Nanotechnology Development and Potential Environmental Implications

EPA Millennium Lecture Series
April 25, 2005

Clayton Teague
Director
National Nanotechnology Coordination Office
Nanoscale Science, Engineering, and Technology Subcommittee
Committee on Technology
National Science and Technology Council

Outline of Talk

- Role of the National Nanotechnology Coordination Office (NNCO) in the National Nanotechnology Initiative
- Development of nanotechnology
- Potential environment, health, and safety implications of nanotechnology – engineered nanomaterials
- What is the NNI doing to address the EHS implications of engineered nanomaterials?

The National Nanotechnology Coordination Office

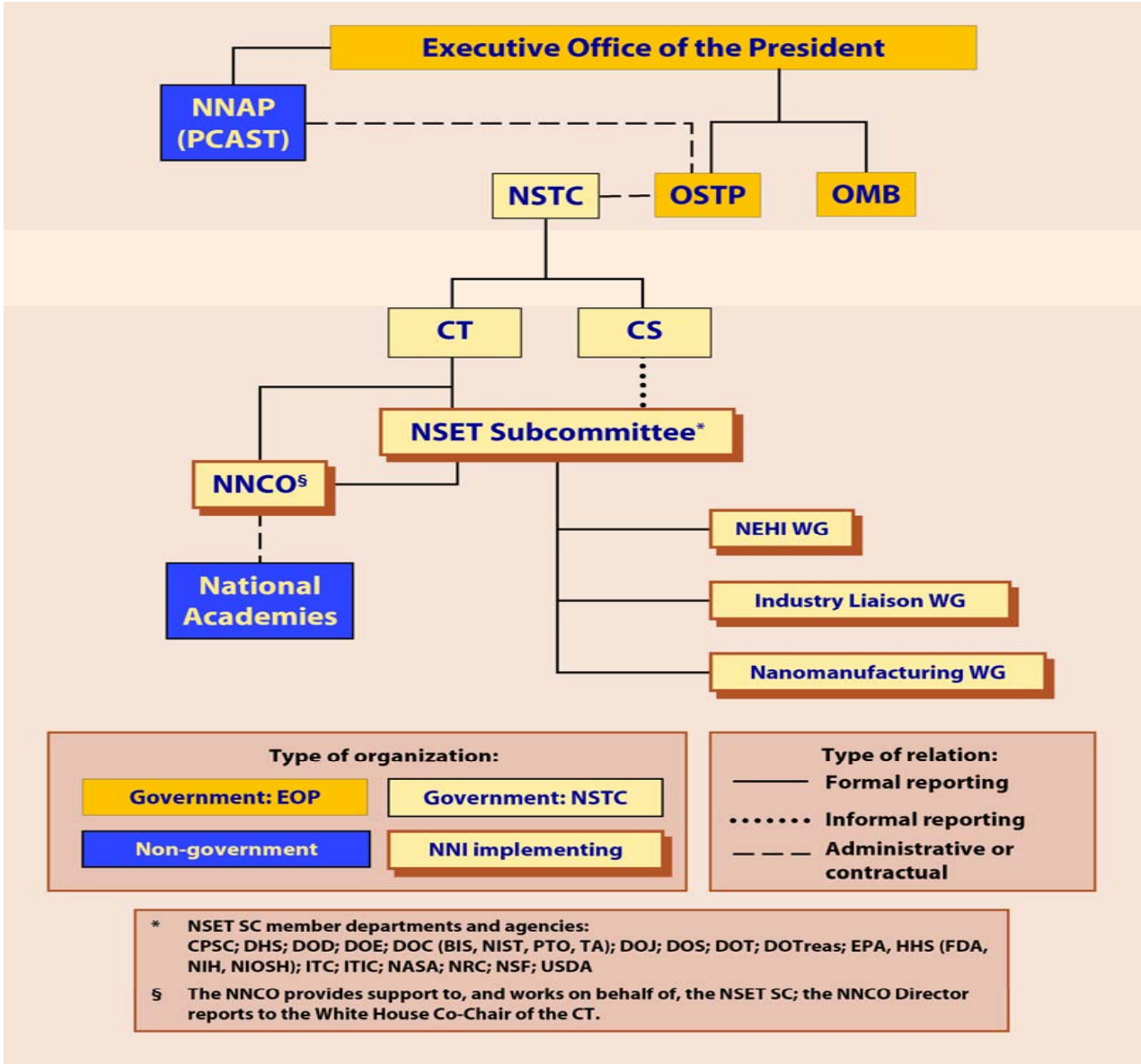
- **The National Nanotechnology Coordination Office (NNCO) was established by a Memorandum of Understanding between DOD, DOE, NIH, DOT, EPA, NASA, NIST, and NSF that became effective on January 15, 2001**

- **The NNCO is financially supported by contributed funds from these agencies in proportion to their requested R&D funding for nanotechnology for each respective year –**
  - *NNCO annual budget has remained at about 0.2% of the requested NNI annual budget*

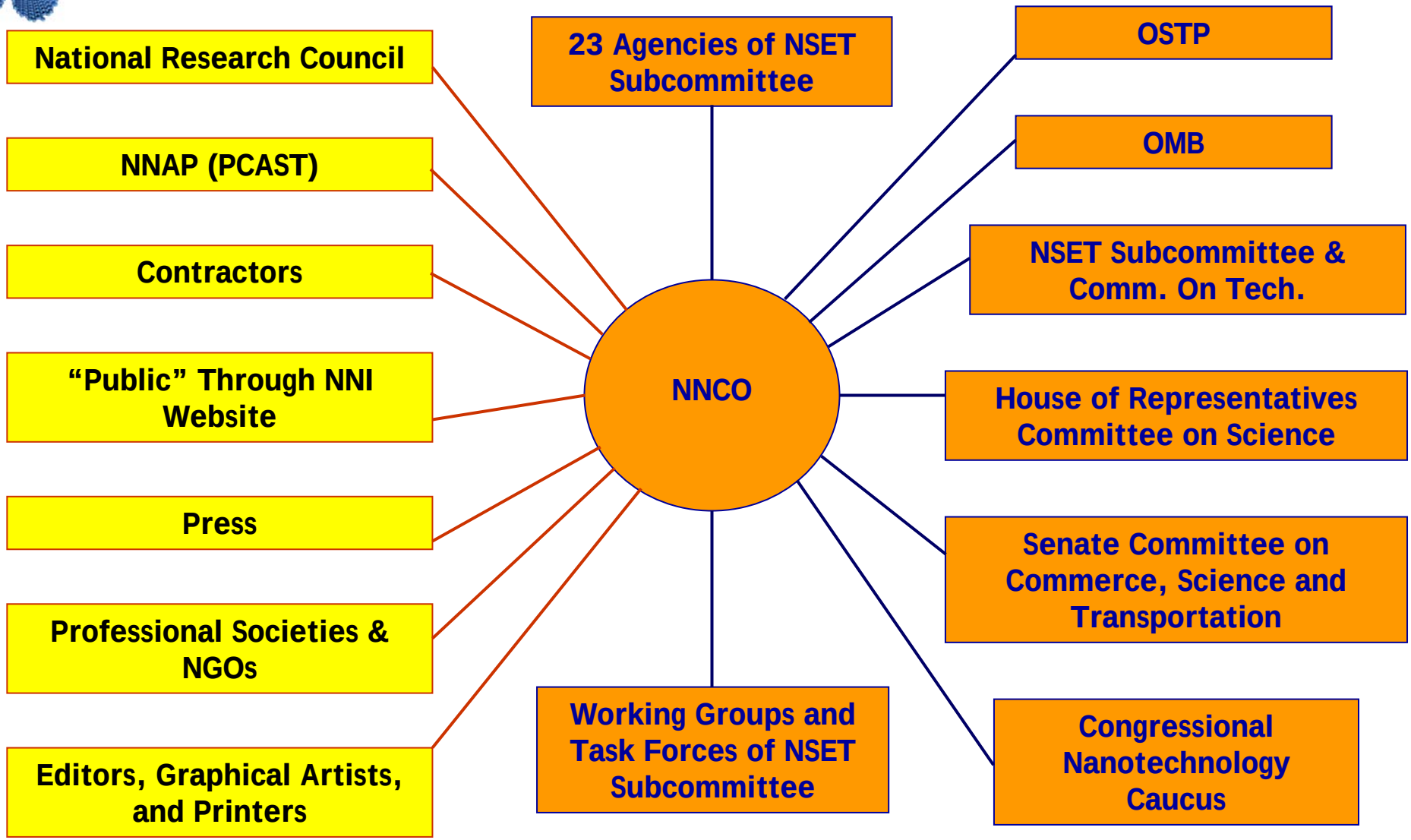
The National Nanotechnology Coordination Office

- **The NNCO:**
  - Serves as the Secretariat for the NSET Subcommittee and supports the interagency coordination activities of the NSET
  - Provides technical and administrative support to the NSET Subcommittee and to working groups established by the NSET Subcommittee
  - Chartered to serve as the point of contact on Federal nanotechnology activities and to conduct public outreach on behalf of the NSET Subcommittee
  - Promotes transfer of the results of Federal nanotechnology R&D for commercial use and public benefit
  - Maintains and updates the NNI website
- **The NNCO was established by law by the 21st Century Nanotechnology Research and development Act (PL 108-153) – signed by the President in December 2003. This Act established a number of new reporting and advisory requirements to be carried out by or facilitated through the NNCO**
  - Enter into an arrangement with the NRC of the National Academy of Sciences to conduct a triennial review of the Program
  - Provide technical and administrative support to the NNAP

NNI Organization

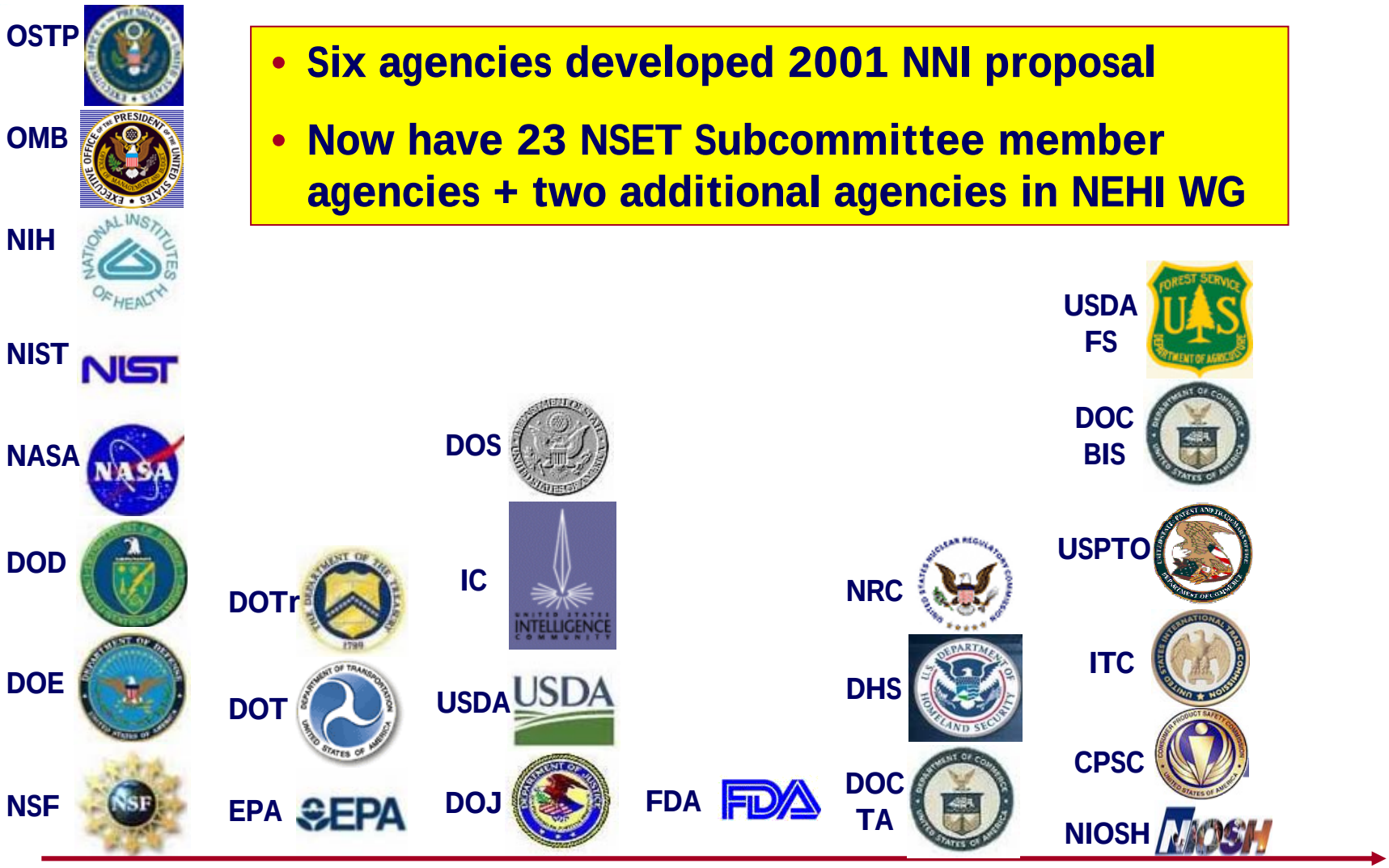


NNCO Working Level Interactions



Growth of NSET Subcommittee

- Six agencies developed 2001 NNI proposal
- Now have 23 NSET Subcommittee member agencies + two additional agencies in NEHI WG



How is the Government Investing $1B NNI Funding?

$1,082 Million is FY2005 Estimated NNI Funding

- NSF - 338
- DOD - 257
- DOE - 210
- HHS - 146
- NIST - 75
- NASA - 45
- EPA - 5
- USDA - 3
- DOJ - 2
- DHS - 1

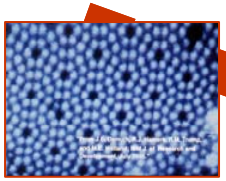
→ Academia ~65 % → Single and Multiple Investigators; Centers and User Facilities

→ Government Intramural ~25% → NRL, AFRL, ARL NIH, NASA, NIST, EPA, FDA, DOE Nat Labs

→ Industry ~10% → SBIR, STTR, ATP, DOD Contracts

NATIONAL NANOTECHNOLOGY INITIATIVE

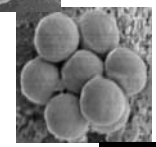
Nanotechnology Development

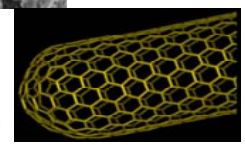


"Seeing"/Visualizing

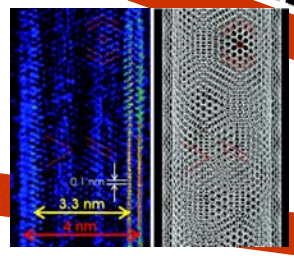
Supra Molecular Chemistry

Atom Clusters S&T





Measuring

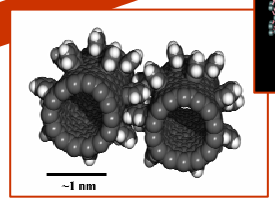


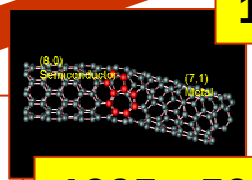
Manipulating/ Controlling

Control of Matter at the Nanoscale

Simulating/Modeling

1985-1990 - Computer aided molecular design; pharmaceuticals, pesticides, proteins





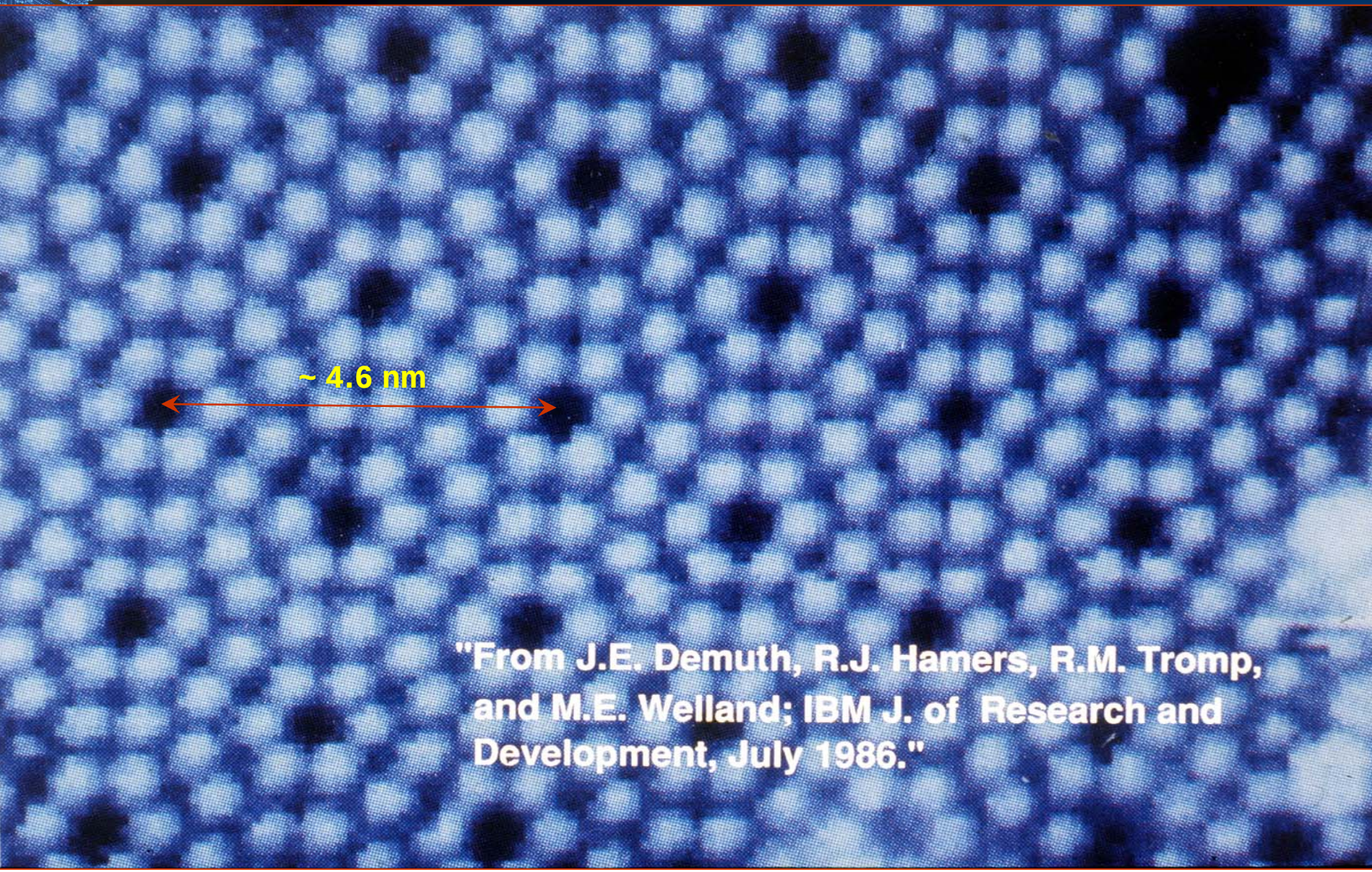
2004 - 50,000 atoms
100 nm long nanotube

1995 - 5000 atoms

Biotechnology

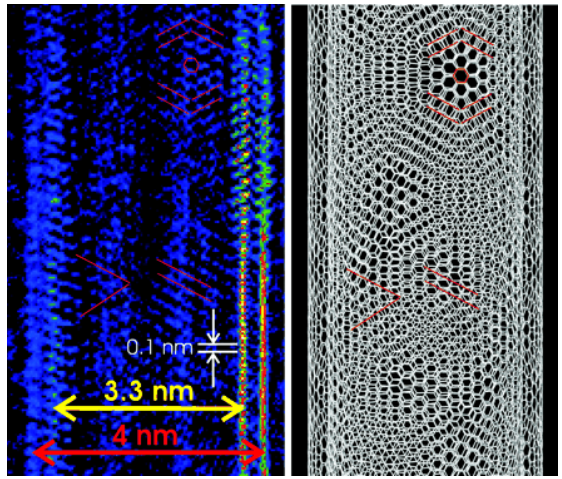
1968 - H_2O

Extraordinary Atomic Level Detail in STM Images

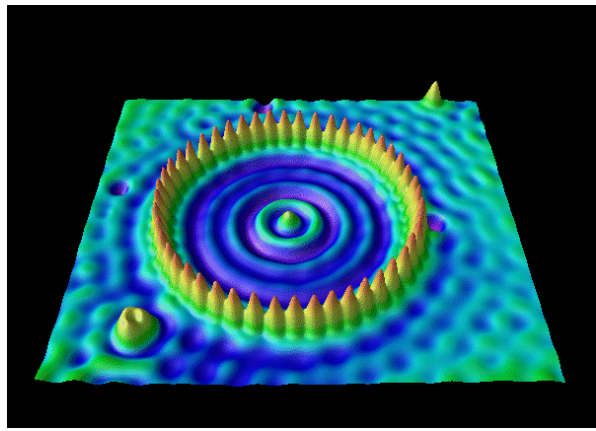


What Is Nanotechnology?

- Research and technology development aimed to understand and control matter at dimensions of approximately 1 - 100 nanometer – the nanoscale
- Ability to understand, create, and use structures, devices and systems that have fundamentally new properties and functions because of their nanoscale structure
- Ability to image, measure, model, and manipulate matter on the nanoscale to exploit those properties and functions
- Ability to integrate those properties and functions into systems spanning from nano- to macro-scopic scales

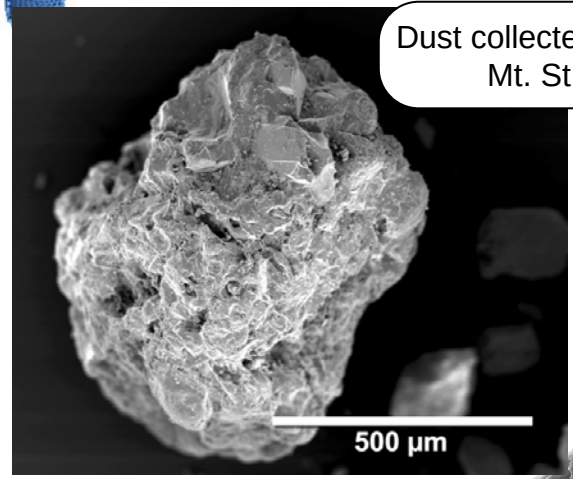


Nanoarea Electron Diffraction of DW Carbon Nanotube – Zuo, et.al



Corral of Fe Atoms – D. Eigler

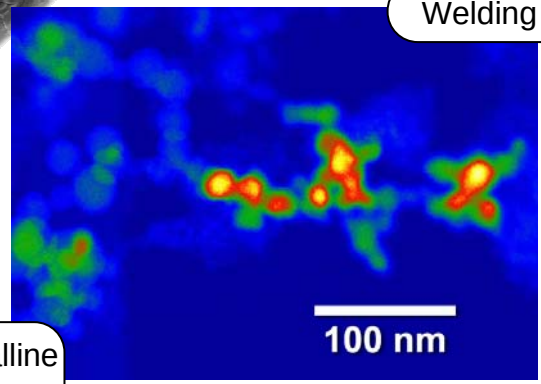
From Micro to Nano..



Dust collected 5 miles from Mt. St. Helens

Human Hair

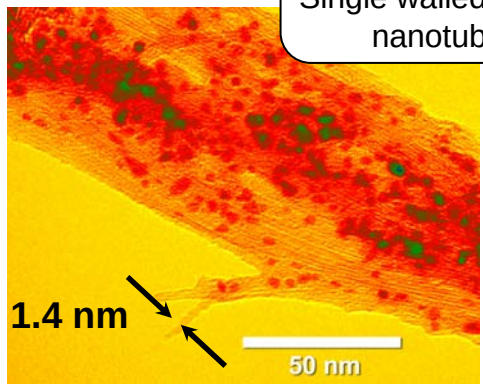
Courtesy of Andrew Maynard



Welding fume

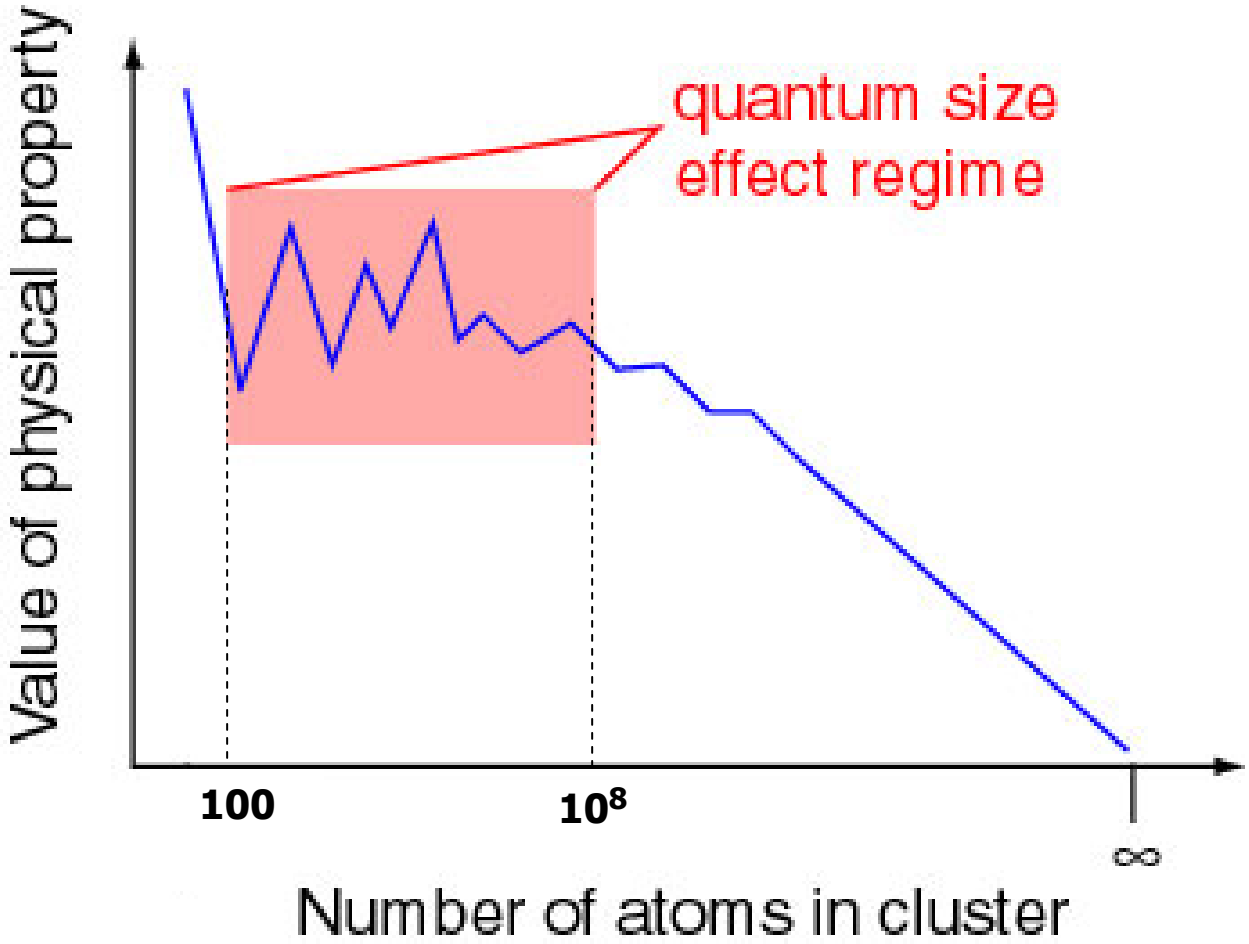
Respirable crystalline silica

Single walled carbon nanotubes

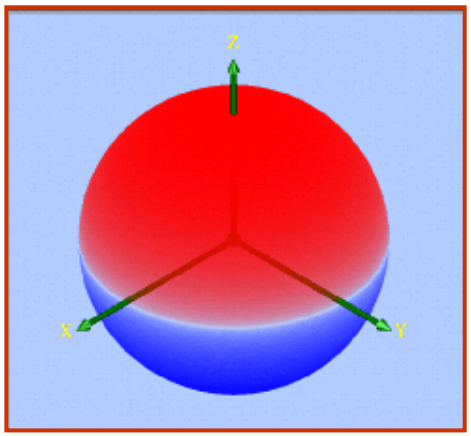


1 mm | 100 µm | 10 µm | 1 µm | 100 nm | 10 nm | 1 nm

Quantum Size Effect



Electron in a Sphere – Quantum Size Effect



Example: for Gold $m^* = m_0$

For $\Delta E = 1.6$ eV (energy for red light emission), D ~ 1.6 nm

If $m^* \neq m_0$ as for some semiconductors, e.g. InSb; $m^* = 0.014\ m_0$, CdTe; $m^* = 0.11\ m_0$; then D ~ 114 nm and 14 nm respectively

$$E_n = \frac{2n^2\pi^2\hbar^2}{mD^2} \Rightarrow E_2 - E_1 = \frac{6\pi^2\hbar^2}{mD^2} = 4.5 \times 10^{-18} \frac{m_0}{m^*} D^{-2}\, eV$$

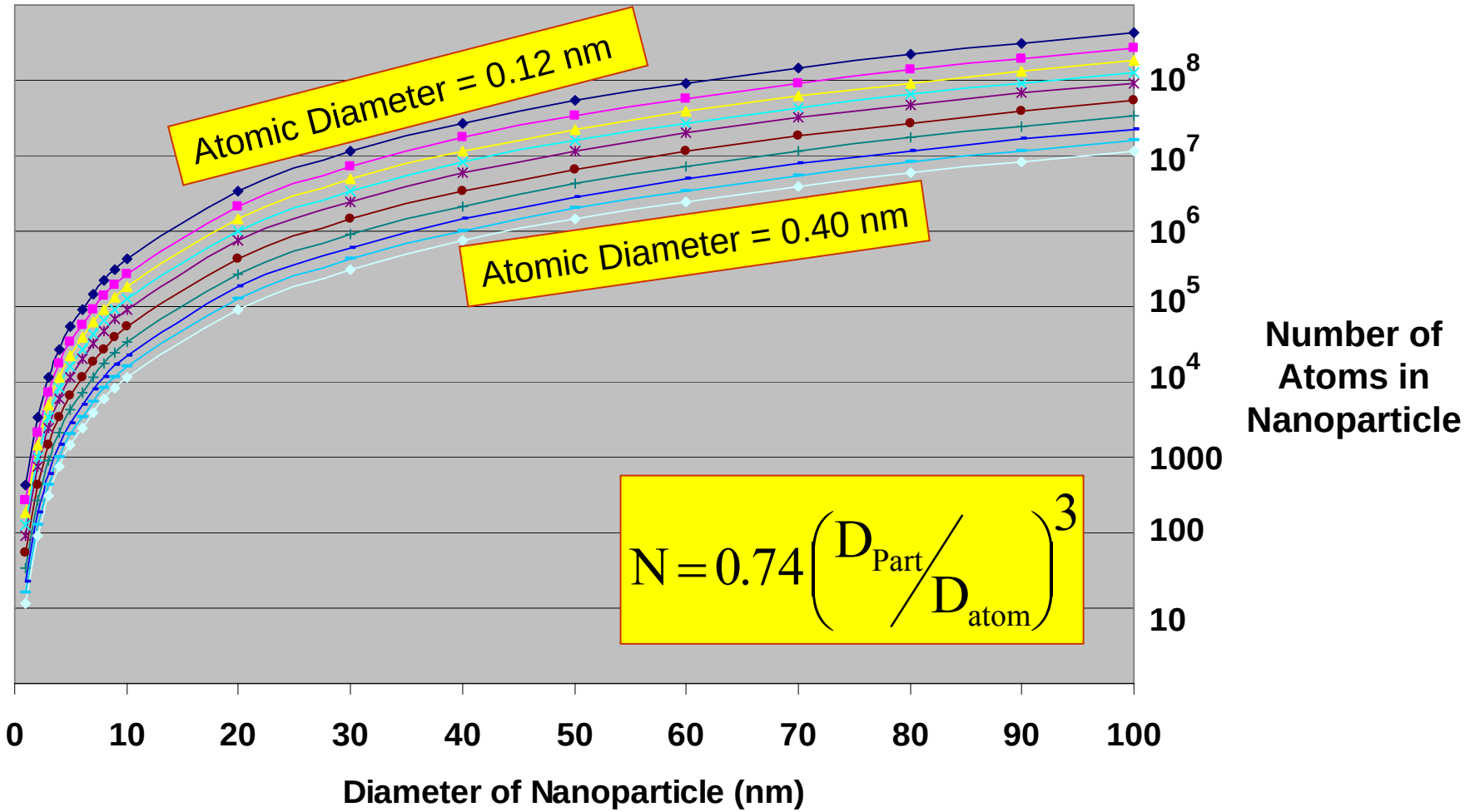
E_n = Radial energy eigenstate

D = Diameter of nanocrystal in meters

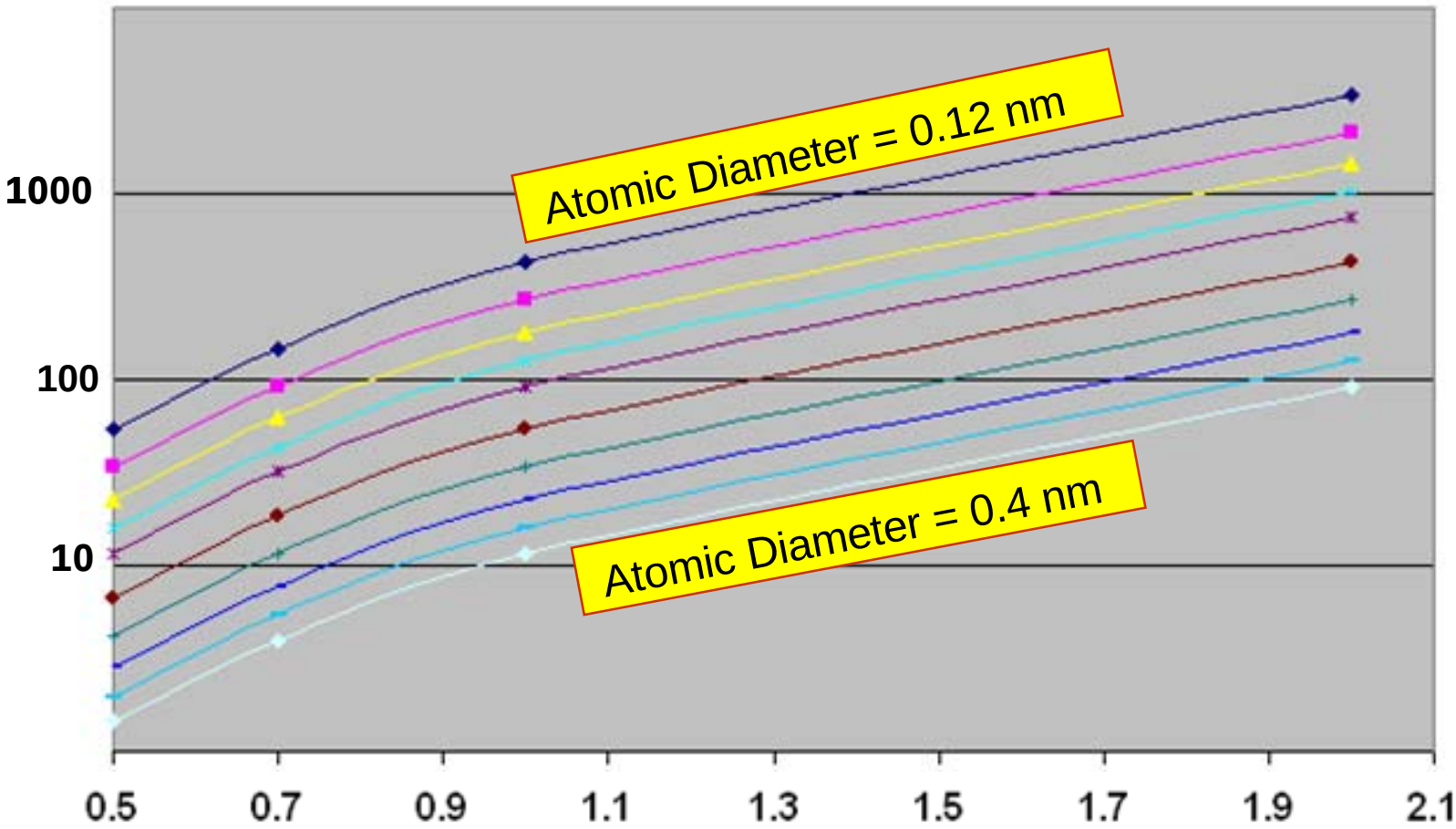
$$\frac{m_0}{m^*} = \frac{\text{Free electron mass}}{\text{Effective electron mass in crystal}}$$

Caution! Very simple model
Many effects from more realistic models not accounted for

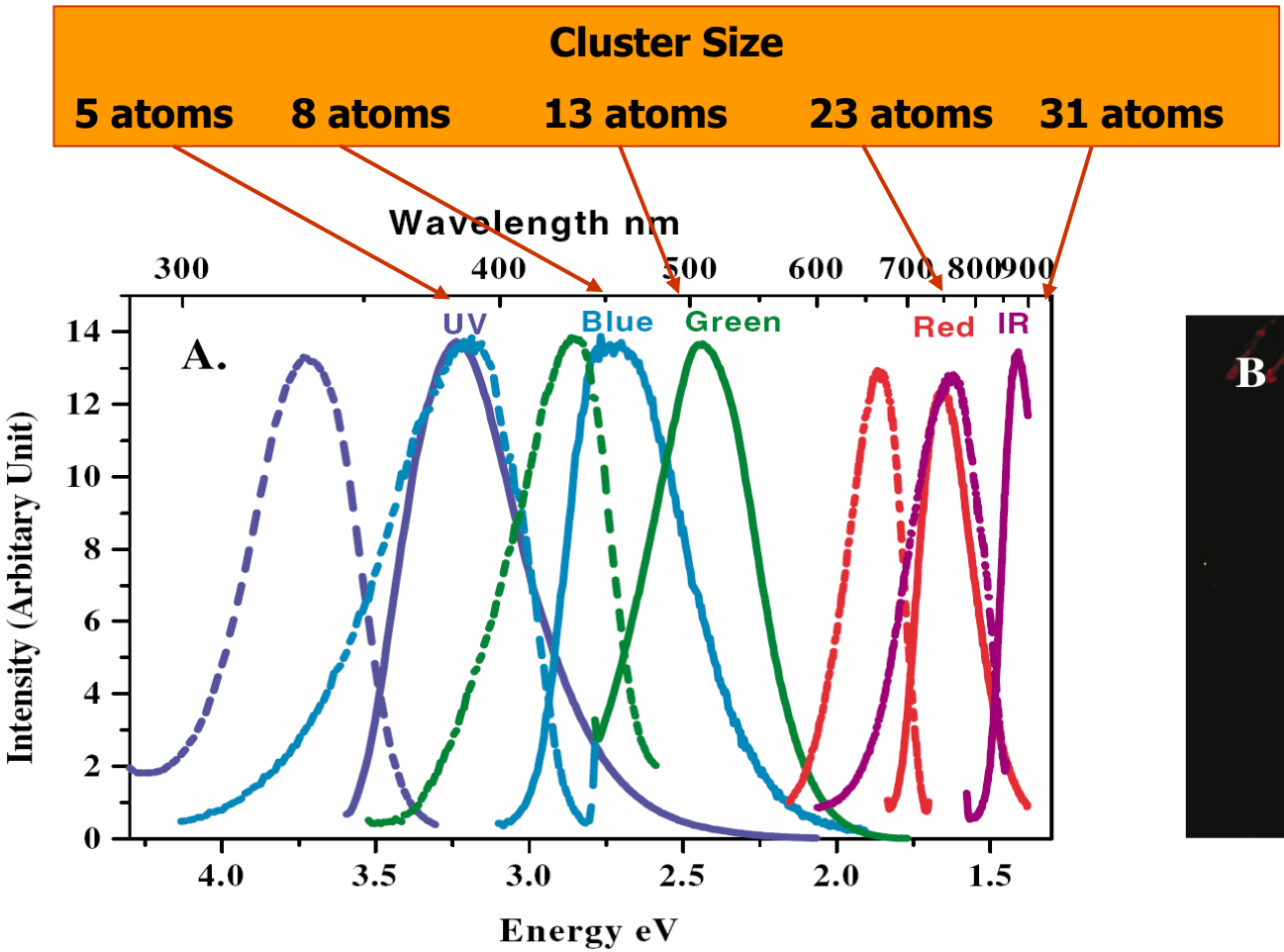
Number of Atoms in Nanoparticle – Close Packing

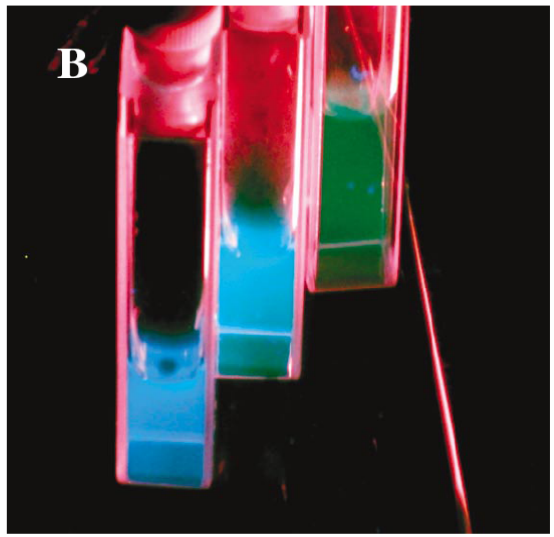


Previous Graph Expanded for Smaller Particles



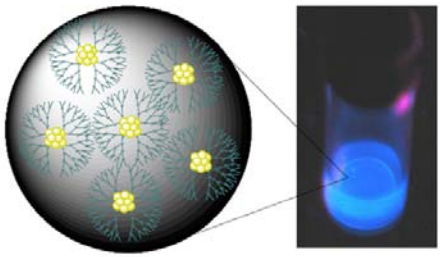
Size-Tunable Gold Nanocrystal Fluorescence

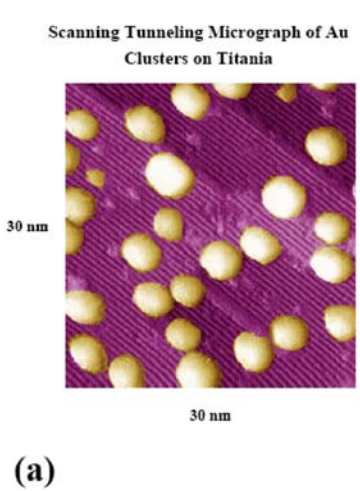


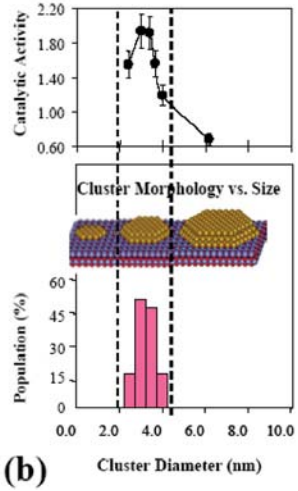


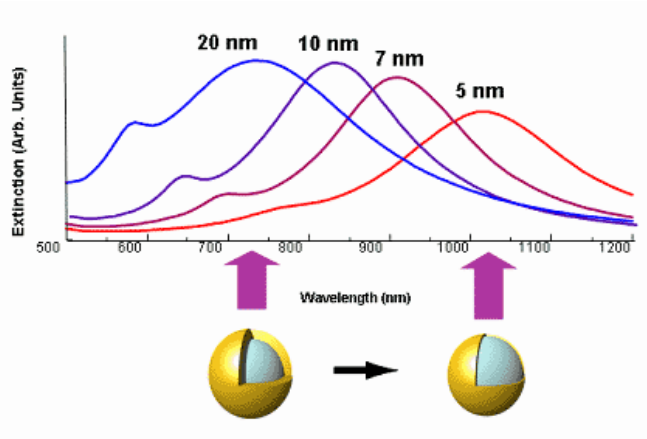
JZheng, CZhang, RMDickson PRL Aug 2004 Vol 93

Various Size Effects in Gold





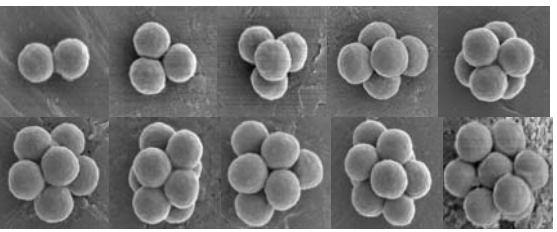


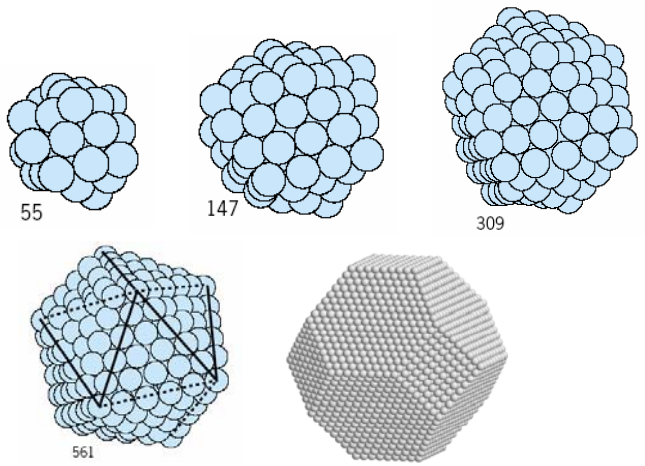


Electron Quantum Size Effect at ≤ 1nm

Enhanced Surface Sites for Catalysis at ~ 3nm

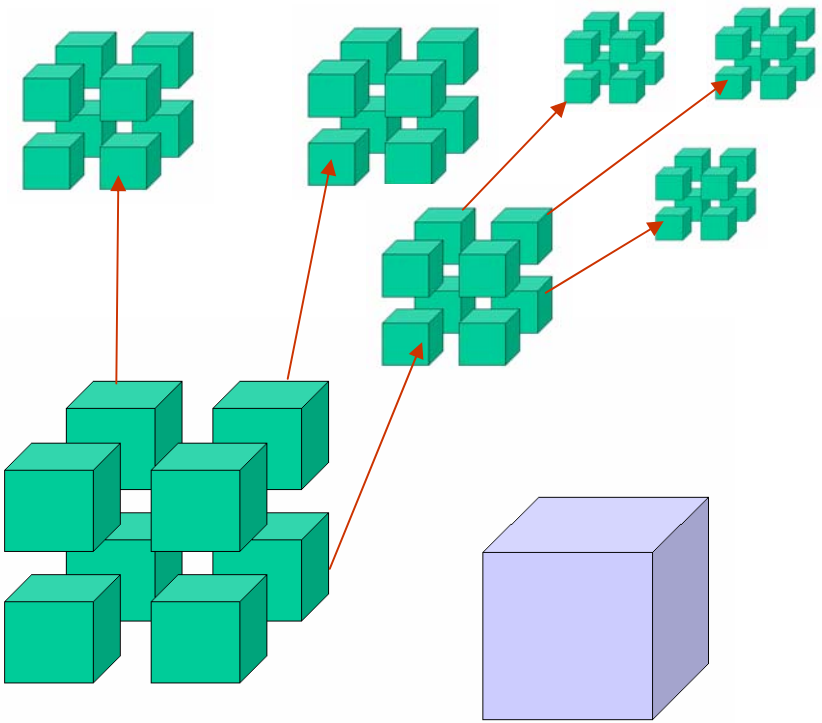
Plasmon Resonances on Nanoshells of varying thickness at ~ 120nm diameter





Nanoscale = High Ratio of Surface Area to Vol.

Repeat 24 times



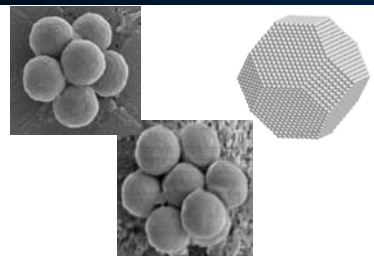
8 Cubes Side L
Each has Surface area 6L ^{2}
Total Surface Area 48 L^2

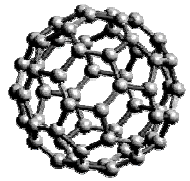
1 Cube
Length of sides 2L
Surface area 24 L ^{2}

For example, 5 cubic centimeters – about 1.7 cm per side – of material divided 24 times will produce 1 nanometer cubes and spread in a single layer could cover a football field

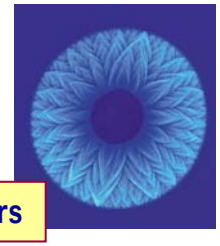
Nanomaterials

- Atom clusters



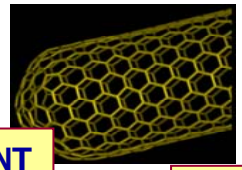


SiC Flowers



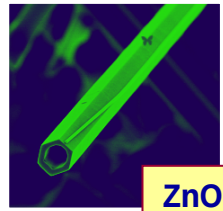
- Nanotubes, rods, spheres, belts … – carbon and other materials

C SWNT

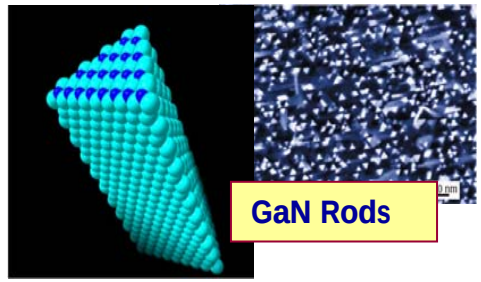


ZnO Belt

ZnO Tube

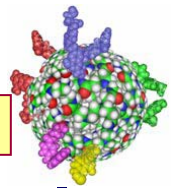


GaN Rods

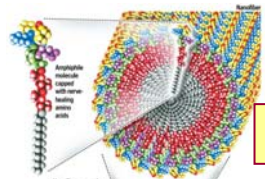


- Dendrimers

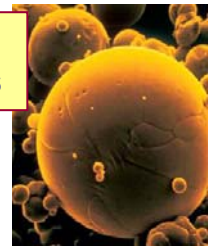
Spherical



Tubular



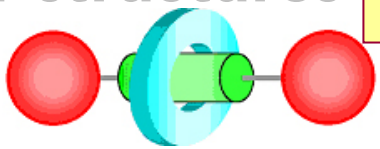
TiO_2 Spheres



- Macro-molecular structures

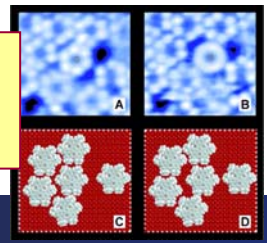
Catenane

Rotaxane

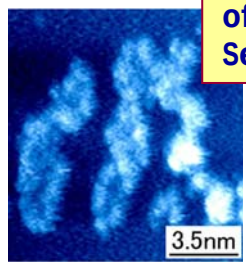


- Biomolecular structures

STM Image and Model of Porphyrin



STM Image of DNA Segment




Nanostructures All made of ZnO
Courtesy ZL Wang; Georgia Tech
100%
5%
100%
100%
100%
100%
100%
100%
10%
20%
5%

NATIONAL NANOTECHNOLOGY INITIATIVE

Nanotechnology is 'Now'

Selected consumer products

Nanoclay Composite

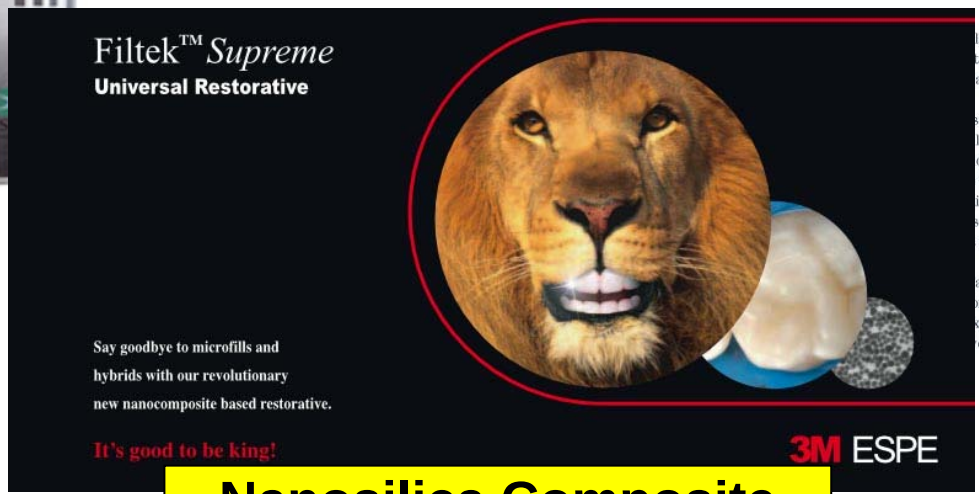
Easton CNT is Real Nanotechnology

Carbon Nanotube Composite

Mountain Bike Handlebars

4.6 oz. weight

Tennis Racket Five Times More Rigid



Nanosilica Composite

Nanotechnology is 'Now'

Selected High Technology products

RNT

High Temperature, Local heat source

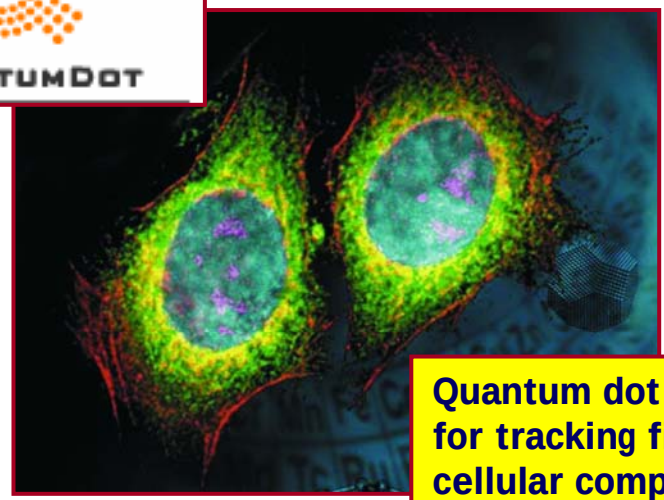
100 mm X 100 mm bond area

Angstrom Medica

Biocompatible nanomaterial bone screws

Bone bonding in 2 weeks and osseo-integration in 4 weeks

QUANTUMDOT



Quantum dot labeling for tracking five cellular components

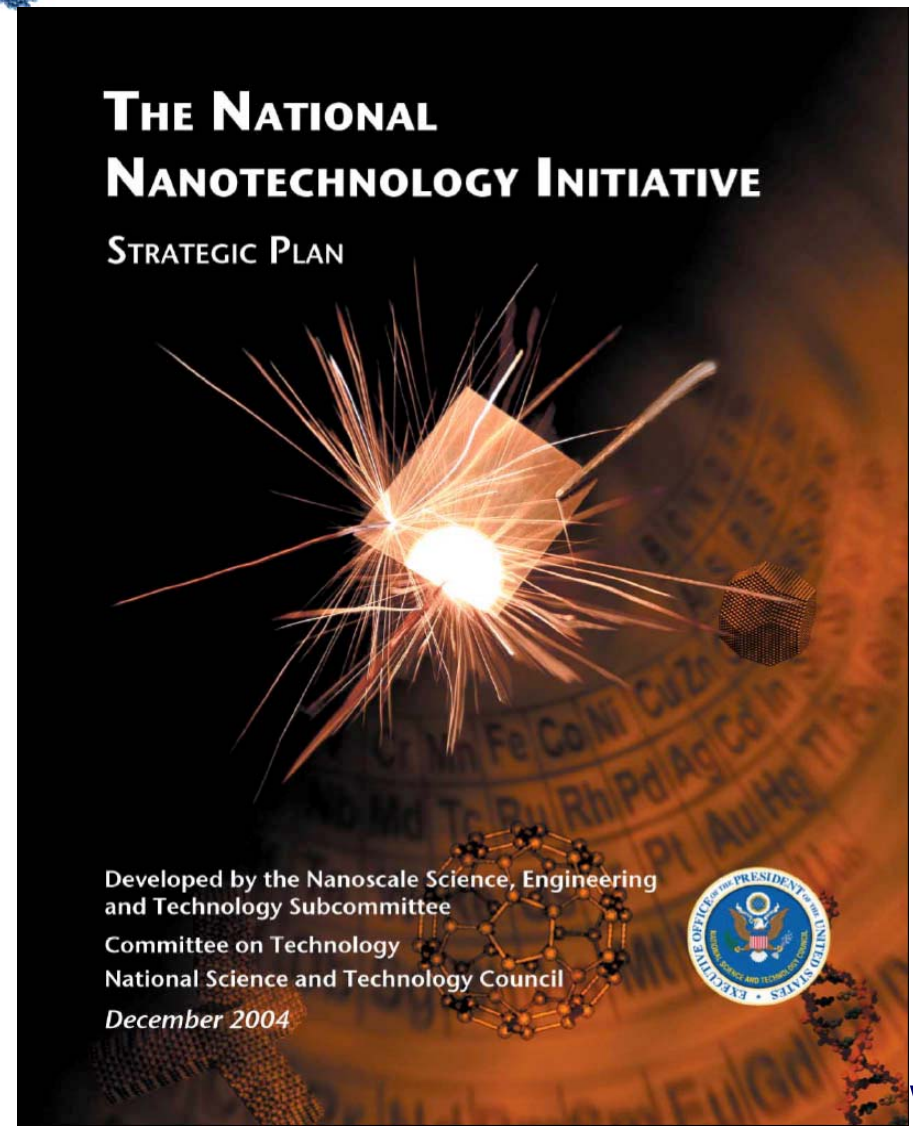
2005 Small Times Study of Nano "Industry"

- **Nanotechnology Companies and Organizations in the United States - headquartered in US or with major business activity in US**
- **Identified 1455 companies, organizations and agencies complying with strict selection criteria based on the US NNI definition of nanotechnology**
- **Includes:**
  - Organizations providing supplies, materials, or professional services to companies in this space
  - Industry associations and nanotech-focused economic initiatives
- **Identified 774 companies in manufacturing, conducting R&D in "nano space," or equipment suppliers**
- **Producing over 600 individual products – largest number of products are in materials and bionanotechnology category**

Unique Properties of Nanoscale Materials

- Chemical reactivity of nanoscale materials greatly different from more macroscopic form, e.g., gold
- Vastly increased surface a[illegible]ss, e.g., upwards of 1000 [illegible]
- Quantur[illegible]ique mechanical, electron[illegible]agnetic properties of nanosca[illegible]
- New ch[illegible]ical forms of common chemical elements, e.g., fullerenes, nanotubes of carbon, titanium oxide, zinc oxide, other layered compounds

NNI Strategic Plan



Goal 4: Support responsible development of nanotechnology:

- Environmental, health and safety implications
- Ethical, legal and other societal issues

Program Component Area 7: Societal Dimensions

- Environmental, health and safety research
- Education
- Broad societal implications

www.nano.gov

Group Organized to Coordinate Nano ESH

- **NSET Working Group on Nanotechnology Environment and Health Implications (NEHI WG)**
- **Membership from all relevant regulatory and research agencies, OSTP, and OMB**
- **Goals of Working Group:**
  - Provide for exchange of information among agencies that support nanotechnology research and those responsible for regulation related to nanoscale materials and nanotechnology-based products
  - Identify/prioritize research needed to support regulatory decision-making and communicate those needs to the research agencies
- **Convened in August 2003 by NNCO in coordination with OSTP; meeting monthly since February 2004**

Topics Being Addressed by NEHI WG

- **Nomenclature for identifying and delineating nanomaterials**
  - ANSI-Nanotechnology Standards Panel formed
  - Supporting establishment of ISO Technical Committee
  - EHS standards for nanotechnology a priority
- **Documentation of "recommended practices" for working with the nanomaterials**
  - Documentation being developed by NIOSH & OSHA
  - Q&As and "Current Intelligence Bulletin" to be forthcoming
- **Data on potential toxicity of nanomaterials**
  - National Toxicology Program under DHHS began study of TiO_2, nanotubes, and quatum dots in October 2003
- **Strategic plan for guiding research –**
  - Under development with input from regulatory and research agencies

Regulatory and Research Topics for EHS

Source/ Inventory

Emission

air

EPA, NSF, USDA, DOE

plants

water

soil layers

sediment

Fate, transport & transformation

Personal Protection Equipment

NIOSH, OSHA & DOD

NIOSH, EPA, FDA, DOE

Exposure Events

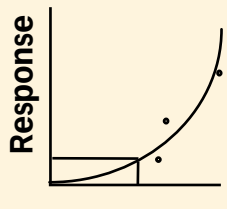
FDA & EPA

Uptake

NIH, EPA & DOE

Biokinetics

Toxicology



NIEHS, NCTR, NTP, EPA

All Agencies

Risk Characterization & Communication

All Agencies

Risk Mitigation

From Mark Alper with mods

DOE Molecular Foundry—Lawrence Berkeley National Laboratory

Instrumentation, Metrology, and Standards

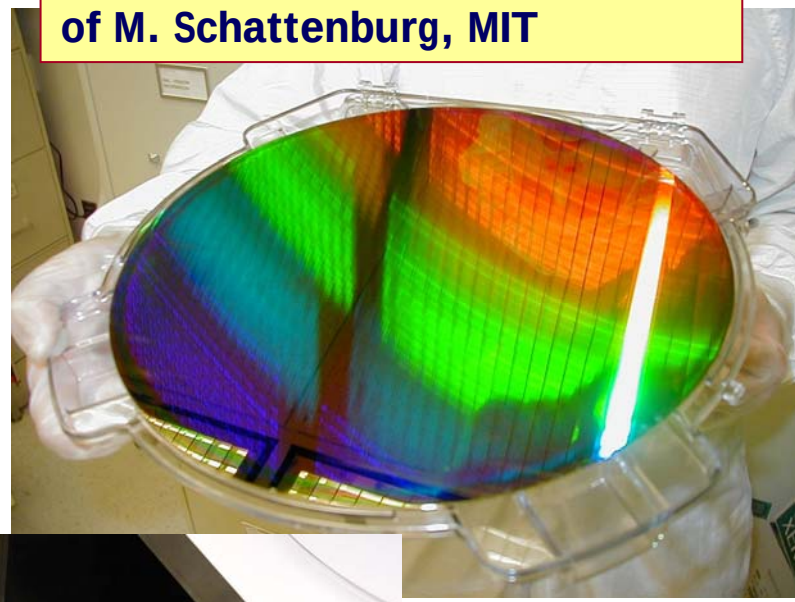
Nanotechnology Standards Panel of the American National Standards Institute (ANSI-NSP)
Priority Recommendations Related to Nanotechnology Standardization Needs

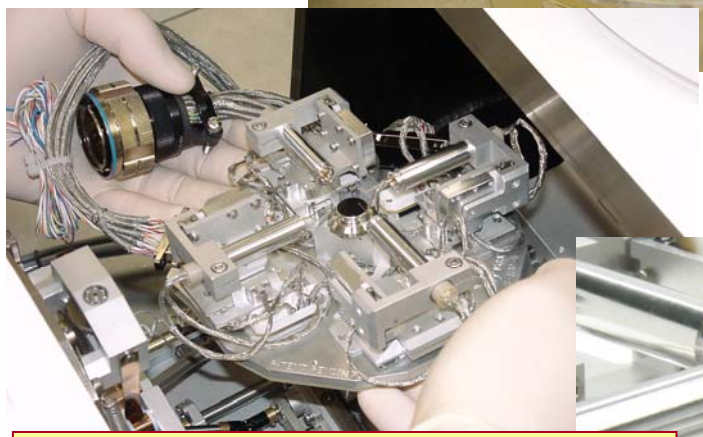
- General terminology and nomenclature - definition of the term "nano" to particle size and shape
- Metrology and characterization
- Environment, health, and safety

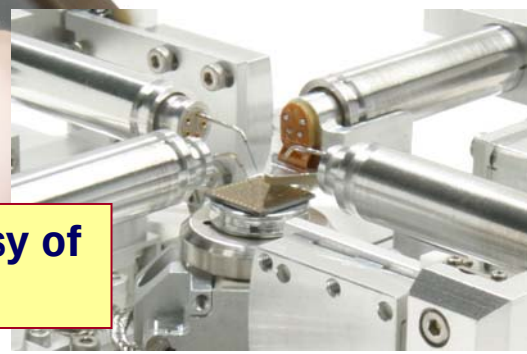
The ANSI-NSP

- serves as the U.S. cross-sector coordinating body for standards in the area of nanotechnology
- provides the forum within which stakeholders can work cooperatively to promote, accelerate, and coordinate the timely development of useful voluntary consensus standards.

UV diffraction grating – courtesy of M. Schattenburg, MIT







Nanomanipulator – Courtesy of Zyvex Corporation

Recommendations for Working With Nanomaterials

- Current data are insufficient to provide definitive strategies for working safely with engineered nanomaterials, they do point toward the need to approach these materials with caution.
- Methods to control airborne nanostructured particle exposure have not been well characterized at small particle diameters
- Theory and limited experimental data indicate that conventional ventilation, engineering control and filtration approaches should be applicable to particles a few nanometers in diameter and larger in many cases.

A.D. Maynard & E.D. Kuempel – submitted for publication

Status of NTP Project for Nanomaterials

- **NIH / NIEHS – support of the new National Toxicology Program, multi-year project initiated in October 2003**
- **Funding for these studies to be ramped up to $5M/yr by FY08**
  - Evalute physical and toxicological properties of major classes of nanomaterials representing a cross section of size, surface coatings and physicochemical properties and use these as model systems to study how nanomaterials interact with biological systems
  - Determine appropriate methods of detection, characterization and quantification of nanoscale materials in tissues and study how materials are absorbed, distributed, taken up and eliminated by cells and organelles
  - Studies to evaluate immunotoxicity of fullerenes and quantum dots
  - Studies of inhalation toxicology of fullerenes in laboratory animals

Environmental, Health, and Safety:
Recent Research by NSET Subcommittee member agencies

New NSF Centers

- **Center on Molecular Function at the Nano/Bio Interface U Pennsylvania –**

  Basic complex biological and physiological processes

- **Center for High Rate Nanomanufacturing Northeastern U, U Mass Lowell; U of NH; and Michigan State U**

  Assess the environmental impact of nanomanufacturing during process development.

EPA – Impacts of manufactured nanomaterials on human health and the environment

Toxicology of manufactured nanomaterials

Fate, transport, and transformation of manufactured nanomaterials

Human exposure and bioavailability

DOD – MURI: models for toxicity of generic classes nanomaterials

Recent & Planned EHS Related Actions by Regulatory Agencies

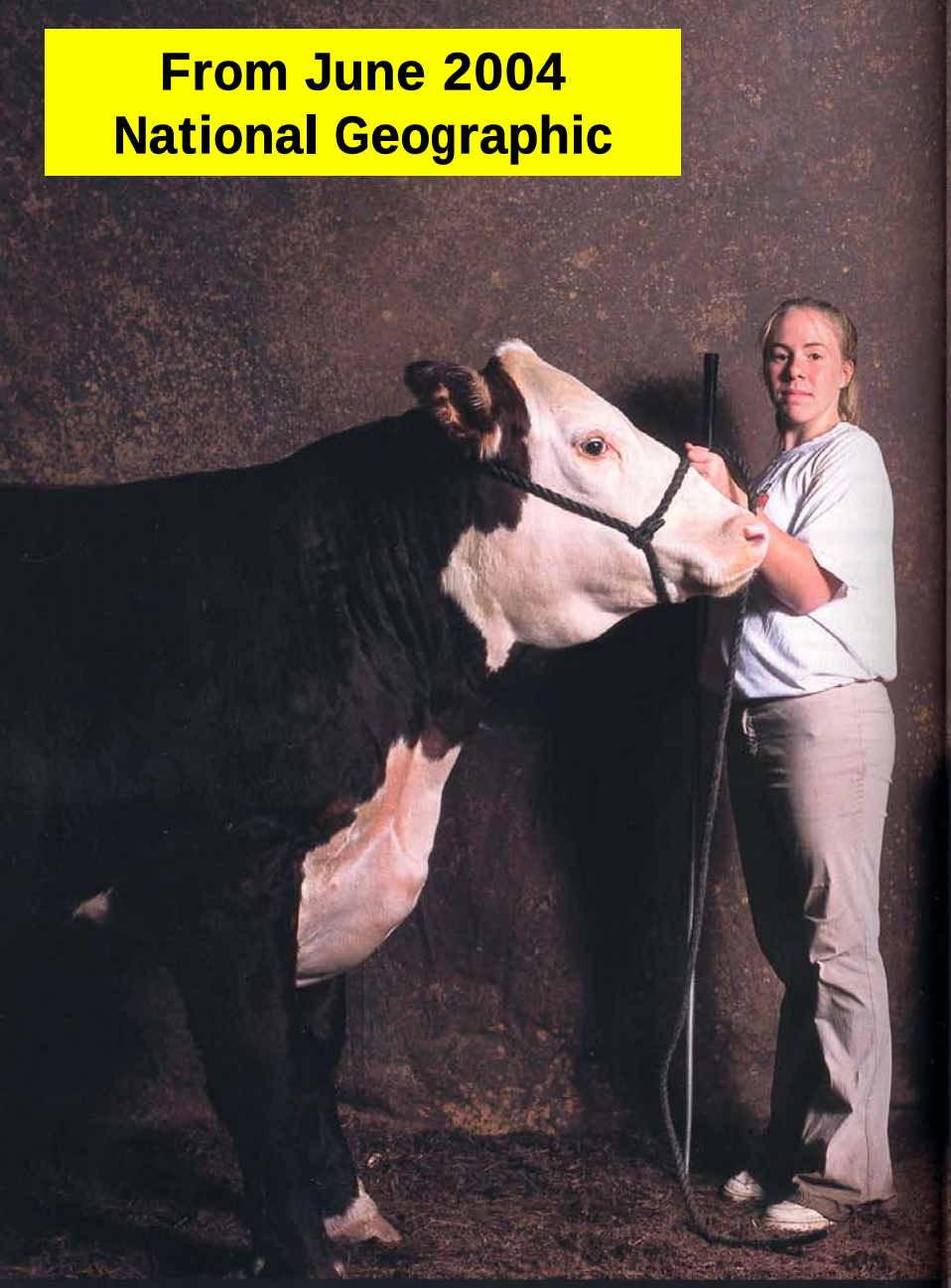
- **FDA has developed a new nanotechnology website: www.fda.gov/nanotechnology - position statement**
  - Expects existing pharmotoxicity tests to be adequate for most nanotechnology products
  - As new toxicological risks are identified, new tests will be required
- **EPA plans to initiate the process for instituting a voluntary reporting program under TSCA for nanoengineered materials**
- **NIOSH, EPA, and OSHA are developing statements by relevant offices of their agencies on positions wrt their regulatory authorities for nanotechnology products**

Humanity's Top Ten Problems for Next 50 Yrs.

Slide From R.E. Smalley

1. *ENERGY*
2. *WATER*
3. *FOOD*
4. *ENVIRONMENT*
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

From June 2004
National Geographic

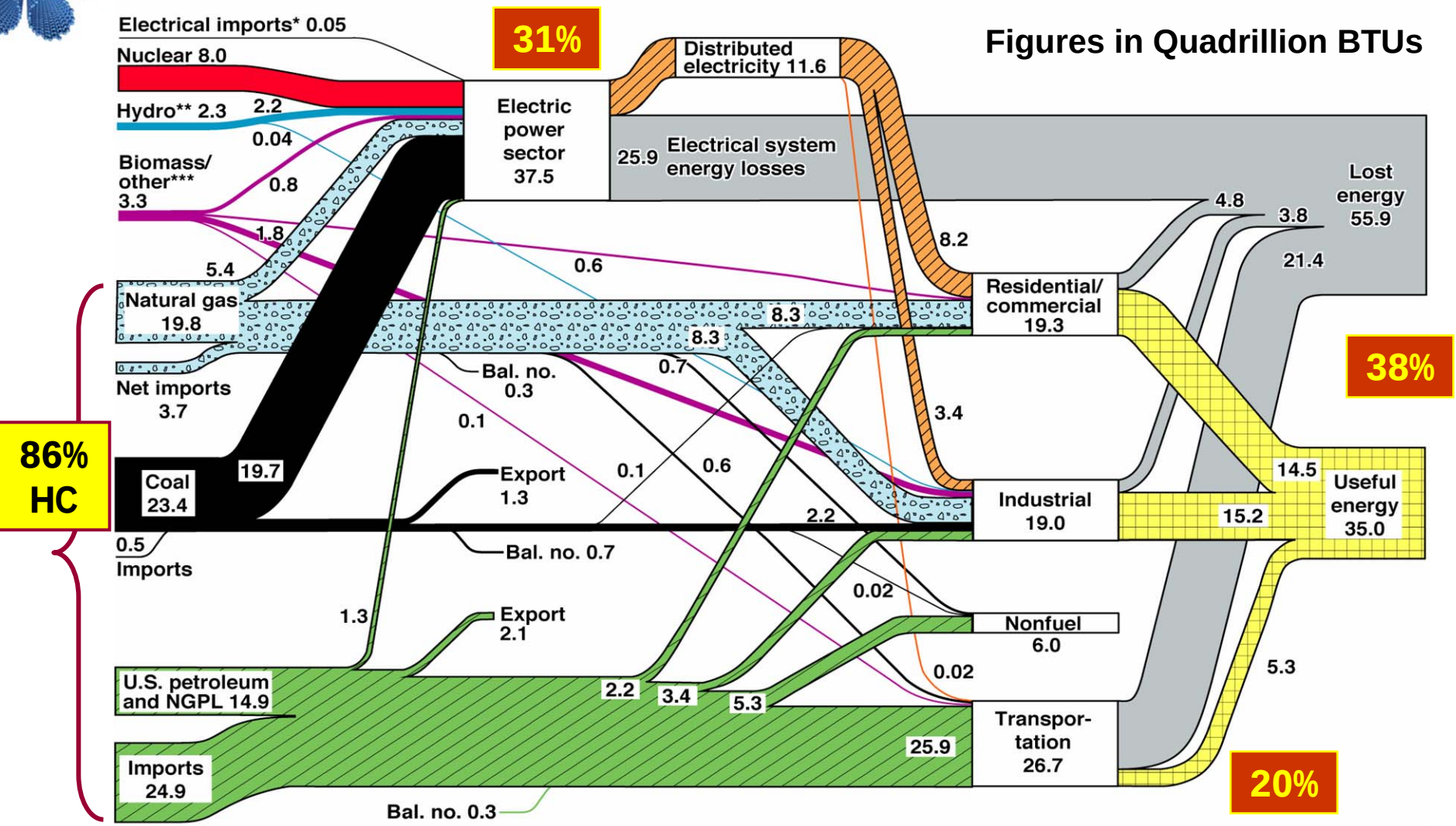


Please Obtain Release from
National Geographic if used

THE PRICE OF STEAK

Raising this Steer Weighing in at 1250 Pounds Took ~ 300 Gallons of Oil

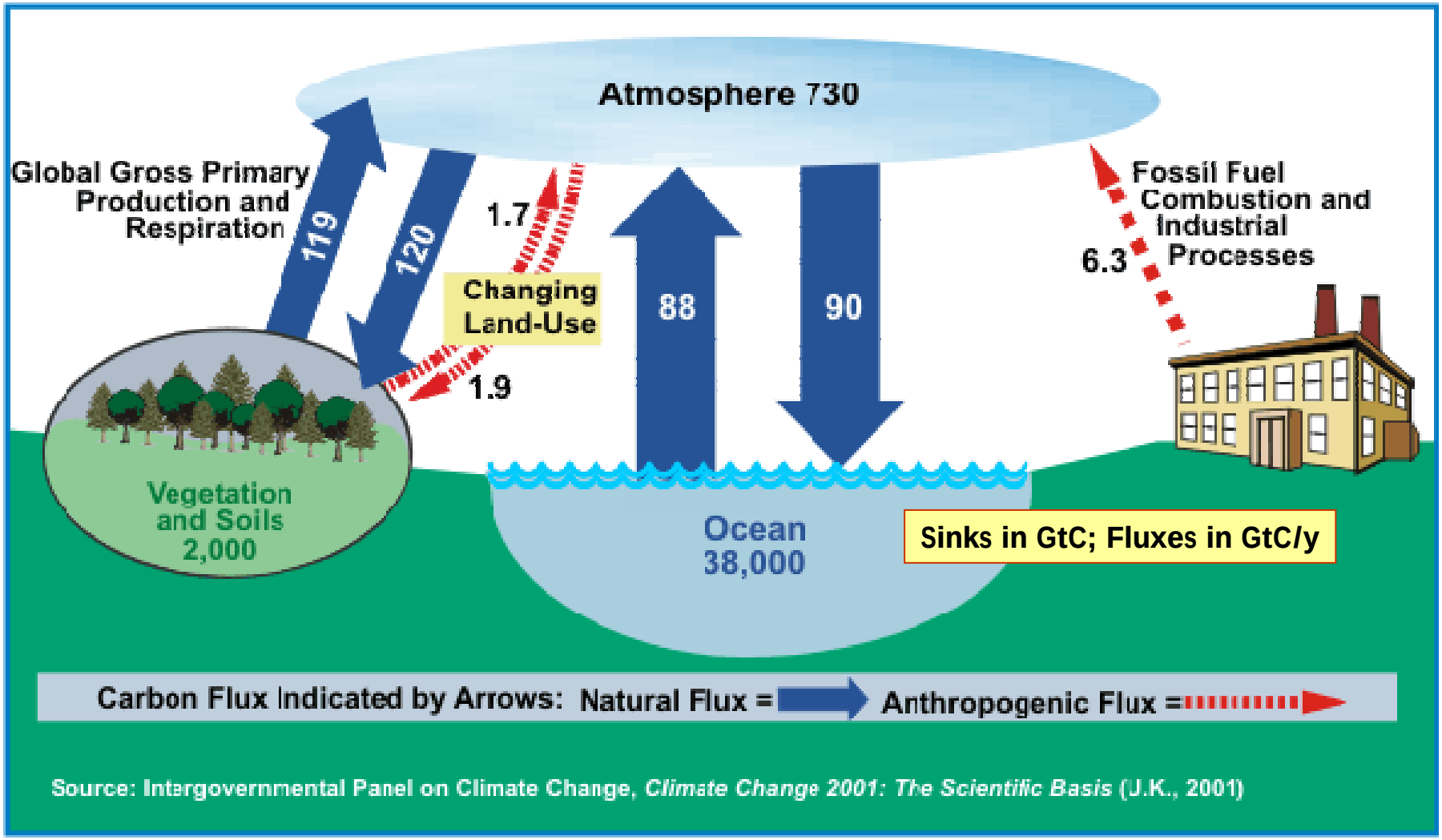
U.S. Energy Flow Trends – 2001
Net Primary Resource Consumption ~ 97 Quads



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2001*
*Net fossil-fuel electrical imports
**Includes 0.2 quads of imported hydro
***Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

August 2003
Lawrence Livermore National Laboratory
http://eed.llnl.gov/flow

CO_2 Emissions in Perspective



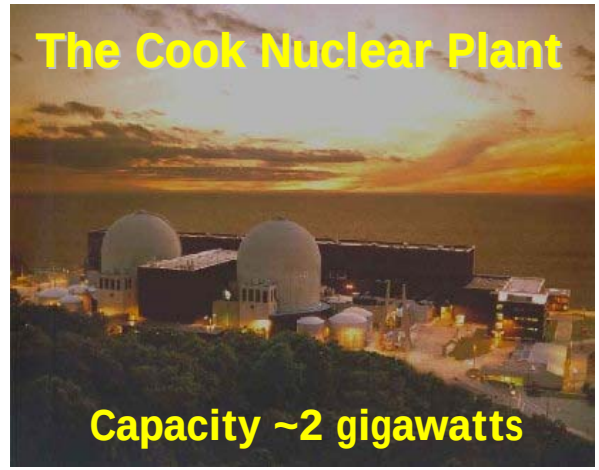
Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (J.K., 2001)

Examples of Nanotechnology Enabled Improvements in Energy Transformation, Storage, Transmission, & Use

- **Transformation**
  - High efficiency, low cost photovoltaic cells
  - High efficiency, low cost thermoelectric materials and devices
  - Direct photo-production of hydrogen
- **Storage**
  - High power and energy density batteries and supercapacitors
- **Transmission**
  - SWCNT power transmission lines
    - Potentially higher capacity than best superconductors
    - Long distances between power line towers
- **Usage**
  - Lighter weight transportation vehicles – planes, trains, automobiles
  - Improved efficiency and lighter weight electric motors
    - Improved strength and light-weight magnets and light-weight conductors
  - Higher efficiency electric lights

Large Increase in Lighting Efficiency

- Dept. of Energy estimates that ~20% of energy used in U.S. is for illumination
- Nanotechnology quantum dot phosphors hold promise of more economical white light LED lighting
- LED-based lighting could cut the electricity used for illumination by as much as 50 percent by 2025; 2X more efficient than fluorescent



Lauren Rohwer displays the two solid-state light-emitting devices using quantum dots her team at Sandia National Labs has developed.

Cutting electricity for lighting in half would result in energy savings roughly equivalent to the annual energy production of 50 power plants

Application: Cut Power Transmission Losses

- Single nanotube can carry up to 20 μA
- SWNTs could have a packing density of ~10^{14}/cm^2
- At 5% of capacity, perfect nanotubes would conduct 100 X10^6 A/cm^2
- Reduction of losses from 7% to 6% => annual savings of 4 X10^{10} kwhr

Applications of Nanomaterials to Improve Efficiency of Automobiles

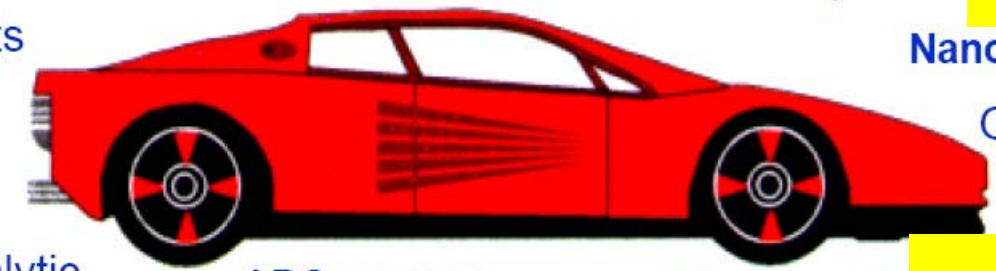
Sample of companies involved:

- *GM, Ford, Toyota, Mitsubishi, BMW, all tire companies:*
  there is no major part of car that has not yet been affected by nanotechnology (2003)
- *Ex: "Nano in Cars" consortium in Germany - 6 car manufacturers, 10 suppliers, and 26 R&D university and laboratories*

SWCNT conductors for lighter motors

High –efficiency, lightweight nanocomposite permanent magnets

High energy density batteries and supercapacitors



Thermoelectric conversion of waste heat

LED Lights

nanotube FE lights

Concluding Remarks

- The NNI has recognized the importance of and invested in EHS R&D since its inception
- By its nature nanotechnology EHS R&D will lag the discovery of new material properties
- NNI investment in nanotechnology EHS R&D has grown along with the investments to advance the technology
- Existing Federal regulatory mechanisms are in place for assessing and regulating workplace, environmental, and health risks of new technology materials
- Active efforts are underway to ensure that these regulatory mechanisms or appropriately amended ones provide proper coverage of nanotechnology-based materials
- Research in Federal laboratories, private industry, and academia is now in progress to determine how the nanotechnology-based materials may differ from conventional ones in their implications for public health and the environment

NATIONAL NANOTECHNOLOGY INITIATIVE

... if you want to know more about the NNI

Point your browser to:

www.nano.gov

http://www.nano.gov/NNI_Strategic_Plan_2004.pdf