Overview of Nano-Technology
Status and Opportunities

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Richmond, August 4th, 2004
OUTLINE

• What is Nanotechnology and Why Now?
• Nanotechnology in the Present
• Future Challenges and Opportunities in Nanotechnology: Towards Broad-Based Nanomanufacturing
• Future Technological Horizons
What is Nano-Technology?

- The ability to engineer systems with components on length scales of 1 - 100 nm.
- Properties / structures are often different / better at such reduced scales.
- If we make things smaller they are cheaper, lighter, use less power to operate, and we can have a lot more of them.
Why now?

• Confluence of critical capabilities in nano-science:
  – Computational methods
  – Fabrication and synthesis methods
  – Measurement methods
  – Improved understanding of nanoscale biological processes

• New materials and phenomena
  – High surface / volume ratio – “old” materials with new properties dominated by surfaces, interfaces
  – Entirely new nanostructured forms of materials
  – New phenomena in quantum regime
  – Control of fundamental units of light, electricity, magnetism

• Existence proofs of enabling impacts upon industries with tens to hundreds of billion dollar annual sales…
  – Micro- (Nano-)Electronics
  – Read-write heads on hard drives
  – Catalysis of chemical reactions
And Money Helps!

The National Nanotechnology Initiative

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*Units: $ million

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The National Nanotechnology Initiative

• NNI Nine “Grand Challenges”
  – Nanomaterials by Design: Stronger, Lighter, Harder...
  – Nano-electronics, -optics and -magnetics
  – Healthcare: Drug delivery, biosensors, biocompatibility...
  – Environment: Particulate removal, catalytic supports
  – Energy: Storage and conversion, solar cells, thermoelectrics
  – Microspacecraft: Light weight, high T coatings; self repair
  – Bio-threat detection: Weapons, HIV, tuberculosis...
  – Transportation: Lighter and safer....
  – National Security: Nanoelectronics, structural mats, failure

• Currently Being Updated for the Next Decade
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Existing Major Achievements of Nanotechnology

I. GMR Read-Write Heads

Top left: Evolution of hard drive storage capacity vs. year first in production (image courtesy S. Parkin, IBM); Bottom left: Schematic image of a magnetic disc drive; Bottom right: Atomistic simulations of a giant magnetoresistive layer structure (image courtesy H. Wadley, U. Virginia)
Existing Major Achievements of Nanotechnology

II. – Nanostructured Catalysts

Research in the chemical industry into new catalyst materials with nm sized pores has captured a market of tens of billions of dollars per year.

La$_2$CeN@C$_{80}$ on Al$_2$O$_3$

La$_3$O$_4$ cluster on Al$_2$O$_3$

La$_2$O$_3$ surface on Al$_2$O$_3$

Use of endohedral metallofullerenes as catalyst precursors for molecular clusters and extended surfaces (Dorn, VT; Tissue, VT; RJ Davis, UVA; Neurock, UVA)

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Existing Major Achievements of Nanotechnology

III. Electronics – Scaling to the Nanoscale

> 100,000,000,000 devices per 30 cm wafer

Minimum dimensions < 100 nm lateral, ~ 1 nm vertical

Cost to the consumer 0.0000001 c each

A $200+ billion / year industry

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Moore’s Law: An Analogy

- If the aircraft industry had evolved at the same rate as the microelectronics industry in the last 25 years, a Boeing 777 today would cost $500, and circle the globe in 20 minutes on 5 gallons of fuel.

So What Else Might Be Possible?
Existing Major Achievements of Nanotechnology

- Other existing applications include:
  - *High performance sports equipment*
  - *Specialized auto / aero components*
  - *Polishing powders and slurries (CMP)*
  - *Stain-free fabrics*
  - *Sun tan lotion and cosmetics*
  - *Selective optical coatings (photographic film etc.)*
  - *Telecommunications components*
  - *Machine tools*
  - *Corrosion and scratch resistant paints / coatings*
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NNI Grand Challenge Workshop on Nanomaterials
Arlington, Virginia 11-13 June 2003
Chairs: R. Hull, UVa; L. Haworth, NSF

Proposed New Grand Challenge

NanoFoundries: Development of Techniques, Methods and Instruments for the Fabrication of Nanoscaled Materials and Systems that Enable Economically Viable Applications of Broad Benefit to Industry, Technology, the Economy, the Environment, Health, and Society
Routes to Commercial NanoManufacturing - I

Low material volume, high precision systems

- E.g. engineered vol. in micro-electronic circuit (>10^8 components) is c. 1 mm^3

- Basic material cost not a key issue

- Fundamental needs – Increasing demands on lithographic precision, cost; Development of new materials technologies

Nanostructured functional coatings

- E.g. 1 µm thick coating on an airplane wing requires volume of c. 100 cm^3

- Challenges in uniform coating of complex surfaces

- Fundamental needs – self interrogation / repair for failure; sensing; internal communications; application methods

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Internally structured / nanocomposite systems

- Porous materials, e.g. aerogel, internal surface areas of 1000 m² per g – air or intercalate.

- Unique thermal, electrical, acoustic, dielectric….properties

- More generally, nanocomposite materials can greatly enhance properties (e.g. strength) with small fraction of “filler”.

- Still requires significant volumes of minority phase material(s); optimize properties per volume required: simulation, understanding.

Scaling of synthesis methods

- Key to multiple macroscopic applications (mechanical components, transportation, civil infrastructure, environmental etc.)

- Just make more!

http://eande.lbl.gov/ECS/Aerogels/saphoto.htm

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Implementing the Grand Challenge

- **Discovery** of new materials and properties, and **invention** of new techniques, instruments
- New techniques for synthesizing and refining **nano-materials in large quantities**.
- New methods for **self-assembly** of materials, based upon both biological and non-biological methods.
- Controlled **hierarchical structures** with multiple length scales down to the nano-scale
- Materials, methods, and instruments for **harnessing sub-atomic properties** e.g. electron spin and quantum interactions.
- Improved instruments and techniques for **structuring and patterning** materials at ever-increasing levels of precision.
- The ability to measure 3D structure, properties, and chemistry of materials down to the atomic scale – a **“nano-GPS”**.
- The development of **computational methods, algorithms, and systems** – both classical and quantum – to enable realistic simulation over all relevant length and time-scales.
- The **interface between nanomaterials and biological systems** – enabling widespread improvements in human health.

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**Discovery** of new materials and properties, and **invention** of new techniques and instruments

- **C₆₀** Fullerene
- **Sc₃N@C₈₀** Metallofullerene
- **Carbon Nanotube**

(n,m) = (5,5) metal

(n,m) = (9,0) semimetal

(n,m) = (10,0) semiconductor

*Eigler et al, IBM*

*Richmond, August 4*th, *2004*
New Fullerenoid Oxides

Hervieu et al, Nature Materials, Online 03/07/04

$\text{Sr}_{32}\text{Bi}_{8.25}\Box_{3.75}$

$\text{Al}_{84}$ Spheres

$O_{126}$ Spheres

$\text{Bi}_{16}$

$O_{40}$

$O_{7.4}\Box_{4.6}$
Spatial resolution ~ 100 nm, charge sensitivity ~ 0.01 e
Yoo et al, Science 276, 579
New techniques for synthesizing and refining nanomaterials in large quantities

FEL Produced Nanotubes (Holloway-W&M, Smith-NASA, Ekland-Penn State)
10 kW demonstrated July 2004!
New methods for *self-assembly* of materials, based upon both biological and non-biological methods

Viral Mediated Assembly of Nanowires and Ordered QD Arrays


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JCOTS Nanotechnology Advisory Committee
UVa Materials Research Science and Engineering Center
The Center for Nanoscopic Materials Design

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Controlled *hierarchical structures* with multiple length scales down to the nano-scale

Hierarchical Assembly of Semiconductor Nanostructures

J. Gray, S. Atha, and R. Hull,
University of Virginia
J. Floro, Sandia National Laboratories

Peapod Fullerenes
D. Luzzi et al, U. Penn.
E.g. Chem Phys. Lett. 315, 31; 321, 169

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Materials, methods, and instruments for harvesting *sub-atomic properties* e.g. electron spin and quantum interactions.

Three terminal magnetic tunnel transistor

GaAs(001)/5 nm Co$_{70}$Fe$_{30}$/4 nm Cu/5 nm Ni$_{81}$Fe$_{19}$/1.8 nm Al$_2$O$_3$/30 nm Au

Non-magnetic Emitter

Tunnel Barrier

GaAs Collector

Spin Valve Base


Quantum Computing

Ion Trap Quantum Computing

NMR Based Algorithms

Proton

Carbon

Cl

www.qubit.org (U.Oxford)

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Improved instruments and techniques for *structuring and patterning* materials at ever-increasing levels of precision.

**STM Atomic Manipulation**
Eigler group, IBM

**Viral Assembly**
Mao, Belcher et.al. e.g. *Proc. Nat. Acad. Sci.* **100**, 6946.

**Nano-Imprinting**
Chou group, Princeton

32 nm Co film
The ability to measure 3D structure, properties, and chemistry of materials down to the atomic scale – a “nano-GPS”.
Development of *computational methods, algorithms, and systems* to enable realistic simulation over all relevant length and time-scales.

**Molecular dynamics simulations of fracture:**
*Vashista et al (USC)*

**Wave function for a GaAs dot:**
*(A. Franceschetti and A. Zunger)*

**Formation of Metallic Glasses,**
*J. Poon,
G. Shiflet, UVa*
The interface between nanomaterials and biological systems – enabling widespread improvements in human health.

20-40x increases in the $^1\text{H}$ MRI $T_1$ spin-lattice relaxivity rates for a Gd Trimetasphere wrt commercial agents (Omniscan, Magnevist) – VT, Luna, VCU

Artificial retina with nanocrystalline diamond (USC, Argonne....)
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• **Major Fields of Future Impact Include:**

- *Electronics / Computation*
- *Communications*
- *Data storage*
- *Energy storage / transmission / generation*
- *Health care*
- *Transportation*
- *Civil infrastructure,*
- *Military applications, national security*
- *Environment.*
Emerging / Future Applications

- **Automotive and aeronautic industries**: nanoparticle-reinforced materials for lighter, stronger bodies, nanoparticle-reinforced tires, self-cleaning and repair materials, electronics, collision avoidance.

- **Electronics and communications**: extension of Moore’s rule to tens of thousands of times higher density, speed, lower power consumption and cost. Magnetic nanoparticle media.

- **Chemical materials**: improved catalysts, smart magnetic fluids for vacuum seals/lubricants, self-cleaning and repair surfaces, adaptive surfaces.

- **Health care**: nanostructured drugs, gene and drug delivery systems targeted to specific sites in the body, biocompatible replacements, self-diagnostics, bone/tissue regeneration and wound repair.

- **Energy technologies**: higher power density batteries, fuel cells, artificial photosynthesis, improved solar cells, improved fuel economy from lighter materials, improved electronics.
• **Manufacturing**: super-hard and tough cutting tools, ultra-precision engineering based on nanoscale microscopies, atomic-scale manufacturing tools and processes, nanopowders, internal sensors for fault detection and repair, self-assembling materials

• **Space exploration**: lighter vehicles, improved energy generation, ultra-small robotic systems, in-flight sensing and repair capacity

• **Environment**: reduced pollution through catalysis, nanostructured traps for pollutant removal, improved recycling, selective membranes for water filtering, cleaner manufacturing processes

• **National security**: detectors and detoxifiers of biological and chemical agents, improved electronic and optical systems, radiation-protected systems, harder coatings and bodies, camouflage materials, improved textiles, self-repairing materials, in-battle medical care
Education and Societal Outreach

• How do these advances affect education at all levels - K-12, undergraduate, graduate, and beyond?
• How can we use nanoscience to educate and inspire society to be technologically literate?
• How can we encourage educational institutions to value and reward interdisciplinarity?
• How can we perform high-risk, high-cost research that will also benefit societies, or portions of societies, that cannot afford it?
The Nano-Economy:

* Estimated world market by 2015: $1 trillion
* Projected U. S. jobs by 2015: 800,000 – 900,000

Opportunities in Virginia:

* Partnerships in Research, Manufacturing, Education Across the Commonwealth (Academic, Industry, Government Sectors)
* INanoVa (VNI), CIT, Research Consortia, CTRF
* Capitalize on Research Facilities, Expertise and People; Leading Educational Programs; Growing Nanomanufacturing Base
Where we should be
The Smalley Argument for Nanotechnology!

How can we sustain this?

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