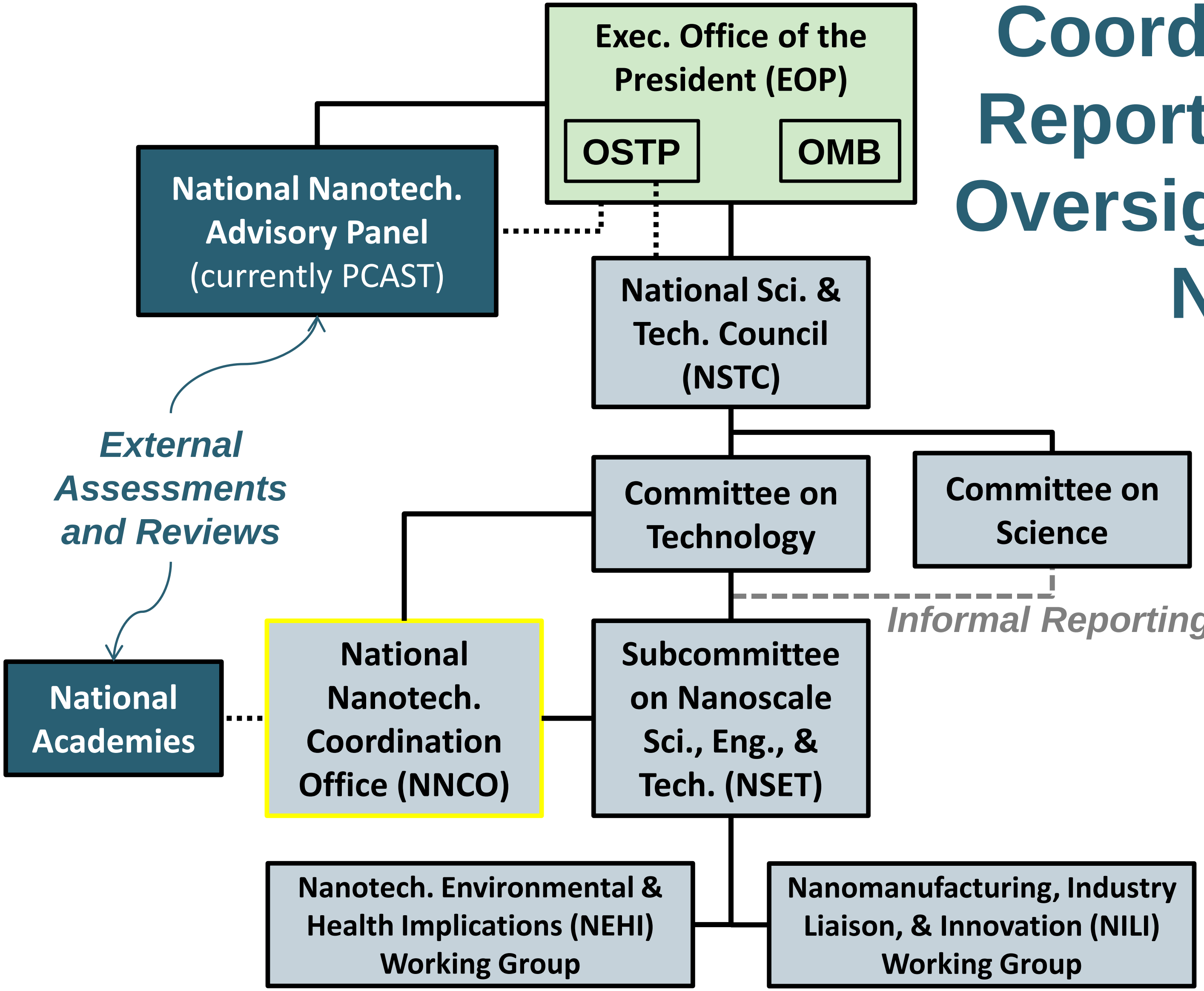
- Understanding and controlling matter at dimensions of roughly 1 to 100 nanometers (nm)
  - 1 nanometer = 1 billionth of a meter = 1 meter/1,000,000,000
  - Unique phenomena enable novel applications
- Nanotechnology = science + engineering + technology
  - Imaging, measuring, modeling, and manipulating matter at the nanoscale
- Physical, chemical, biological properties of nanomaterials differ from both individual atoms or molecules and bulk matter
- Goal of nanotechnology R&D is understanding and creating improved materials, devices, and systems that exploit these new properties

National Nanotechnology Initiative

- Launched in 2000 to promote and coordinate US nanotech R&D
- Collaborative R&D to advance understanding and control of matter at the nanoscale for:
  - National economic benefit
  - National security
  - Improved quality of life
- 20 Federal Departments and Independent Agencies
  - 11 have specific nanotech budgets
- 2014 budget: $1.6 billion
  - Cumulative $21 billion investment since 2001



Coordination, Reporting, and Oversight of the NNI



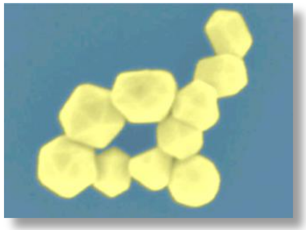
NNI Signature Initiatives

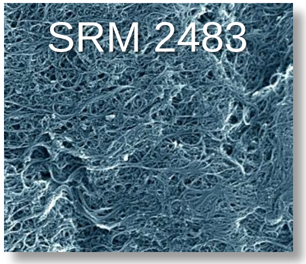
- Spotlight areas of national significance that can be more rapidly advanced through focused and closely-coordinated inter-agency collaboration.

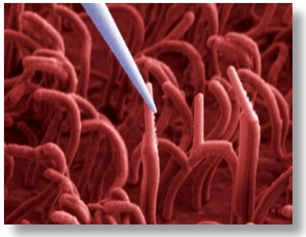
  1. Nanotechnology for Solar Energy Collection and Conversion (2010)
  2. Sustainable Nanomanufacturing: Creating the Industries of the Future (2010)
  3. Nanoelectronics for 2020 and Beyond (2010)
  4. Nanotechnology Knowledge Infrastructure: Enabling National Leadership in Sustainable Design (NKI) (2012)
  5. Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment (2012)

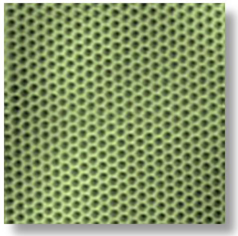
“Building” at the Nanoscale: Diverse Building Blocks

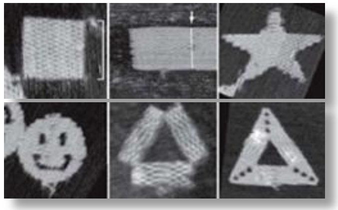
- Nanoparticles
  - Metallic, magnetic, insulating, functionalized,…
- Nanotubes and Nanowires
  - Carbon nanotubes, semiconductor “nanowires”,…
- Nanosheets and membranes
  - Graphene, silicon membranes,..
- Macromolecular and Biomolecular nanostructures
  - Organic dendrimers, DNA “origami”, virus scaffolds, protein nanopores,…



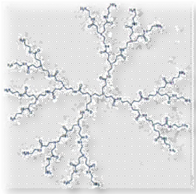








Rothemund, Nature 2006



Dendritech

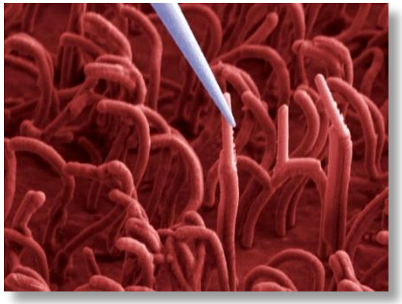
Astounding variety of structure and function.

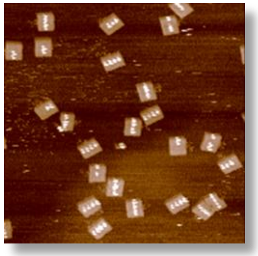
The Breadth of Nanotechnology

…biosensors enabling early treatment of diseases; biosensors applied to drug discovery; radiative cooling paint; cold lighting systems; dye solar cell; biosensors for diagnostics; molecular electronics; nanoparticles for total UV protection; food wraps that use nanoparticles to improve gas barriers; nano-enhanced windows - self cleaning, solar control, switchable, photovoltaic; paint additives to allow dark surfaces to stay relatively cool and light surfaces to absorb heat; temperature sensors; stain resistant fibers for clothing; air quality monitors and enhancers; stress sensors embedded in building materials; "smart spaces" that sense and act, communicate, reason, and interact; magnetic sensors; magnetic storage; electronic switches; optical filters; new lasers; nanostructured catalysts; reinforced materials; probes; thermal barriers; ink-jet inks; molecular sieves; high hardness tools; antimicrobials; nanocomposite materials; contrast agents; labs-on-a-chip; water purification materials; enhanced batteries; stronger materials; lubricants; rocket propellant; improved coolants; synthetic bone; cosmetics; wear resistant materials; porous membranes; translucent ceramics; radar absorbing coatings; hydrogen storage devices; coal liquefaction systems; conductive plastics; displays; lightning arrestors; electron microscopes; electrostatic dissipators; antistatic materials; conductive adhesives; nanomechanical systems and sensors; x-ray zoneplates; fast-absorbing drugs and nutrients; ultra-capacitors; novel semiconductor devices; novel optoelectonic devices; quantum computers; light aerospace materials; food storage and packaging materials; scratch resistant optics; tissue engineering materials; functional food; functional fertilizer; all optical information processing; neural prosthetics; nanoplasmonics; polymer films used in displays for laptops, cell phones, digital camera, smart goods; nanoelectronics; pervasive electronics; imaging systems; nanosurgery; transistors; nanofluidics; molecular scale motors; atomically precise assembly; space elevator; tennis, golf, and bowling balls; water repellants; magnetic disk materials; disk drive heads; bandages; man-made skin; packaging to sense spoiled food; high density phase change memory; dental bonding agent; compasses; self repairing materials; tags and markers; nanofabrication; nanoscale analysis; …

Major Thrusts in Nanotechnology

- Post-CMOS Electronics
  - Extend the electronics enterprise
- Nanophotonics
  - Enhance communications, lighting, and inspection
- Nano-enhanced energy
  - Optimize the first step in conversion, storage, transport
- Nanomanufacturing (including coatings, composites)
  - Allow industry to capitalize on discovery
- Nano-biotechnology and nano-medicine
  - New diagnostics and therapeutics to improve outcomes and reduce cost
- Nano-EHS
  - Science-based regulation to protect the population and reduce risk for commercial innovation

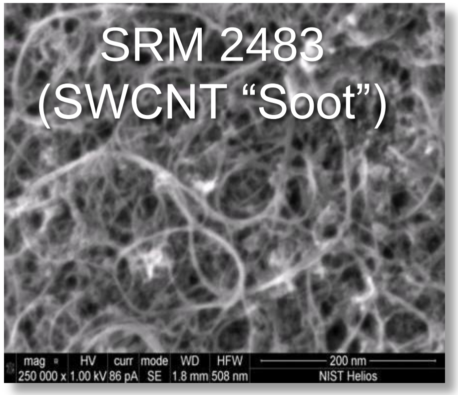




Already ~$1 billion global market.

Nanotechnology at NIST

- Perform NIST's traditional roles
  - Discipline oriented laboratory research
  - Workshops to identify industry needs
  - Standards setting (physical & documentary)
  - Calibrations



- Form public-private partnerships
  - Nanoelectronics Research Initiative
  - Nanomanufacturing (planning stages)
- Operate a multidisciplinary user facility, including a shared resource for nanofab.
- Support nanotechnology through research grants and cooperative agreements
- Coordinate and collaborate with industry stakeholders, other US federal Agencies and international partners

NIST Nanotechnology Research

- Discipline oriented research flows as logical extension of responsibility for measurement on larger scales:

  Milli $\rightarrow$ micro $\rightarrow$ nano

meter $\rightarrow$ nanometer

- Strong nano-related programs in:
  - Characterization & metrology
  - Energy
  - Photonics & Plasmonics
  - Materials and Chemistry
  - *Environmental, Health & Safety**
  - Theory & modeling
  - Electronics
  - Magnetics
  - Mechanics
  - *Fabrication and Manufacturing**
  - Biotechnology
  - Simulation & visualization

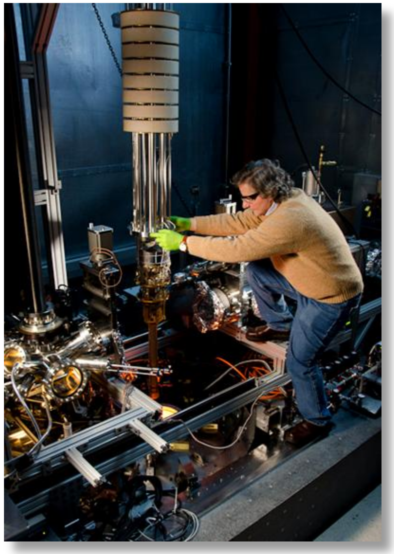
**Recent program growth areas*

NIST Center for Nanoscale Science and Technology (CNST)

- NIST's nanotechnology user facility.

  Provides rapid access to tools needed to make and measure nanostructures, with emphasis on helping U.S. industry.

- In the ***NanoFab***, researchers can use a commercial state-of-the-art tool set at economical hourly rates, along with help from a dedicated, full-time technical support staff.



- In the ***NanoLab***, researchers get access to the next generation of tools and processes through collaboration with our multidisciplinary research staff, who are developing new measurement and fabrication methods in response to national nanotechnology needs.

- The CNST serves as a hub linking the external community to the nanotechnology-related measurement expertise at NIST (nano@nist.gov).

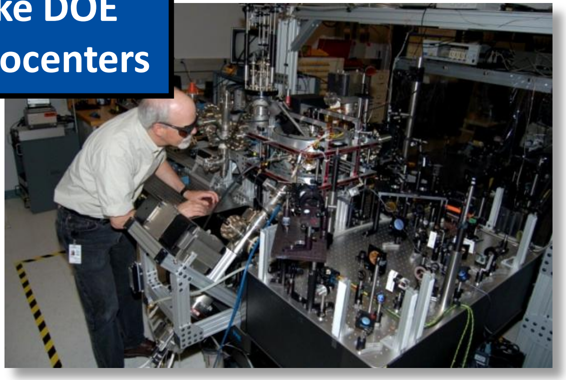
The CNST in Brief

Established in 2007 to develop nanoscale measurement and fabrication methods *specifically* to advance nanotechnology "*from discovery to production*"

- A User Facility with a unique, hybrid design
- The **Nano****Fab** is a shared resource with commercial state-of-the-art tools for nanofabrication, open to all
- The **NanoLab** advances nanotechnology by developing new measurement solutions, and supports the NanoFab with expert consultation
- **Budget**: $32M (FY2013)
- **Staff (fall 2013)**: 106 (93 technical)
- Cooperative Agreement with the University of Maryland Nanocenter
  - Contributes to all phases of the CNST mission

Like NSF-supported, university nanocenters

Like DOE nanocenters



MARYLAND NANOCENTER

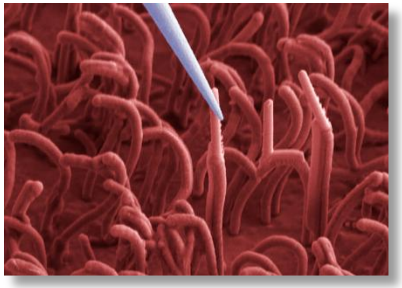
The CNST NanoFab

A national, state-of-the-art, shared resource for the fabrication and measurement of nanostructures:

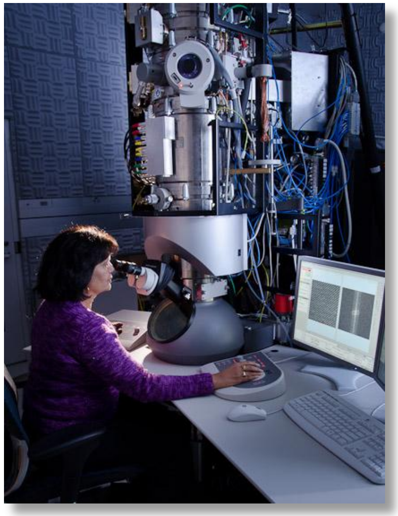
- 60,000 ft^2 (5600 m^2) of labs and cleanroom
  - 19,000 ft^2 (1800 m^2) cleanroom;
    8,000 ft^2 (750 m^2) at class 100
  - Open (staffed) weekdays from 7 am to midnight
- Leverages the expensive tools needed for nanotechnology through cost sharing (charged "*a la carte*")
  - About 100 major tools, including advanced lithography (e-beam x2, ASML stepper), microscopy (FE-SEM, FIB, TEM)
- Staffed with talented technical team (18) who train and assist users, operate and maintain the tools, and develop and control the processes
- Connects external researchers to extensive measurement resources in the NIST Laboratories and Centers

The CNST NanoLab

- Project Leaders developing measurement and fabrication capabilities, with current priorities in:



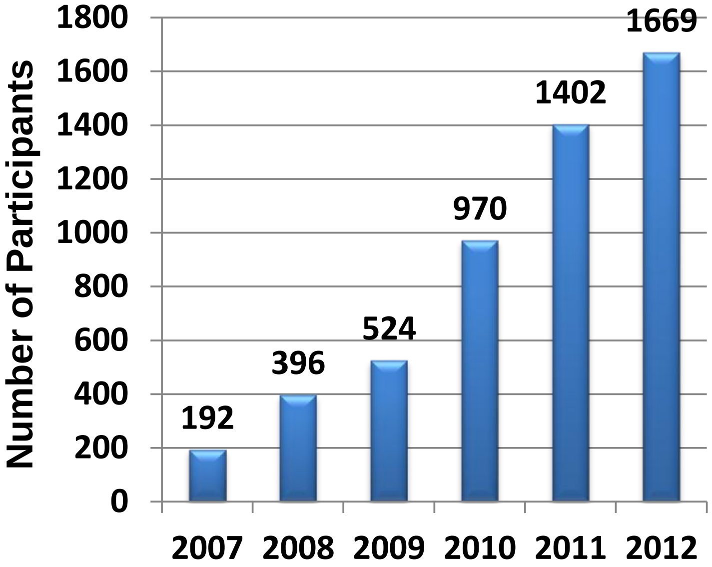
  - **Future Electronics:** Nanoscale devices, architectures, interconnects
  - **Nanomanufacturing and Nanofabrication**: Top-down and bottom-up fabrication and assembly
  - **Energy:** Conversion, storage, and transport at the nanoscale
- Provides access to next-generation measurement tools and fabrication methods through ***collaboration*** with the Project Leaders



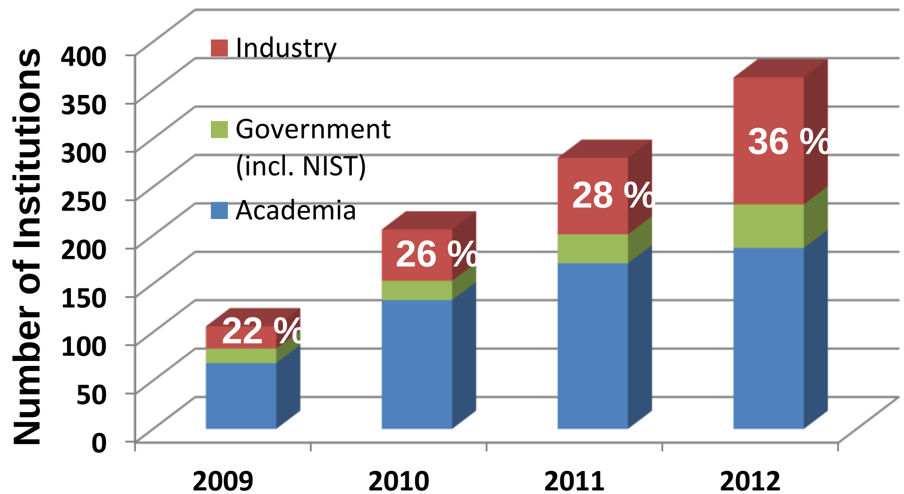
- Designed to be agile: priority areas will change with NIST and national nanotechnology needs
- Integrated tightly with the NanoFab, providing expert consultation and beyond-state-of-the-art measurements
- Complements and supports the NIST metrology and engineering laboratory programs

Research Participation Growing Rapidly

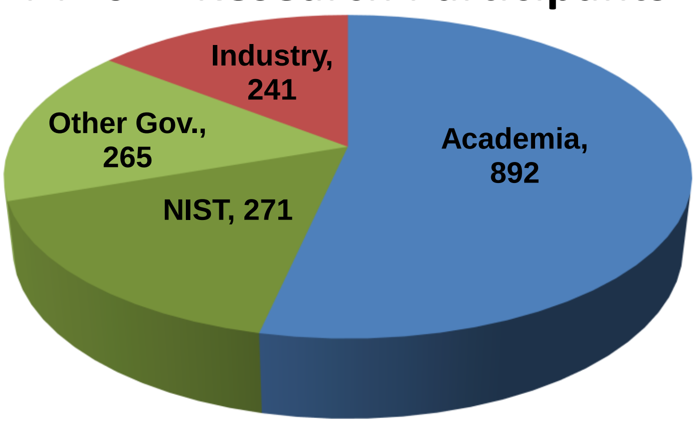
Research Participants By Fiscal Year



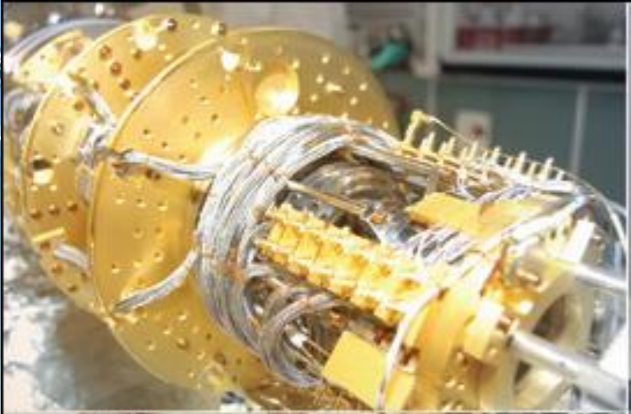
Participating Institutions By Fiscal Year



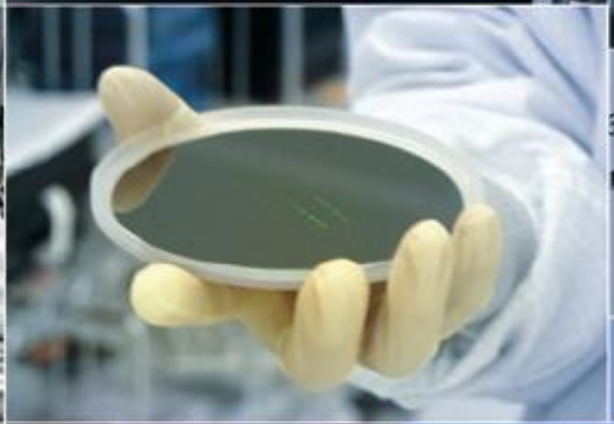
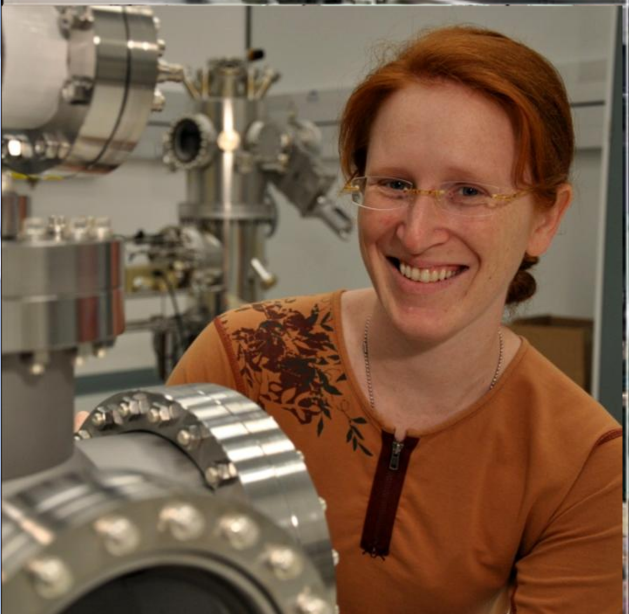
FY2012 Research Participants



FY2012 Institutions (363)	
Companies:	131
Universities:	187
Gov. Labs:	45
States + DC:	40






Thank you for your attention!

whitman@nist.gov
lwhitman@nnco.nano.gov