00: Introduction
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Today’s agenda

- What is nanotechnology/nanomanufacturing and why is it important?
- Some history
- Course specifications
- Examples of nanomanufacturing research, applications, and emerging trends
- Introductions
- Advice for taking this course
Today’s readings (@ctools)

- Feynman (1959), There’s plenty of room at the bottom
- Gimzewski (2008), Nanotechnology: the endgame of materialism
- Foley and Hersam (2006), Assessing the need for nanotechnology education reform in the United States
- ASTM (2006), Standard terminology relating to nanotechnology
- Augustine (2008), Scilence
- Nature Nanotechnology (2009), The other nanotech

+ a few more..
Nanotechnology is the ability to understand, control, and manipulate matter at the level of individual atoms and molecules

- National Science Foundation (NSF)
- National Nanotechnology Initiative (NNI)
(M. Roco, Handbook of Nanoscience, Engineering, and Technology, p. 3-2)
What fields does nanotechnology include?

Figure 1 | The position of nanoscience and nanotechnology over a base map of science. Each node in this map\textsuperscript{b} is one of the 175 subject categories in the SCI. The size of each node is proportional to the number of nanopapers published in journals in each subject category during the period January-July 2008. Location on the axes in this Kamada–Kawai algorithm representation has no inherent meaning: the connecting arcs and proximity reflect similarity based on cross-citation patterns, reinforced by colouring to reflect the clustering of subject categories into macrodisciplines (see Methods). See Table 1 for full macrodiscipline names.

Figure 2 | Fields of science that are cited by nanotechnology papers. The arrows show the 40 subject categories most cited by papers published in the nanoscience and nanotechnology subject category during the period January-July 2008 (highlighted on the map of science shown in Fig. 1). It can be seen that papers from many different fields of science have influenced research on nanoscience and nanotechnology. See Table 1 for full macrodiscipline names.

Length scales

100,000 LIGHT YEARS
Diameter of the Milk Way’s disk

1 LIGHT YEAR
Longest pillar in the Eagle Nebula

1 MILLION KILOMETERS
Diameter of the Sun

100,000 KILOMETERS
Diameter of Saturn

10,000 KILOMETERS
Closest approach of NASA’s New Horizons space probe to Pluto

1,000 KILOMETERS
The Horn of Africa

1 KILOMETER
Diameter of Arizona’s Meteor Crater

1 METER
Length of an M16 assault rifle

1 CENTIMETER
Diameter of a human iris

1 MILLIMETER
Length of a fully-grown water bear

1 MICROMETER
Size of an anthrax spore

1 NANOMETER
Diameter of a Carbon-60 Buckyball

SEED - December 2006

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Beneath 1 millimeter

- Ant: ~ 5 mm
- Dust mite: 200 μm
- Human hair: ~ 10-50 μm wide
- Red blood cells with white cell: ~ 2-5 μm
- DNA: ~ 2-1/2 nm
- 5 Atoms of silicon: 1 nm

**The Millimeter**

- Head of a pin: 1-2 mm
- Micro Electro Mechanical Devices: 10-100 μm wide

**The Micrometer**

- Pollen grain
- Red blood cells

**The Nanometer**

- Cellulose nanofibrils: 20-100 nm wide
- Stacks of clay mineral platelets, each platelet with ~ 1 nm thickness
- Carbon nanotube: ~ 2 nm diameter

[http://www.sustainpack.com/nanotechnology.html](http://www.sustainpack.com/nanotechnology.html)
Lots of atoms!
Nano is not new...

Duomo di Milano

US Patent, 1889

MANUFACTURE OF CARBON FILAMENTs.

SPECIFICATION forming part of Letters Patent No. 405,480, dated June 18, 1889.
Application filed August 20, 1886. Serial No. 212,109. (No model.)
Robert Hooke, 1665

Microscopic view of a mold colony described by Robert Hooke in 1665. The reproductive structures (sporangia) are characteristic of the microfungus Mucor. Sporangia in different stages are identified by the letters A, B, C, and D. Hooke included a scale reference; the length of the bar under the diagram represents 1/32 of an inch.

Source: From “Micrographia,” reproduced courtesy of the Lilly Library, Indiana University, Bloomington, Indiana.
But now we can see what’s happening

Structure of carbon nanotubes (Iijima, 1991)

“Quantum corral” of Fe atoms (IBM, 1993)
Scanning electron microscope (SEM) 

Atomic force microscope (AFM) 
Binnig, Quate, Gerber
(and sometimes we find imperfections)

Figure 1 HR-TEM images of the pentagon–heptagon pair defect. a, A 5–7 pair defect found in an SWNT after heat treatment at 2,273 K. b, An enlarged image of the area enclosed by the green line in a) in which the 5–7–7–5 defect can be more clearly seen. Each carbon ring appears with a bright spot at its centre. c, The green dots indicate the hexagons with six neighbours, the two red dots have seven neighbours, and the two blue dots have five neighbours.

We’re starting to close the loop
Molecular “rack and pinion” (Chiaravalotti et al., 2007)

3D DNA “origami” (Douglas et al., 2009)
Manufacturing: top-down vs. bottom-up

“Building blocks” for nanomanufacturing

Nanoclusters
Magic #’s of atoms
≤1 nm size

| Nanoparticles
100s-1000s of atoms
~1-100 nm diameter

Nanowires
Filled
both ~1-100 nm dia, up to mm long and beyond!

Nanotubes
Hollow
Manufacturing: top-down vs. bottom-up


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Generations of Products and Productive Processes
Timeline for beginning of industrial prototyping and nanotechnology commercialization (2000-2020)

1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

2nd: Active nanostructures
Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures

3rd: Systems of nanosystems
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

4th: Molecular nanosystems
Ex: molecular devices ‘by design’, atomic design, emerging functions

Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

Slide by M. Roco
Nanomanufacturing Process Needs

- Embedded Sensors
- Automation
- Automation with Self-calibration and Adjustment
- Remote Manufacturing
- Fabrication Techniques

Modeling and Control
- Modeling and Simulation (M&S) Tools
- Automatic Comparison to M&S Data
- Accurate Modeling at nm scale
- Interfaces to Micro and Macro

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Economics
- Cost
- EHS
- High Throughput

International Standards
- Identification of New Measurement Parameters
- Calibration Tools Nano-characterization

Metrology
- Whole System Scale-up
- Rapid Characterization of 3D structures
- Nanostructures into Devices / systems

Lockheed Martin Corporation
Need and opportunity

Education
A key challenge for nanotechnology development is the education and training of a new generation ...it is estimated that about 2 million nanotechnology workers will be needed worldwide in 10-15 years. (M. Roco, NSF)

International standards

Economic growth

<table>
<thead>
<tr>
<th>Field</th>
<th>$US billion per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>340</td>
</tr>
<tr>
<td>Electronics</td>
<td>300</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>180</td>
</tr>
<tr>
<td>Chemicals</td>
<td>100</td>
</tr>
<tr>
<td>Aerospace</td>
<td>70</td>
</tr>
<tr>
<td>Nanotools</td>
<td>20</td>
</tr>
<tr>
<td>Healthcare</td>
<td>30</td>
</tr>
<tr>
<td>Sustainability</td>
<td>45</td>
</tr>
</tbody>
</table>

Nanomanufacturing: our mission

- Understand the fundamental properties of nanostructures, e.g., nanoparticles, nanotubes, and nanowires
- Understand how nanostructures interact with one another and their surroundings
- Understand how to make and assemble nanostructures; how to control their size, structure, and placement
- Understand how the properties of nanostructures scale based on their assembly and interactions
- Combine our knowledge to design new devices, materials, and manufacturing processes
Course outline

0: Introduction to nanotechnology

1: Properties of nanostructures (“building blocks”)

2: Interactions among nanostructures

3: Synthesis of nanostructures

4: Assembly of nanostructures and property scaling

5: Case studies and project presentations

Assignments:

- problem sets (5)
- exam (1),
- literature review (1)
- project (1)
Some applications of nanotechnology

Quantum dots for solar cells

[Image of quantum dots]

Carbon nanotube memory

[Image of carbon nanotube memory]

Lieber, Nantero Inc.

High-power nanostructured batteries

[Image of high-power battery]

A123 Systems

Drug delivery and bio-imaging

Nanocomposite sports equipment

[Image of nanocomposite sports equipment]

Zyvex, Easton

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Semiconducting nanocrystals “quantum dots”

CNT-based memory (Nantero, Inc.)

The concept (1998)

Reversible electromechanical junction

Exceptional properties of CNTs

- High recoverable strains and reversible kinking

- Thermal conductivity exceeding diamond; 3500 W/m-K for an individual SWNT

- Ballistic electron transport over micron length scales
  Li et al., *PRL* 96:057001, 2006.

- Current density of
  \(~10^9 \text{ A/cm}^2\)

Compiled from National Academy of Sciences report (2005)
[http://www.nap.edu/catalog/11268.html](http://www.nap.edu/catalog/11268.html) and many other sources
Configurations

Order = length, alignment, quality
Quantity = #/volume

Order

high

low

few

many

individual

forest (aligned)

network (tangled)

dispersion

yarn/sheet

Quantity [#/vol]
### Applications

<table>
<thead>
<tr>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transistors</td>
<td>Filtration/desalination</td>
</tr>
<tr>
<td>Interconnects</td>
<td>3D energy devices</td>
</tr>
<tr>
<td>Emitters, memory</td>
<td>Thermal interfaces</td>
</tr>
</tbody>
</table>

#### Enabled by ultra-long CNTs
- Lightweight conductors
- Organized composites

#### Now commercialized
- Batteries (powder electrodes)
- ESD/plastics

#### Limited by current mfg technology
- Higher precision of CNT diameter required

#### Order
- Quantity [#/vol]
  - few (<< 1g)
  - high
  - low
  - many

#### Enabled by ultra-long CNTs
- Order
  - Quantity [#/vol]
  - few (<< 1g)
  - high
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“Bulk” nanomaterials produced commercially today

- Merck produces 10’s of tons of silica particles per year for cosmetic purposes
- 3M produces TiO$_2$ nanoparticles for dental fillings
- Cabot produces > 10 tons of carbon black nanoparticles as polymers additives
- Showa Denko (Japan), Mitsui (Japan), and Hyperion (USA) produce > 500 tons of carbon nanotubes
Looking forward…
Forecast: an endgame?

Nanotechnology: The Endgame of Materialism

James K. Gimzewski

SMALL AND BIG

Technology is destructive only in the hands of those who realize that they are one and the same people.

—Alan Watts

Nanotechnology is typically discussed using nanometer, which is a billionth of a meter. We classify many technologically and biologically objects on the scale of the nanometer (nm), which has a diameter of around several tenths of a meter but is around a nanometer in diameter but several long. Proteins have dimensions of a few nanometers typically several thousand nanometers. In the world, the insulating gap in a transistor, for example, the technology evolution will lead to a total hybridism of mind-machine and art-science and new forms of personal interrelationship. The neuronal

THE ENDGAME

Over the last 6 years there has been ever-increasing hype about the dreams for a new future and the nightmarish scenarios postulated should human dominion over matter get out of control. Nanotechnology, in the long term, is not vaporware, and many of the promises for an ecologically friendly, socioeconomically sustainable future will rely on it. The products we do see on the market remain far from these dreams.

Imagine that one could arrange atoms in any form one wanted: What kind of mind would it take to change the world through this metamorphosis of rearrangement and design? The ultimate endgame of our current technological capability to make material things is determined by our own creativity. The author examines how technological interfaces join the human mind to objects of experience from the nanometric to the planetary scale and theorizes the impact this perceptual condition will have on the personal and collective psyche.

Fun: marketing

I NEED TO BE MANAGING A SEXIER PROJECT TO BOOST MY CAREER.

IT ONLY HAS TO SOUND GOOD AND NOT FAIL UNTIL I GET A BETTER JOB.

HOW ABOUT A NANO-TECHNOLOGY STEM CELL FOR FIGHTING TERRORISTS?

O-O-OKEY.

MY BOSS WANTS ME TO INVENT NANO-TECHNOLOGY STEM CELLS BECAUSE IT SOUNDS GOOD.

TRY POINTING TO YOUR EMPTY HAND AND SAYING, "YOU CAN'T SEE THEM BUT THEY'RE ALMOST DONE!"

THEN TRICK HIM INTO GIVING YOU A HIGH-FIVE AND YELL, "YOU CRUSHED THEM! AAAG!!!"
Zero Gravity Nano Drives Upside Down!!!

PARENTS TO ORDER
FILL IN THE FOLLOWING FORM

QUANTITY:
Imperative: communication and outreach

- 2008 – over 80% of Americans reported having heard ‘just a little’ (28%) or ‘nothing at all’ (54%) about nanotechnology.
Imperative: communication and outreach

Kahan et al., Nature Nanotechnology doi:10.1038/NNANO.2008.341
Scheufele et al., Nature Nanotechnology doi:10.1038/NNANO.2008.361
Technology trends

Fig. 1 The expectations of a new technology as a function of time. (I) In the beginning, there is a period of exaggerated expectations, during which exciting—but sometimes irreproducible—results and unrealistic claims are made. (II) When these high expectations go unmet, a period of disappointment sets in. (III) There is then a return to the fundamental aspects of the technology; science is linked with applications; new tools are developed; and real commercial investment begins.

Introductions
then closing advice
Stay on the leading edge!
Collaborate and learn from others

“The thing I want to say is collaborate. Collaborating with talented people is not easy, but it’s the way to really shine – you shine brighter if you are working with really great people. The important thing in the end is not that you are proved right every time, the important thing is that the music is the best that it can be. I want to wish you all that you would find your own voice. But if you are so disposed that you would find collaborators to work with, that you would shine as you could never shine on your own.”

Dave “The Edge” Evans (U2), at Berklee College of Music Commencement, Boston, MA, May 2007.
Those who stay...

Posted above the exit door to the field, home team locker room at Michigan football stadium
(B. Schembechler, 1969)
One word…

http://www.youtube.com/watch?v=WnvBK4_LGtU