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

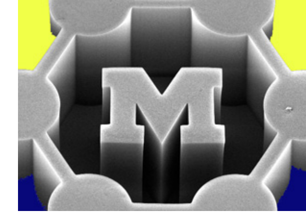
Today's readings (@ctools)

- 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..

Definition



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?

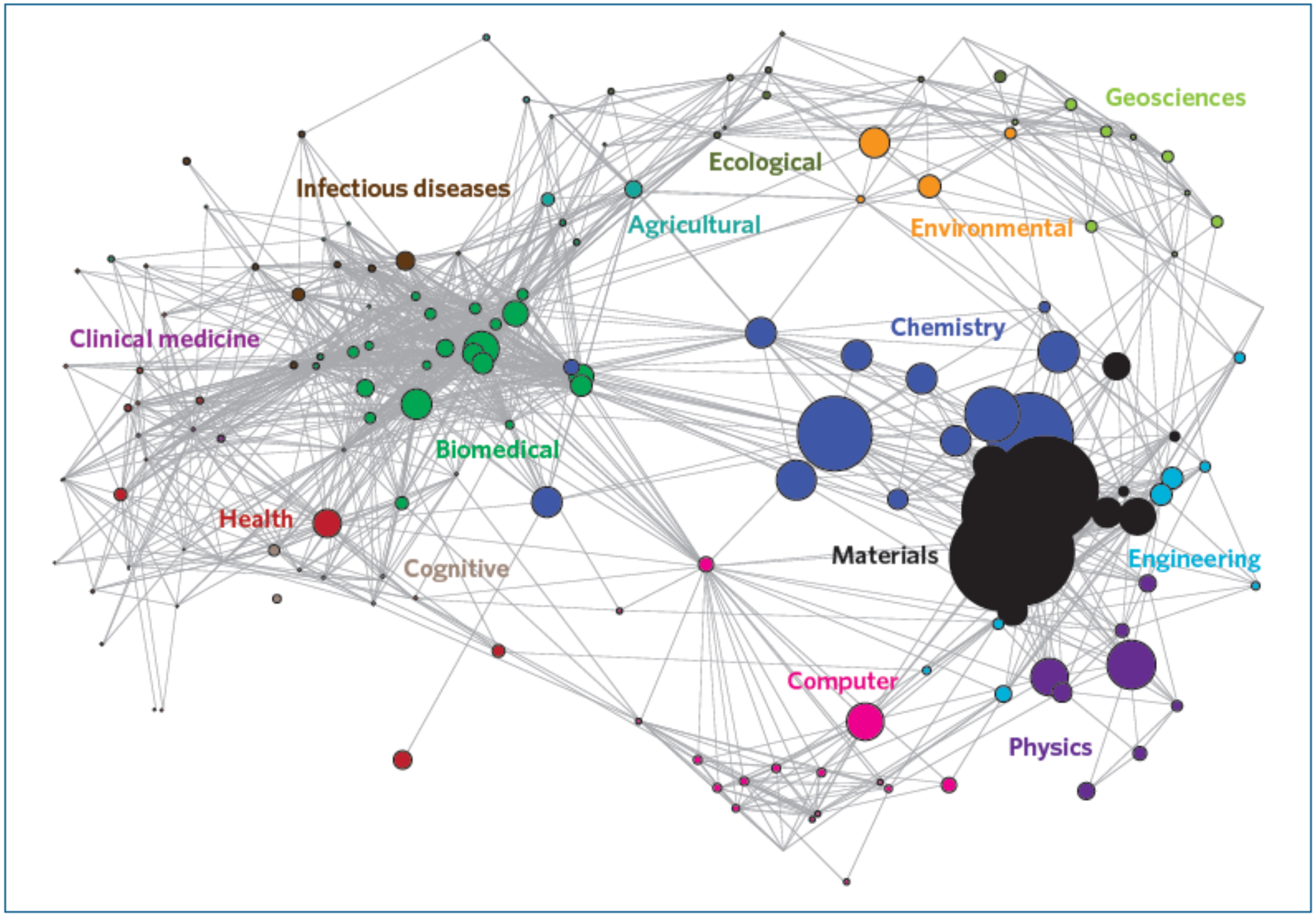


Figure 1 | The position of nanoscience and nanotechnology over a base map of science. Each node in this map[15] is one of the 175 subject categories in the SCI. The size of each node is proportional to the number of nanopapers published in journals in each subject category during the period January–July 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.

Porter and Youtie, *Nature Nanotechnology*, 2009.

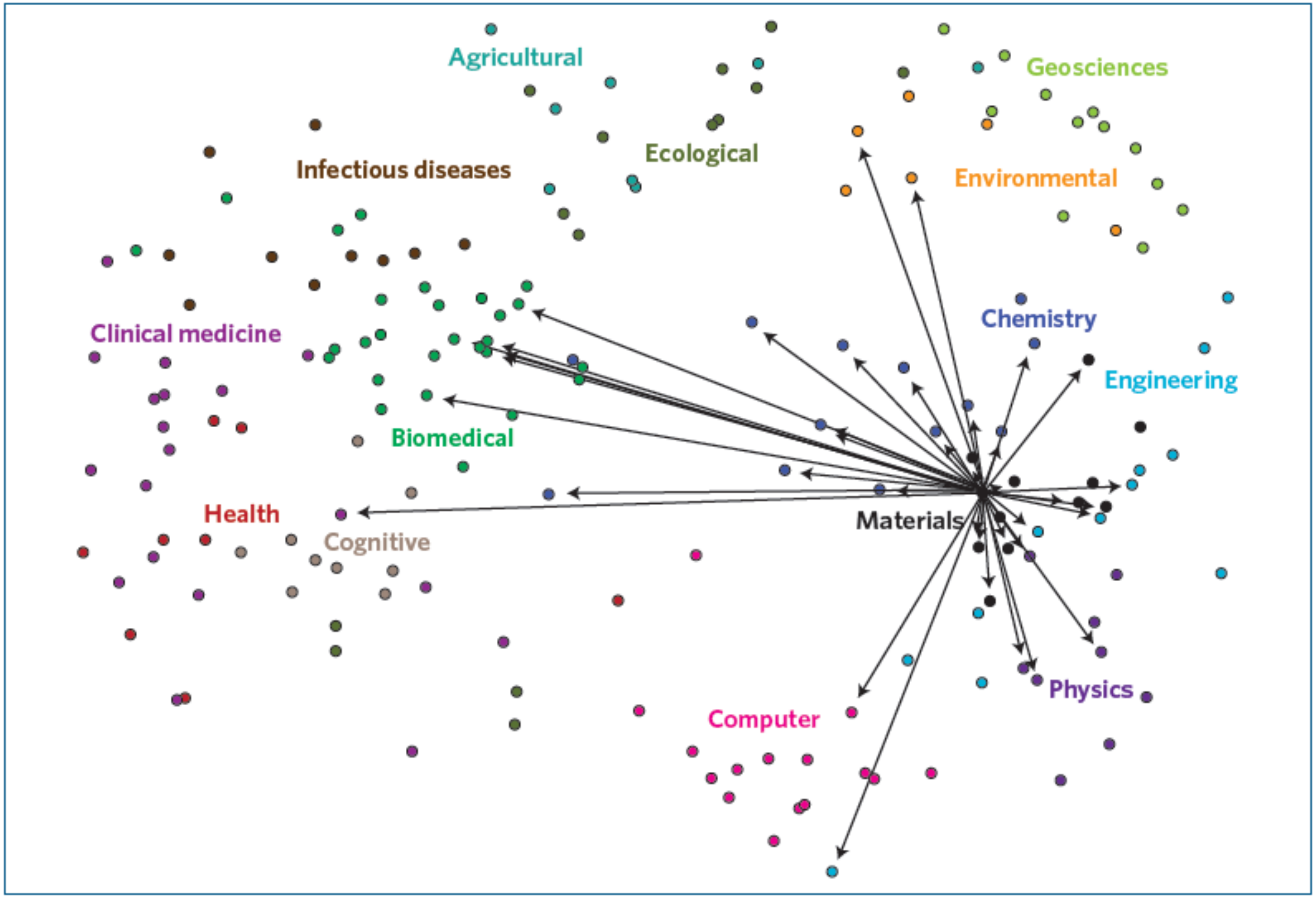
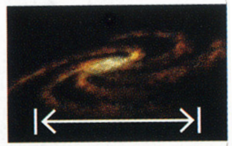


Figure 2 | Fields of science that are cited by nanotechnology papers. The arrows show the 40 subject categories most cited by papers published in the nanoscience and nanotechnology subject category during the period January–July 2008 (highlighted on the map of science shown in Fig. 1). It can be seen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

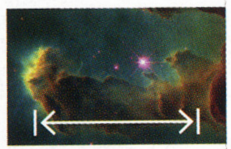
Porter and Youtie, *Nature Nanotechnology*, 2009.

Length scales

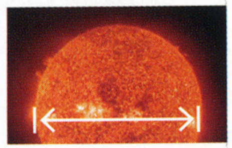
100,000 LIGHT YEARS
Diameter of the Milk Way's disk



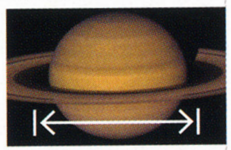
1 LIGHT YEAR
Longest pillar in the Eagle Nebula



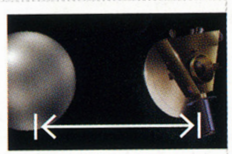
1 MILLION KILOMETERS
Diameter of the Sun



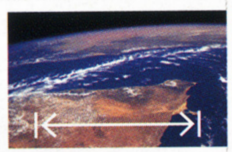
100,000 KILOMETERS
Diameter of Saturn



10,000 KILOMETERS
Closest approach of NASA'a New Horizons space probe to Pluto



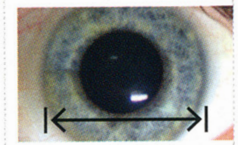
1,000 KILOMETERS
The Horn of Africa



1 KILOMETER
Diameter of Arizona's Meteor Crater

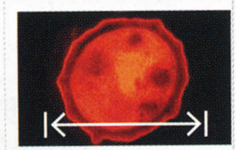
1 METER
Length of an M16 assault rifle

1 CENTIMETER
Diameter of a human iris

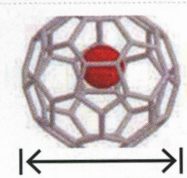


1 MILLIMETER
Length of a fully-grown water bear

1 MICROMETER
Size of an anthrax spore

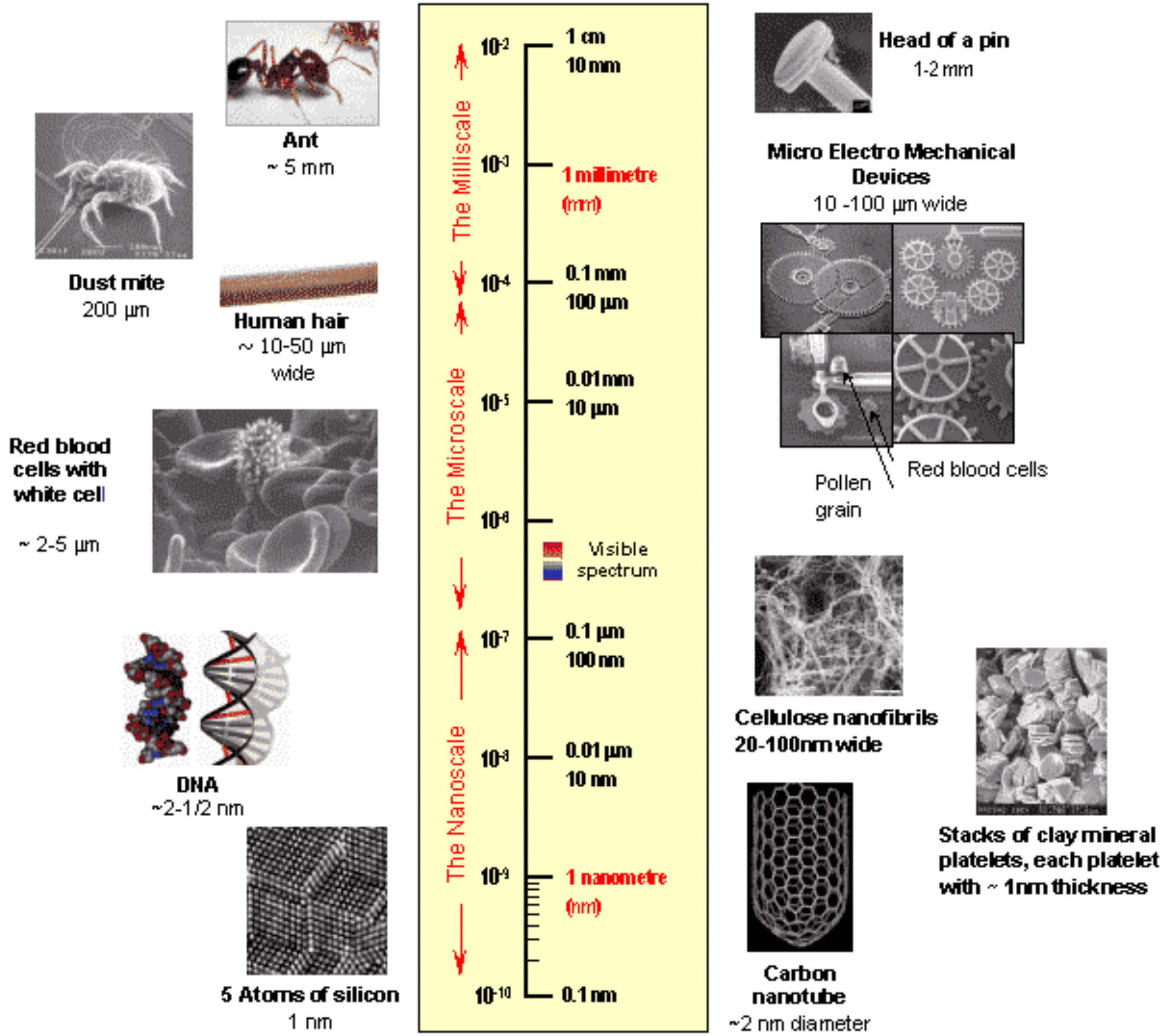


1 NANOMETER
Diameter of a Carbon-60 Buckyball

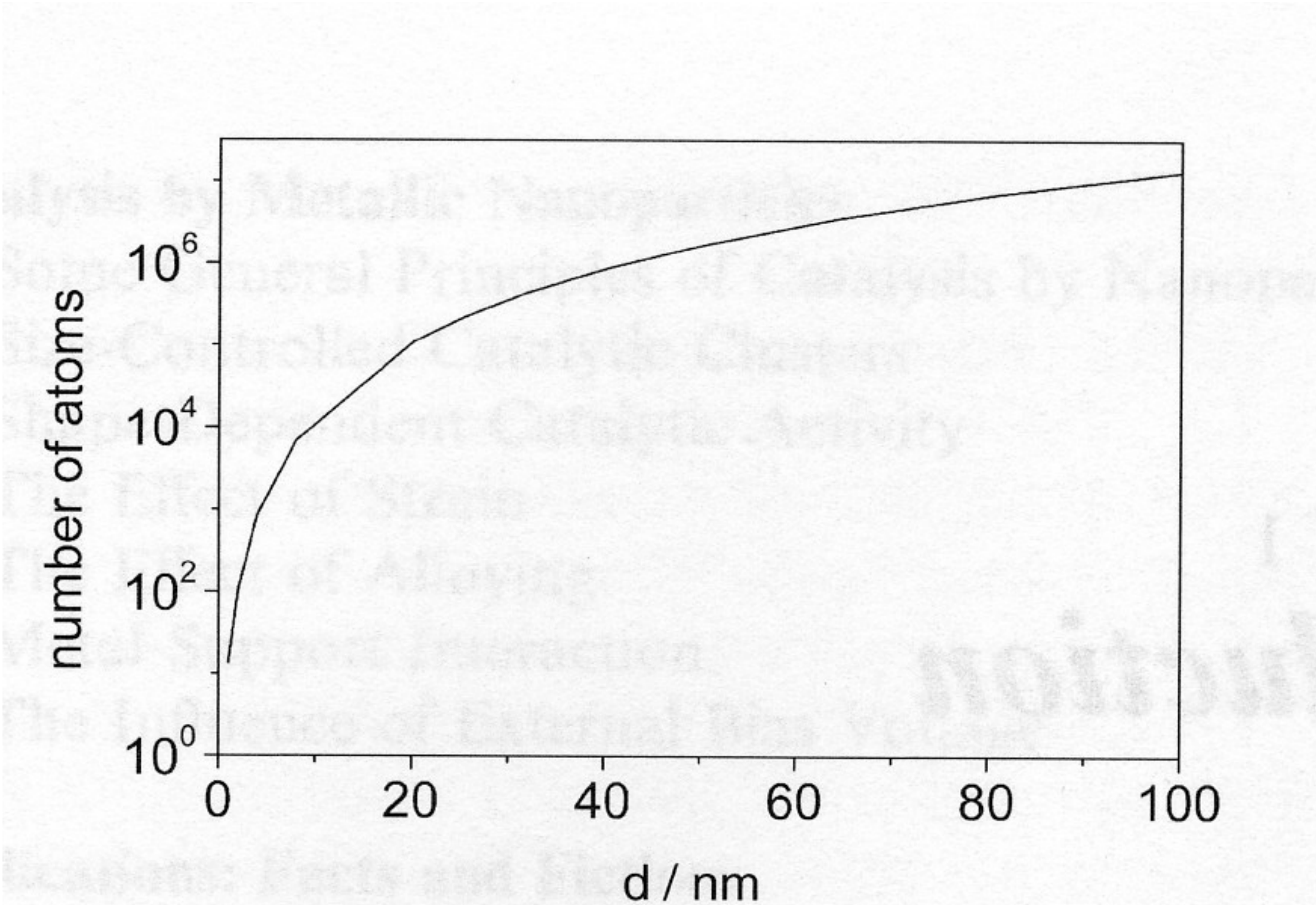


SEED · *December 2006*

Beneath 1 millimeter



Lots of atoms!



Nano is not new…

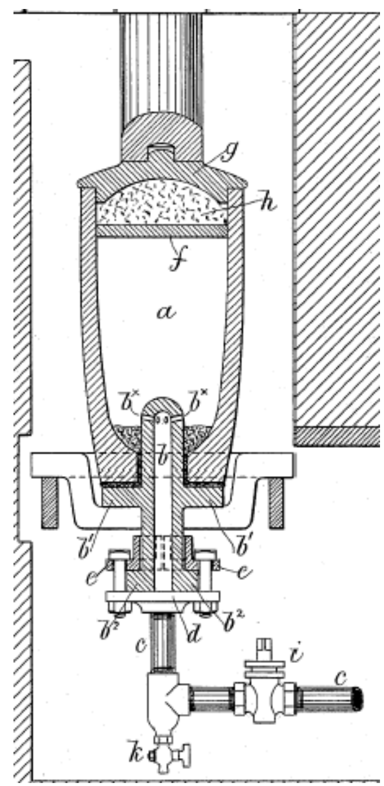
Duomo di Milano

US Patent, 1889

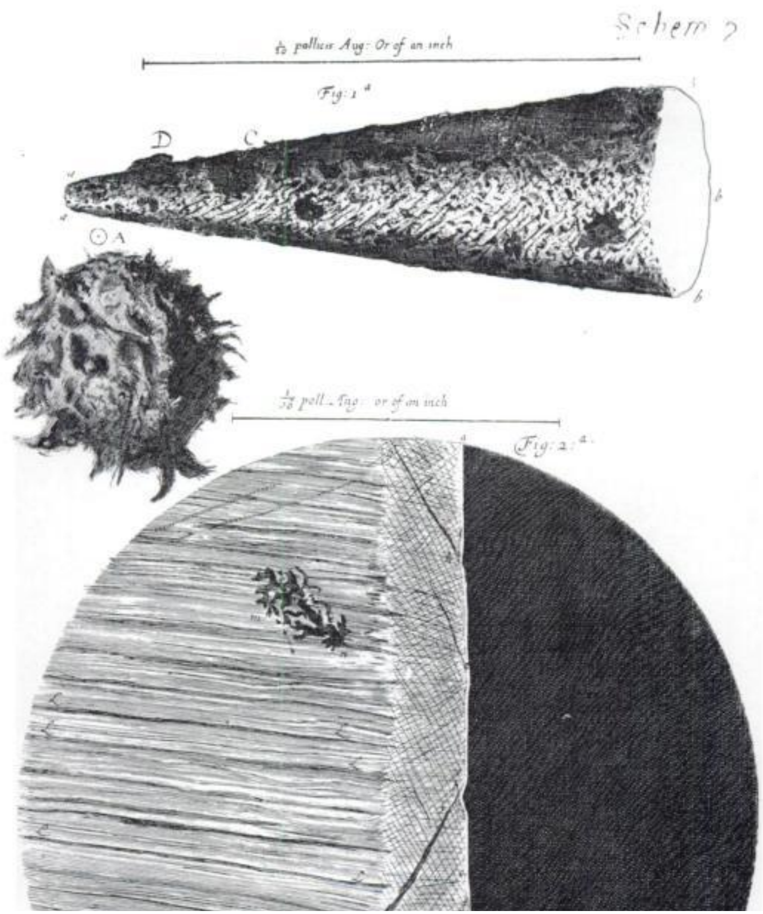
MANUFACTURE OF CARBON FILAMENTS.

SPECIFICATION forming part of Letters Patent No. 405,480, dated June 18, 1889.

Application filed August 30, 1886. Serial No. 212,199. (No model.)



Robert Hooke, 1665



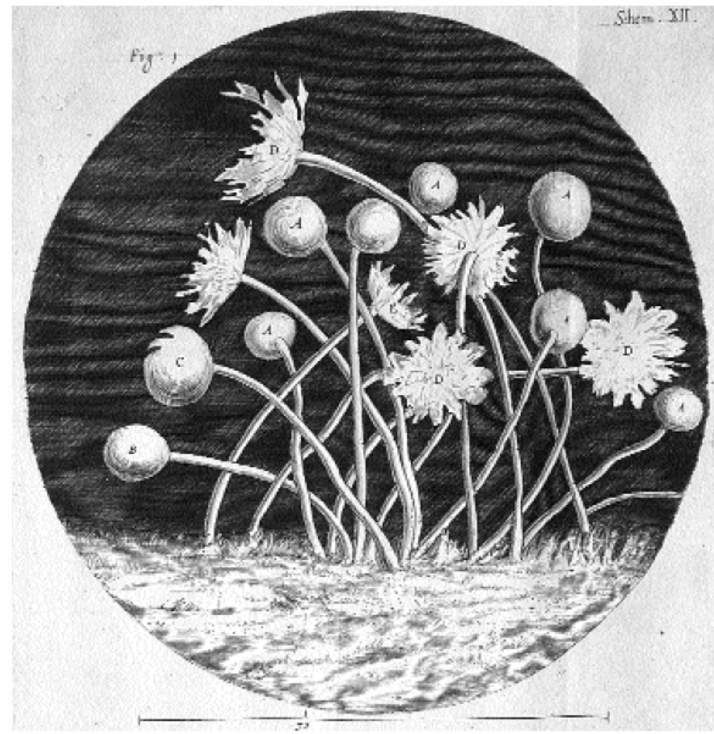


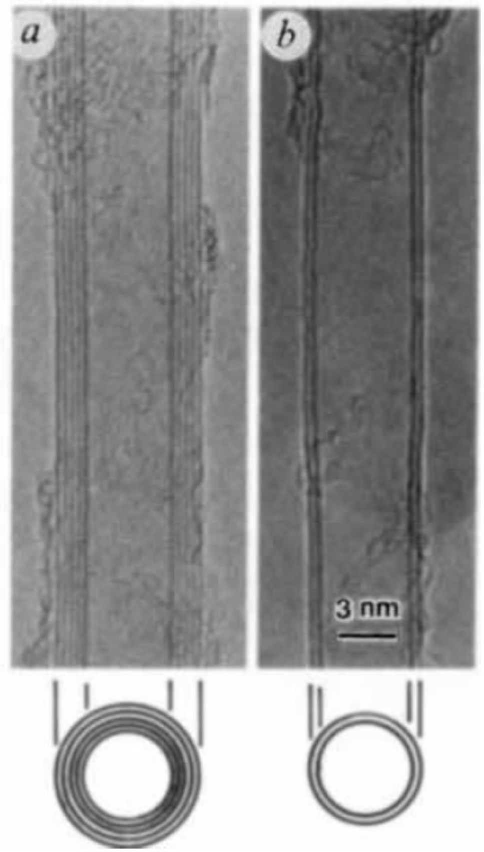
FIGURE 1

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.*

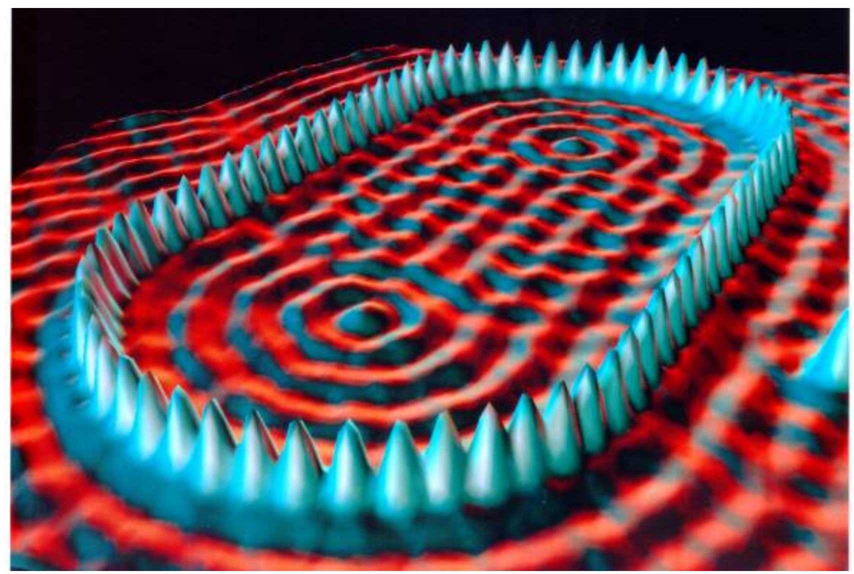
SOURCE: FROM "MICROGRAPHIA," REPRODUCED COURTESY OF THE LILLY LIBRARY, INDIANA UNIVERSITY, BLOOMINGTON, INDIANA.

But now we can see what's happening

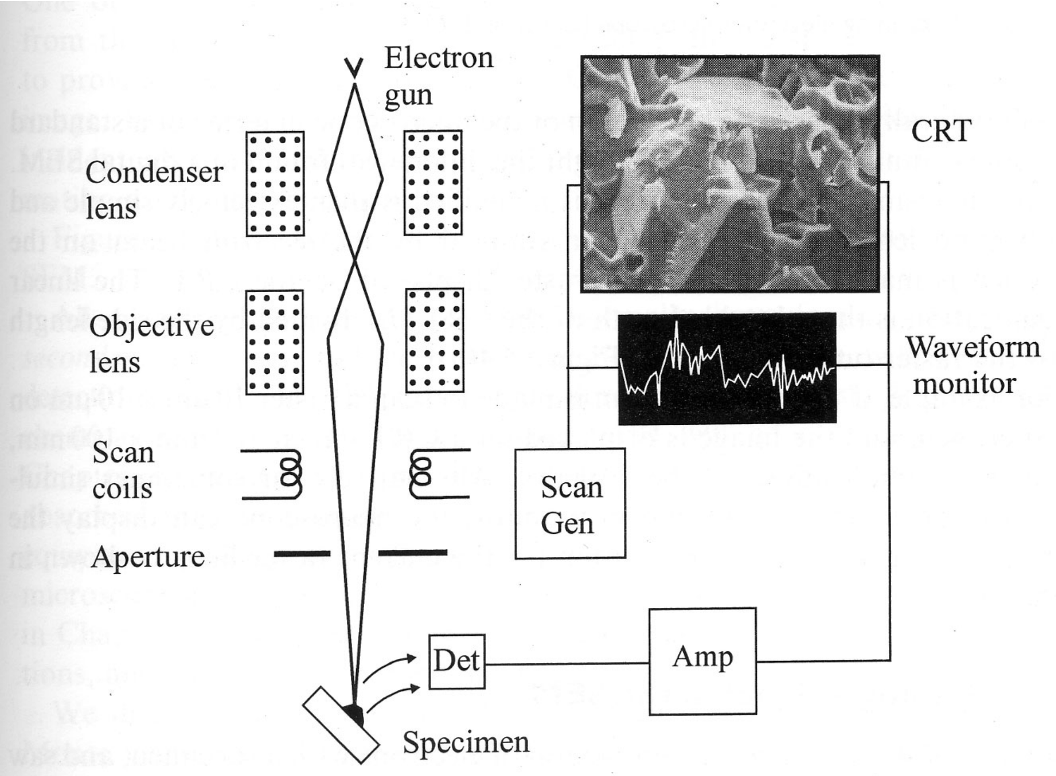
Structure of carbon nanotubes (Iijima, 1991)



"Quantum corral" of Fe atoms (IBM, 1993)

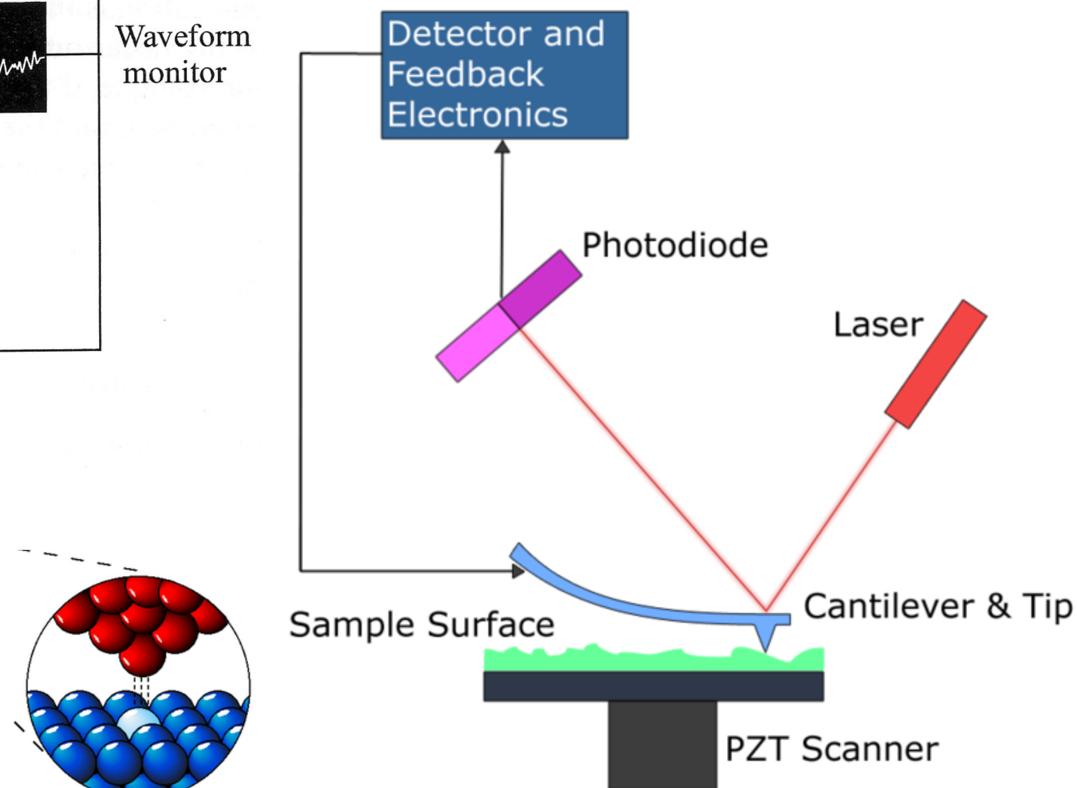


Scanning electron microscope (SEM)



Atomic force microscope (AFM)

Binnig, Quate, Gerber



(and sometimes we find imperfections)

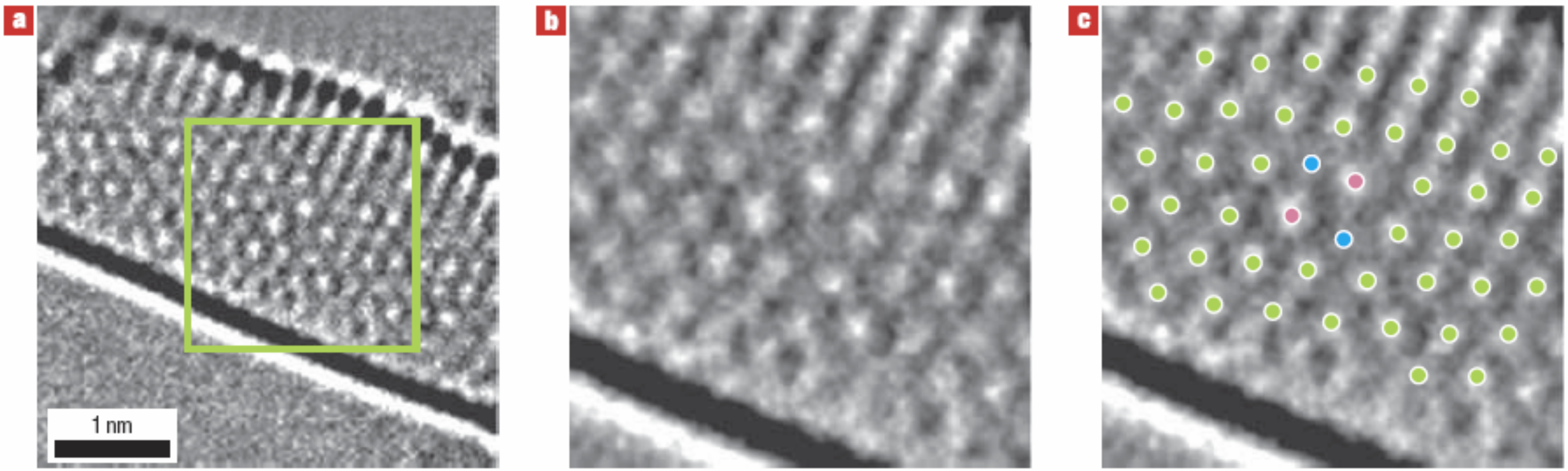
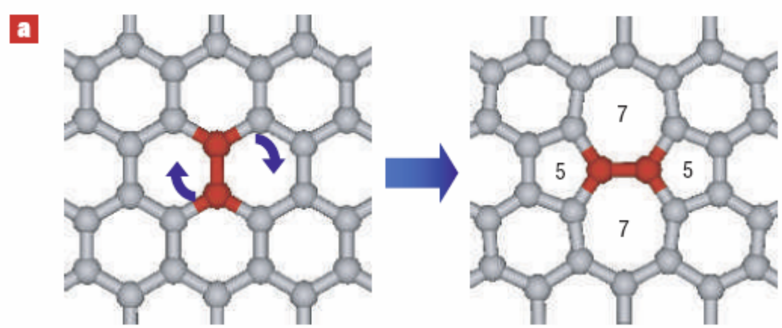


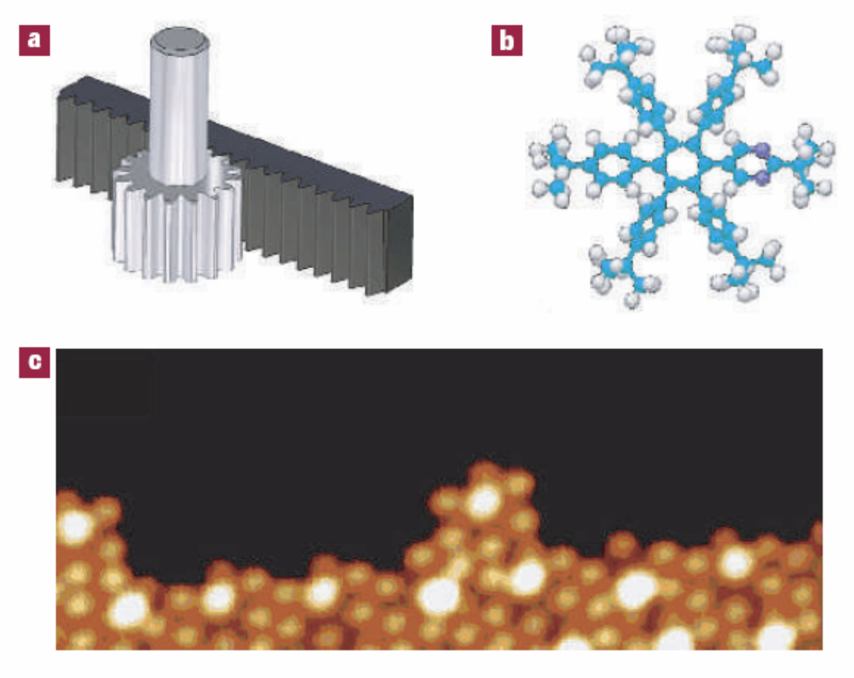
Figure 1 HR-TEM images of the pentagon–heptagon pair defect. a, A 5–7 pair defect found in an SWNT after heat treatment at 2,273 K. **b**, An enlarged image (of the area enclosed by the green line in **a**) in which the 5–7–7–5 defect can be more clearly seen. Each carbon ring appears with a bright spot 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.



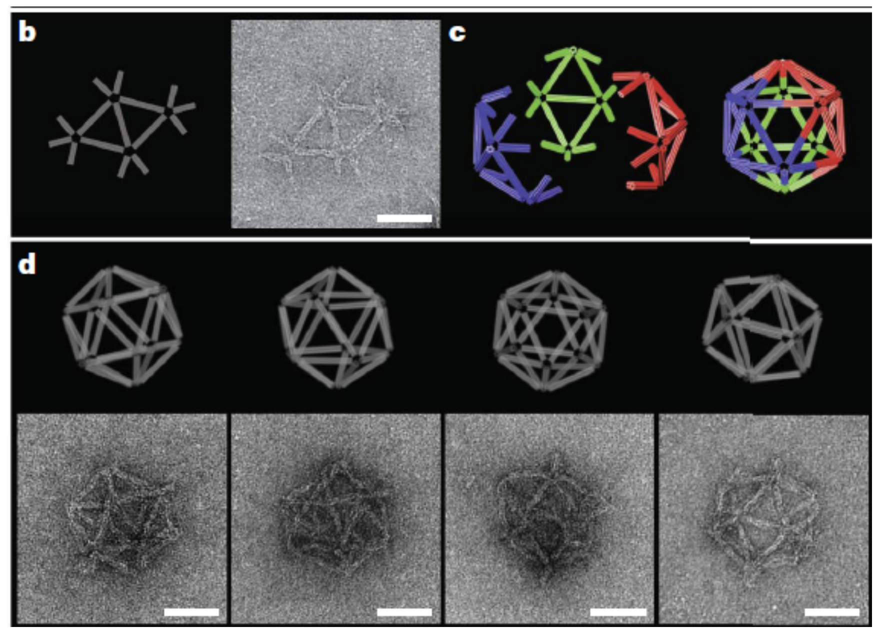
Suenaga et al., Nature Nanotechnology, 2:358, 2007.

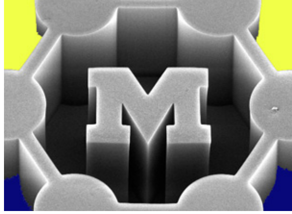
We're starting to close the loop

Molecular "rack and pinion" (Chiaravalotti *et al.*, 2007)

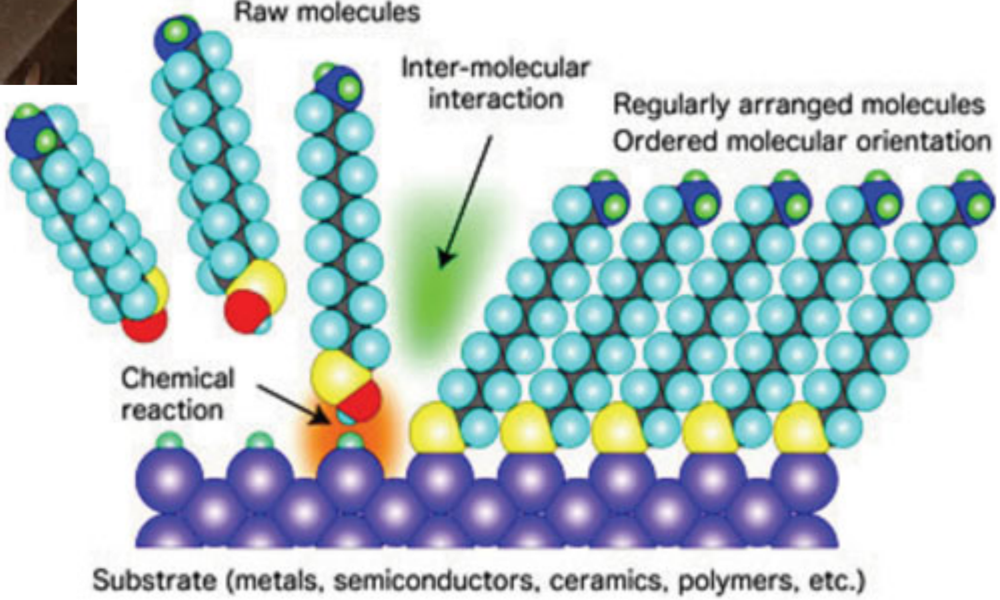


3D DNA "origami"
(Douglas *et al.*, 2009)



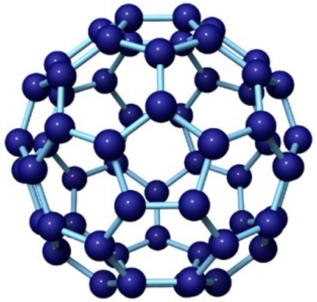


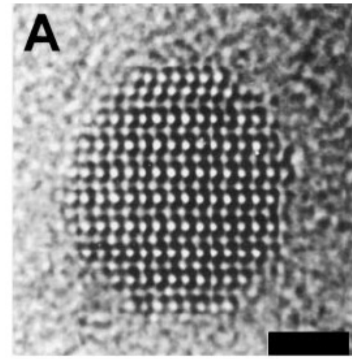
Manufacturing: top-down vs. bottom-up

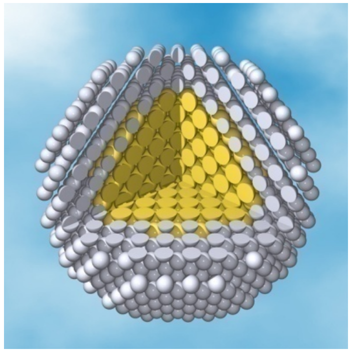


http://www.aist.go.jp/aist_e/aist_today/2007_23/nanotec/nanotec_02.html

“Building blocks” for nanomanufacturing



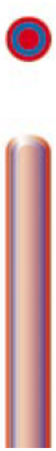


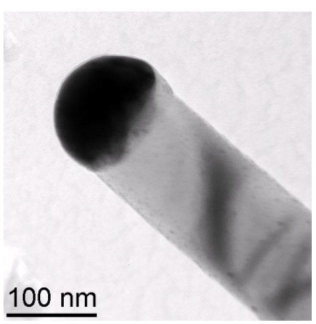


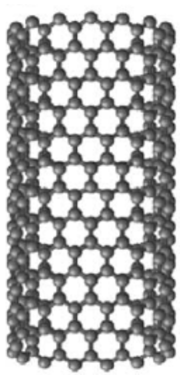
Nanoclusters | Nanoparticles

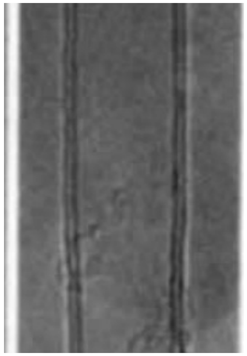
Magic #’s of atoms
≤1 nm size

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









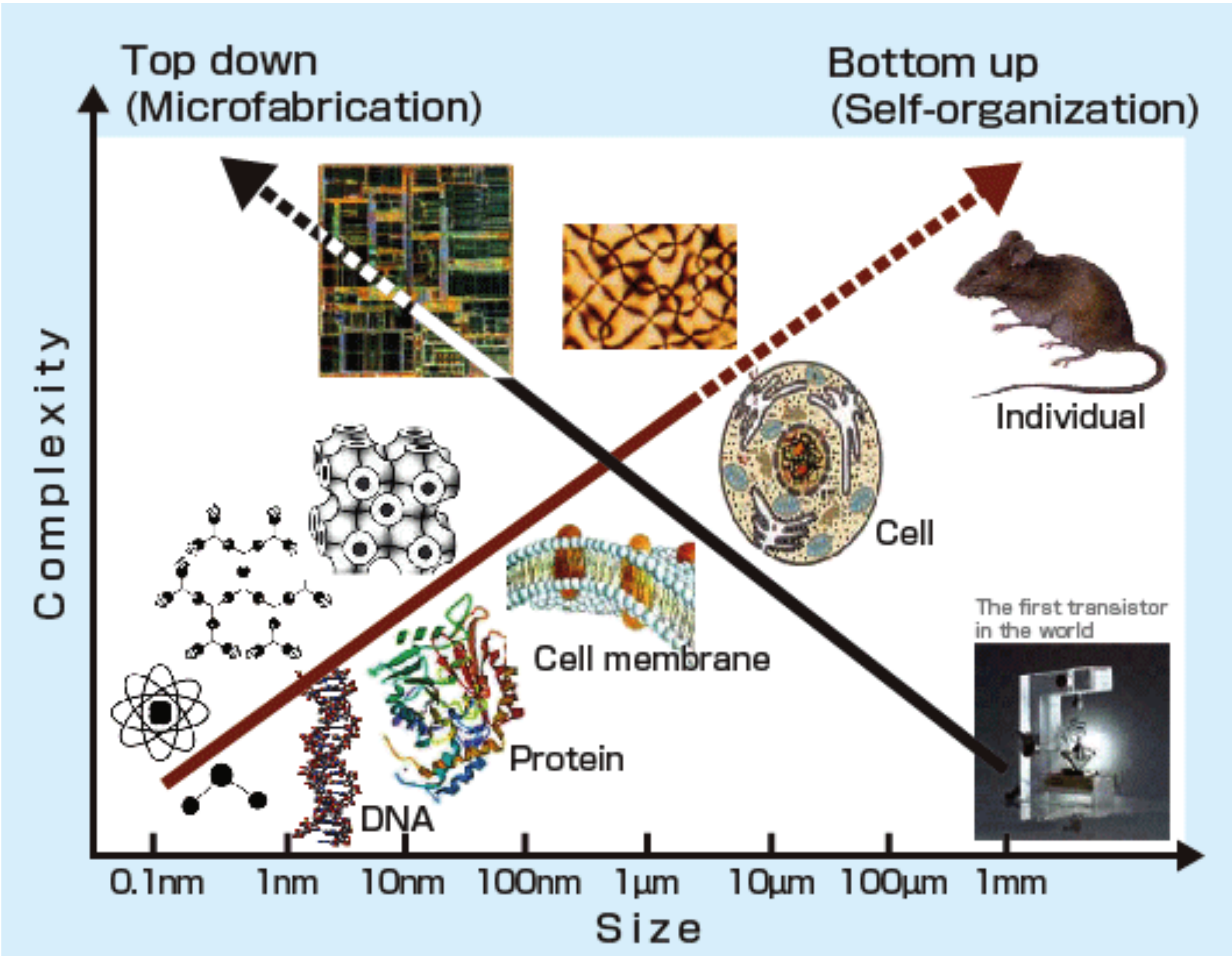
Nanowires | Nanotubes

Filled

Hollow

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

Manufacturing: top-down vs. bottom-up



http://www.aist.go.jp/aist_e/aist_today/2007_23/nanotec/nanotec_02.html

Generations of Products and Productive Processes

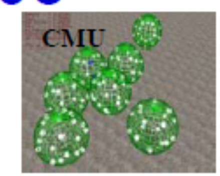
Timeline for beginning of industrial prototyping and nanotechnology commercialization (2000-2020)

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

~ 2000

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

~ 2005



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

~ 2010

4th: **Molecular nanosystems**
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

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

Increased Complexity, Dynamics, Transdisciplinarity

Slide by M. Roco

Reference: AIChE Journal, Vol. 50 (5), 2004

Nanomanufacturing Process Needs

Fabrication Techniques

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

Modeling and Control

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

Economics

-Cost
- EHS
- High Throughput

Metrology

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

Nanostructures into Devices / systems

- Interfaces to Micro and Macro
- Whole System Scale-up
- Rapid Characterization of 3D structures

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)

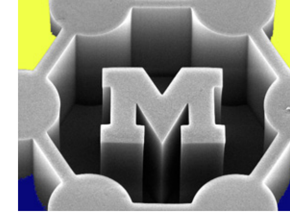
Economic growth

Table 1. Economic impact of nanotechnology in next 15–20 years

Field	$US billion per year
Materials	340
Electronics	300
Pharmaceuticals	180
Chemicals	100
Aerospace	70
Nanotools	20
Healthcare	30
Sustainability	45

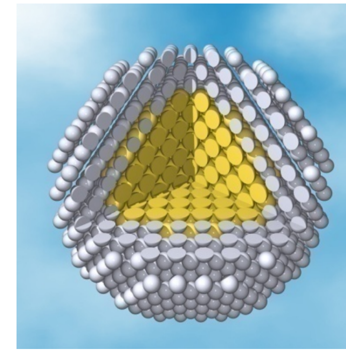
J. Gimzewski, Leonardo 41(3):259-264, 2008.

International standards



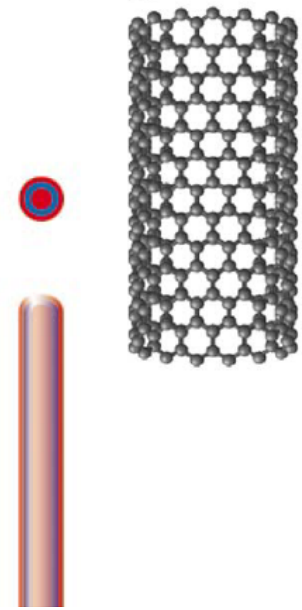
Nanomanufacturing: our mission

- Understand the fundamental properties of nanostructures, e.g., nanoparticles, nanotubes, and nanowires



- Understand how nanostructures interact with one another and their surroundings

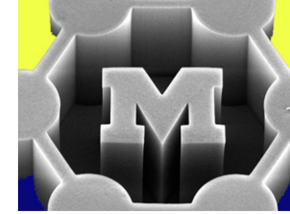
- Understand how to make and assemble nanostructures; how to control their size, structure, and placement



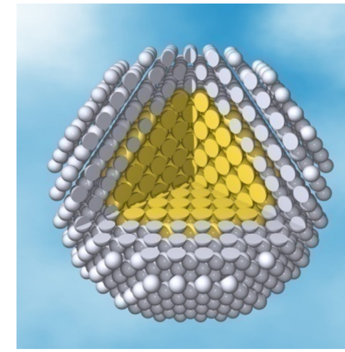
- Understand how the properties of nanostructures scale based on their assembly and interactions

- Combine our knowledge to design new devices, materials, and manufacturing processes

Course outline



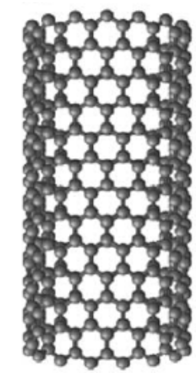
0: Introduction to nanotechnology

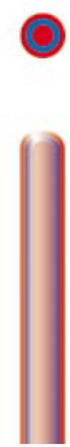


1: Properties of nanostructures ("building blocks")

2: Interactions among nanostructures

3: Synthesis of nanostructures





4: Assembly of nanostructures and property scaling

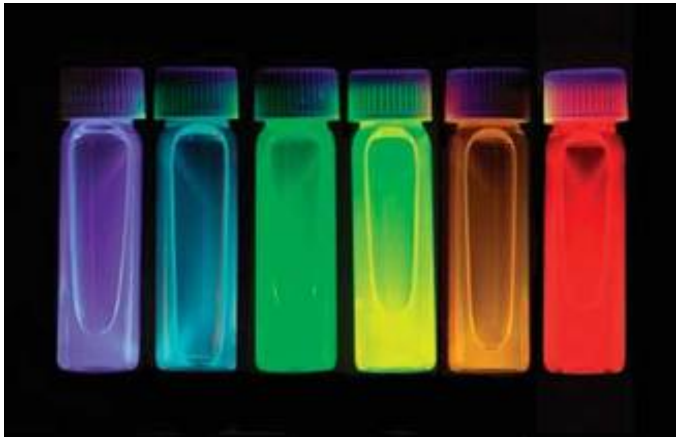
5: Case studies and project presentations

Assignments:

problem sets (5)
exam (1),
literature review (1)
project (1)

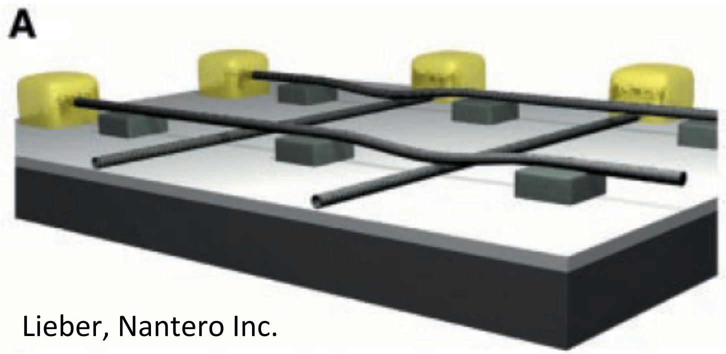
Some applications of nanotechnology

Quantum dots for solar cells



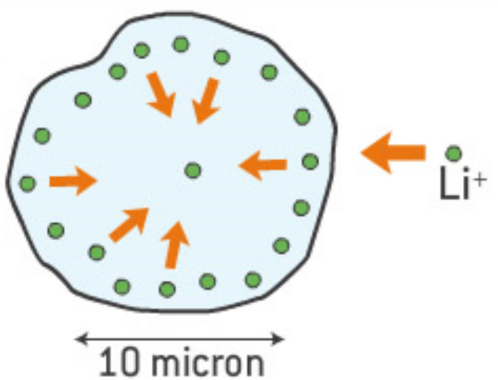
F. Frankel

Carbon nanotube memory

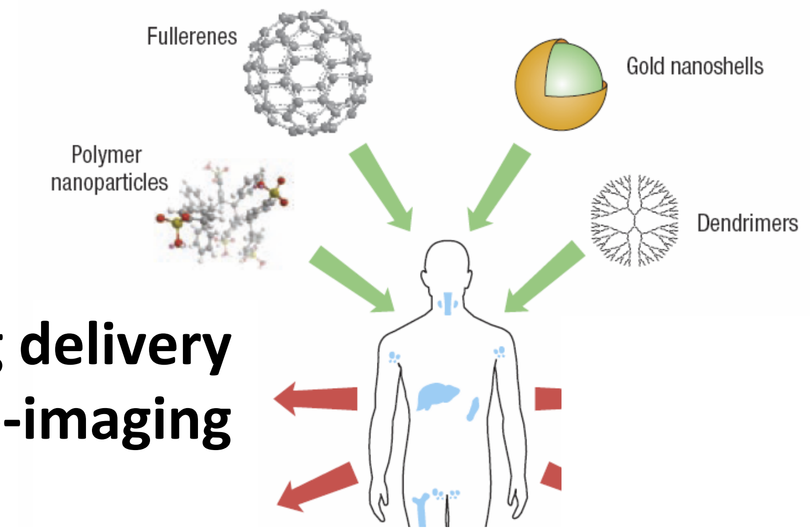


Lieber, Nantero Inc.

High-power nanostructured batteries



A123 Systems



Drug delivery and bio-imaging

Nanocomposite sports equipment

Zyvex, Easton

Semiconducting nanocrystals "quantum dots"

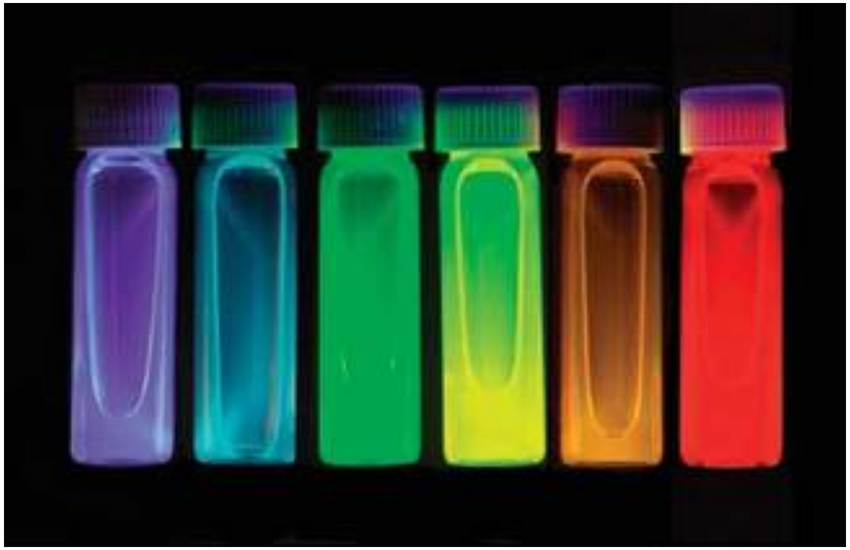
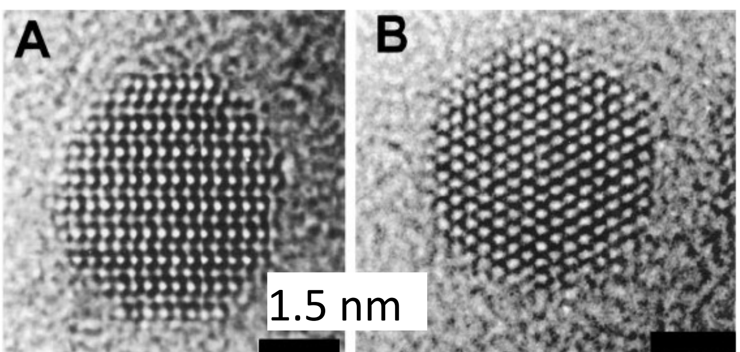
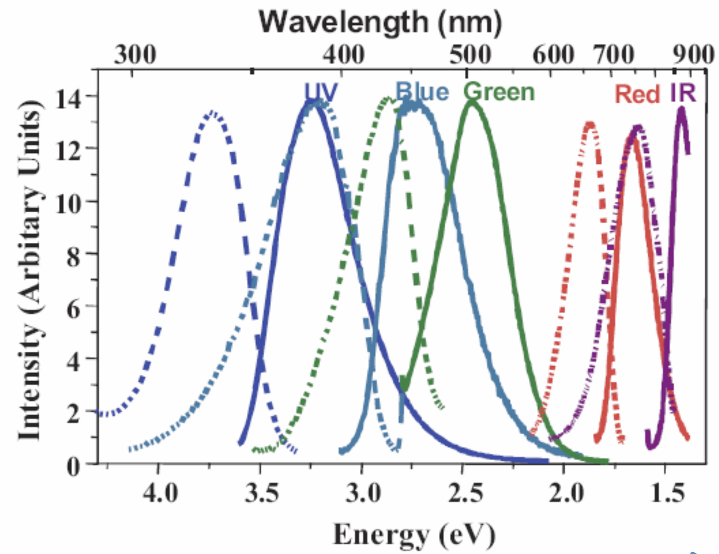


photo by F. Frankel, MIT

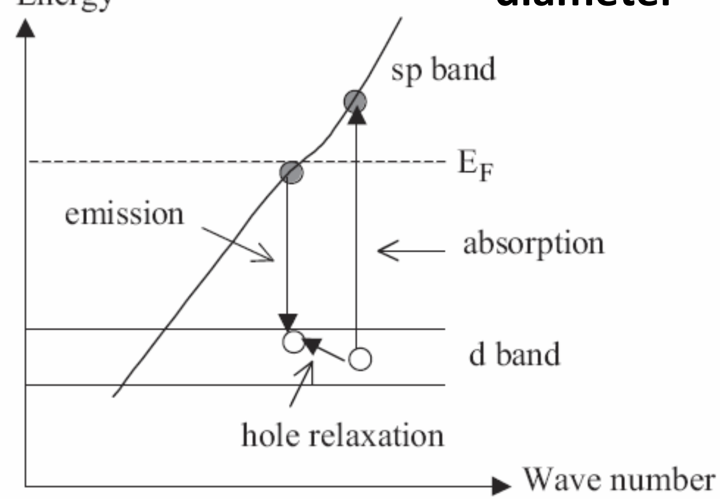
<100> CdSe **<001> CdSe**



for Au nanoclusters



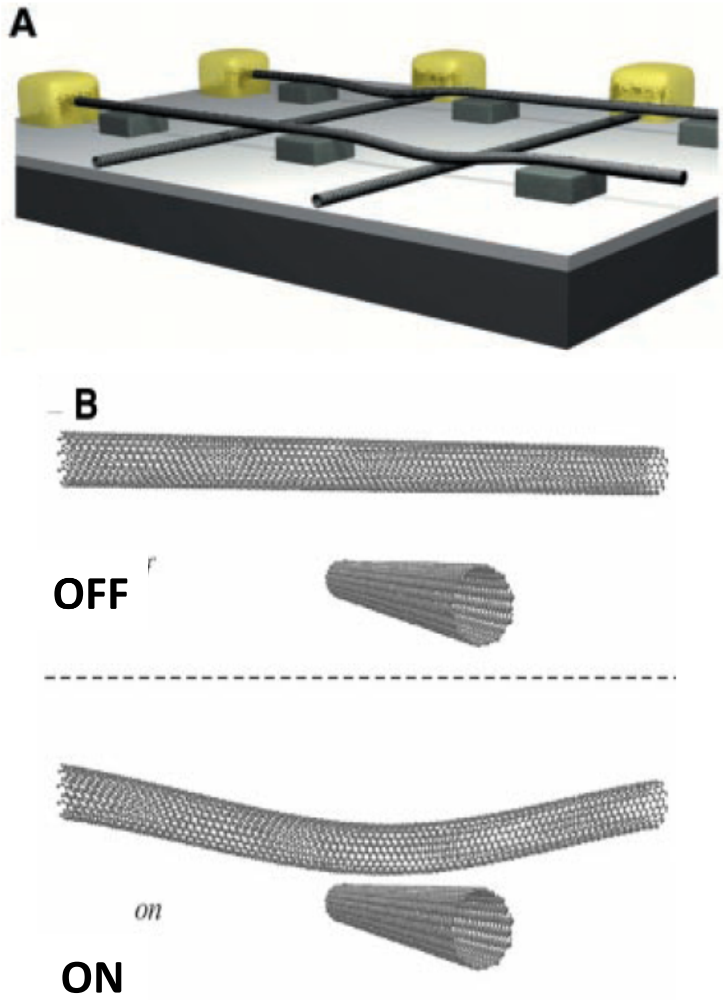
diameter

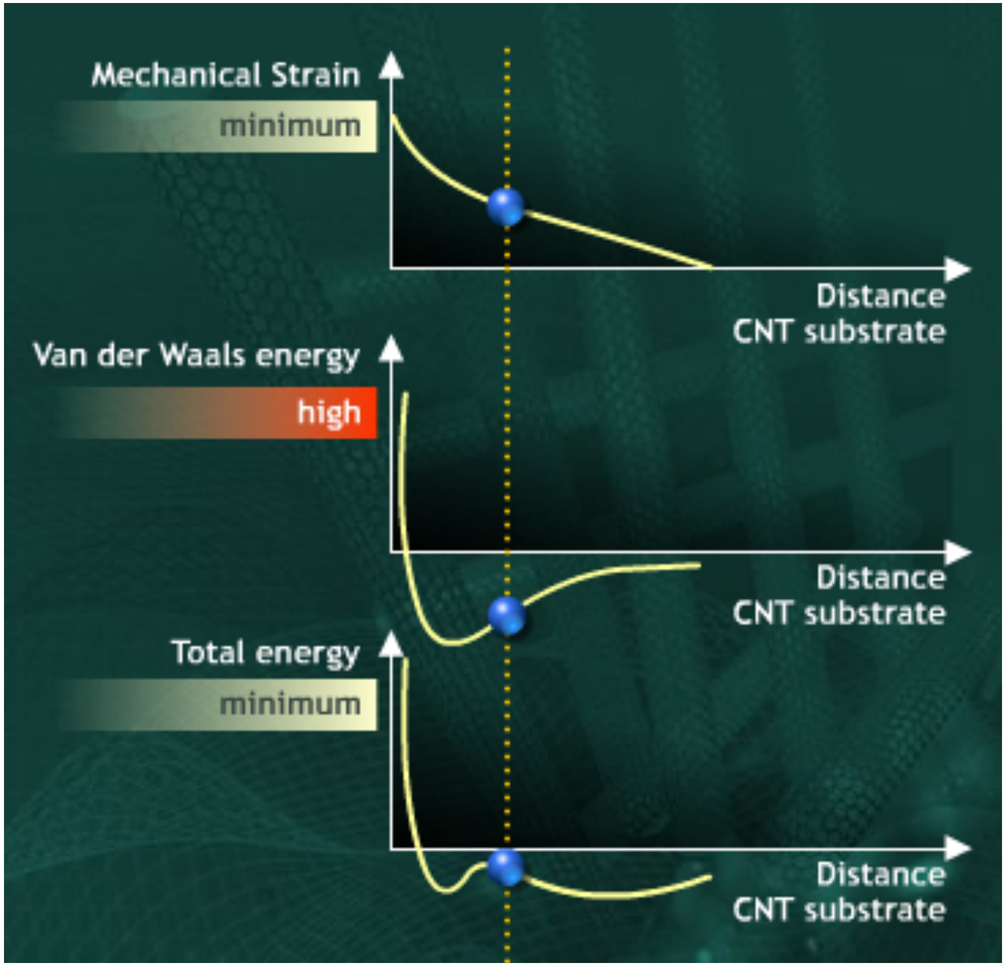


Hodes, Advanced Materials, 19:639, 2007.

CNT-based memory (Nantero, Inc.)

The concept (1998)

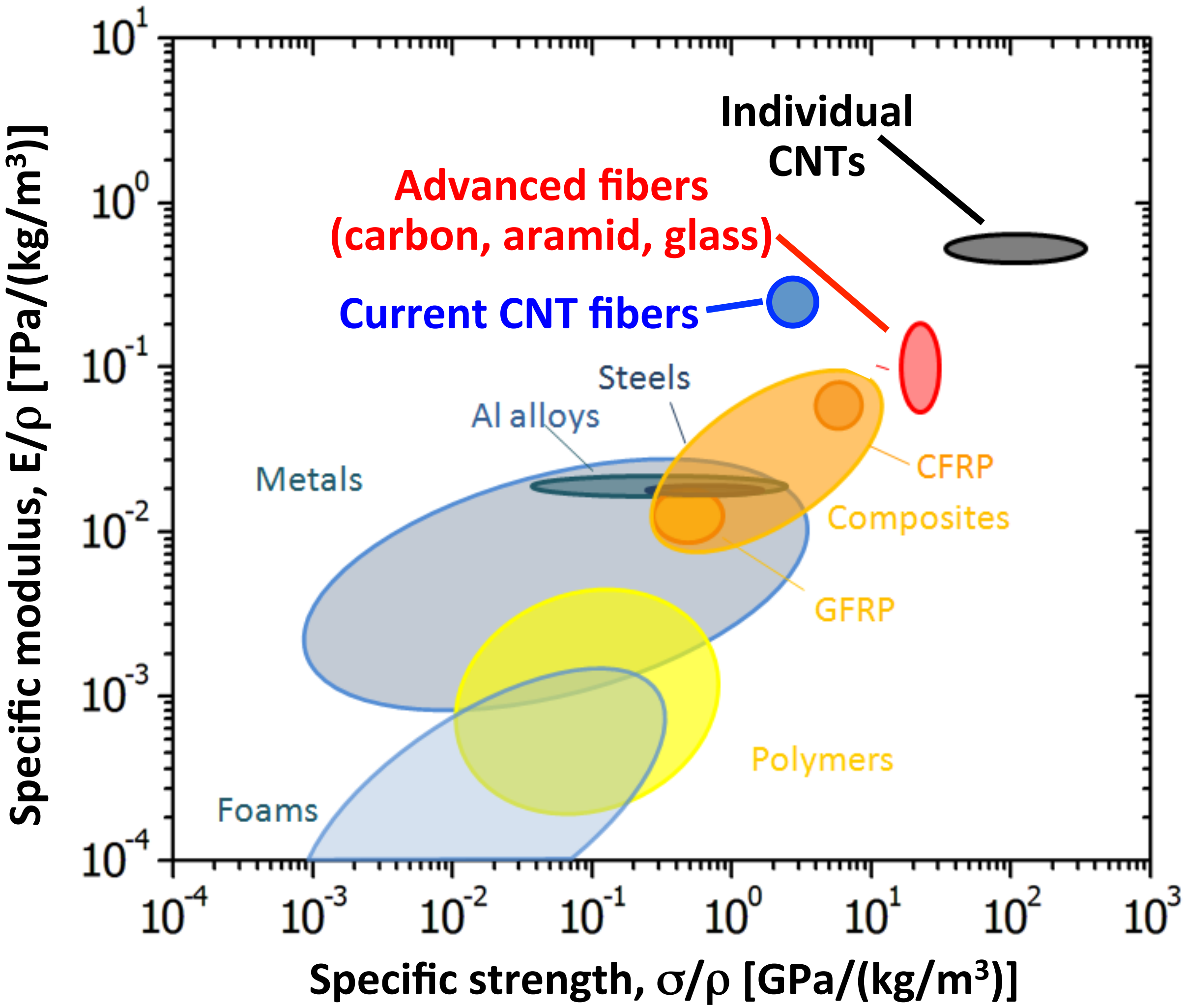




Reversible electromechanical junction

Rueckes et al, *Science* 289, 2000; http://www.nantero.com

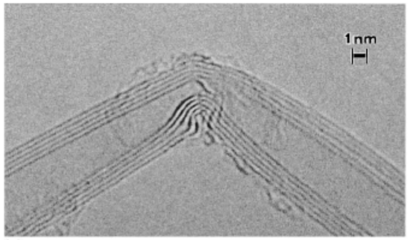
Exceptional properties of CNTs



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

- High recoverable strains and reversible kinking

  Iijima et al., *J. Chem Phys.,* 104:2089:92, 1996.



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

  Pop et al., *Nano Lett.* 6:96-100, 2006.

- Ballistic electron transport over micron length scales

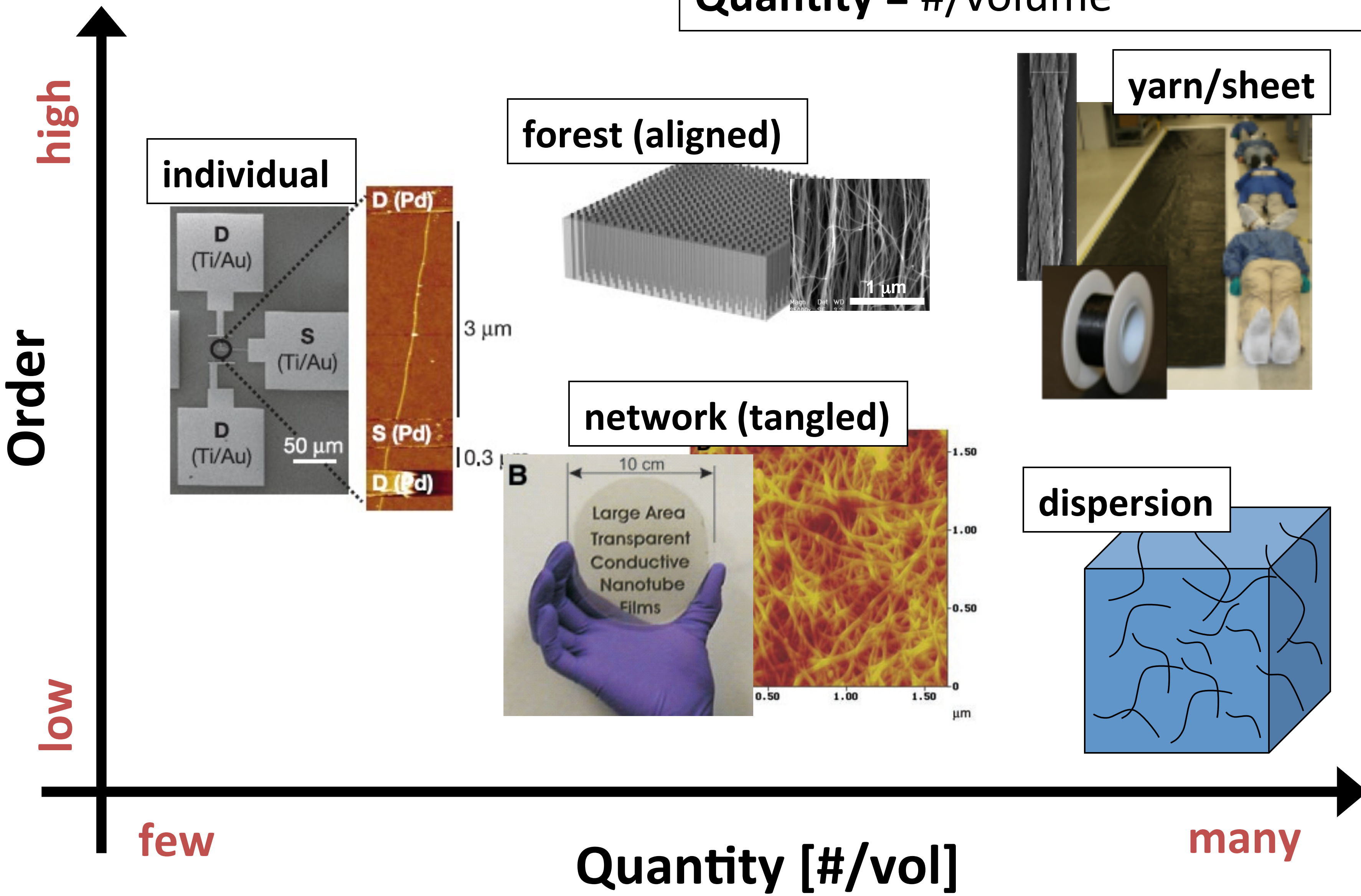
  Li et al., *PRL* 96:057001, 2006.

- Current density of ~10^9 A/cm^2

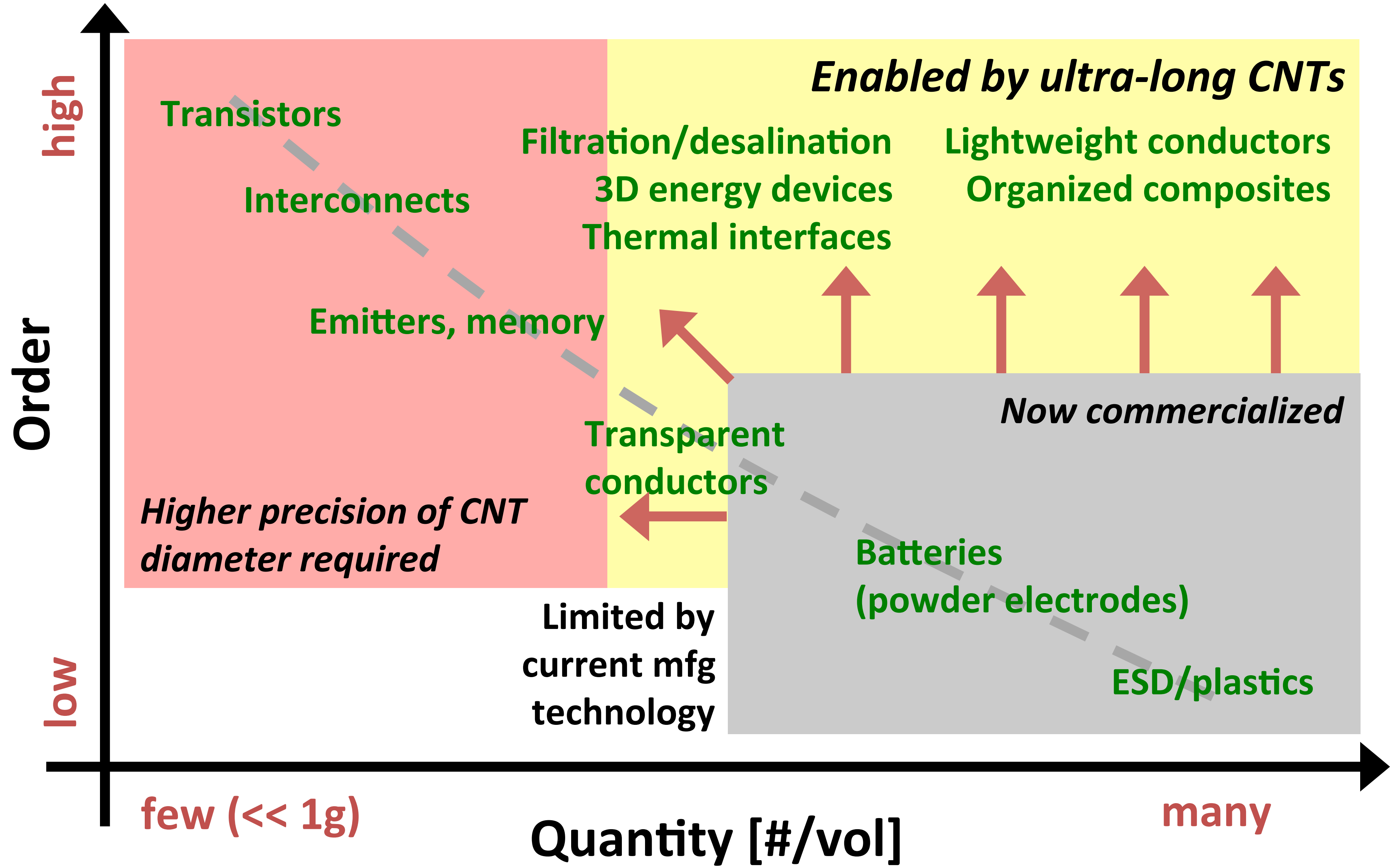
  Wei et al., *APL* 79:1172-4, 2001.

Configurations

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



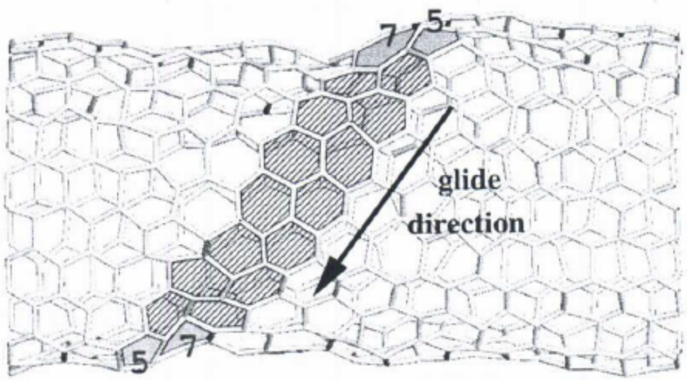
Applications

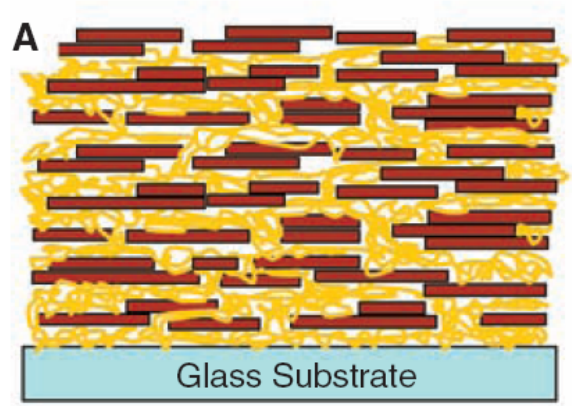


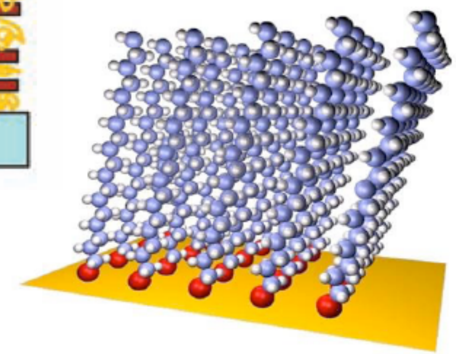
“Bulk” nanomaterials produced commercially today

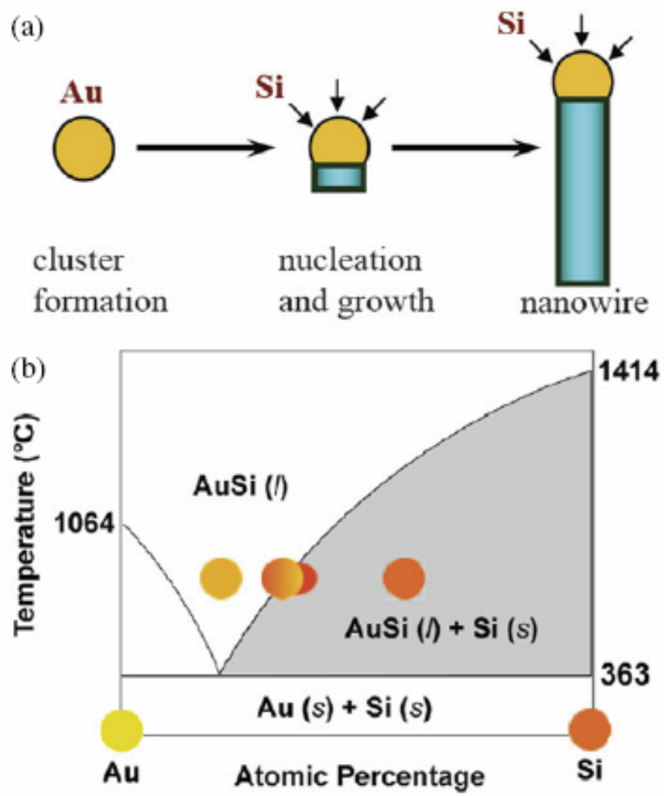
- Merck produces 10’s of tons of silica particles per year for cosmetic purposes
- 3M produces TiO_2 nanoparticles for dental fillings
- Cabot produces > 10 tons of carbon black nanoparticles as polymers additives
- Showa Denko (Japan), Mitsui (Japan), and Hyperion (USA) produce > 500 tons of carbon nanotubes

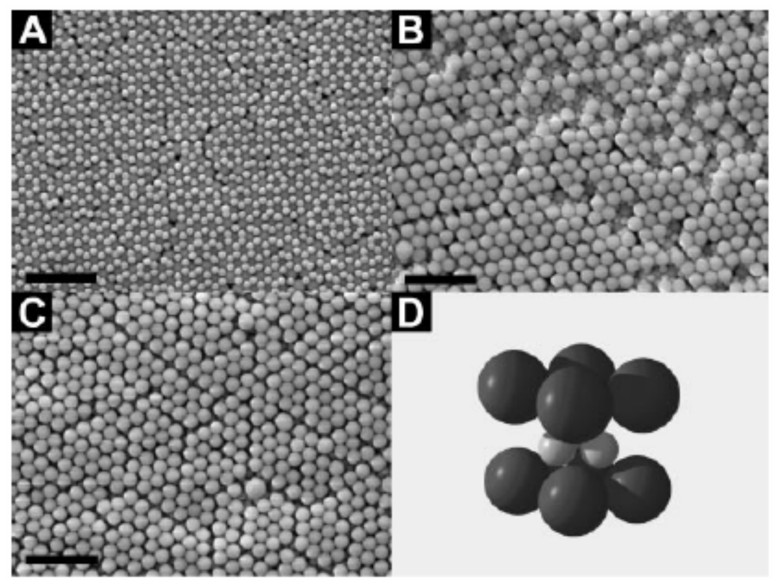
Looking forward…











Forecast: **an endgame?**

Nanotechnology: The Endgame of Materialism

James K. Gimzewski

THE PHYSICS OF

SMALL AND BIG

Technology is destructive only in the hands
realize that they are one and the same pr

—Alan Watts

Nanotechnology is typically discussed usi
nanometer, which is a billionth of a met
classify many technologically and biolo
jects on the scale of the nanometer (nm)
has a diameter of around several tenths
is around a nanometer in diameter but
long. Proteins have dimensions of a few
typically several thousand nanometers.
world, the insulating gap in a transistor

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ee that
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y world
of sub-

r techni-
m to be.

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.

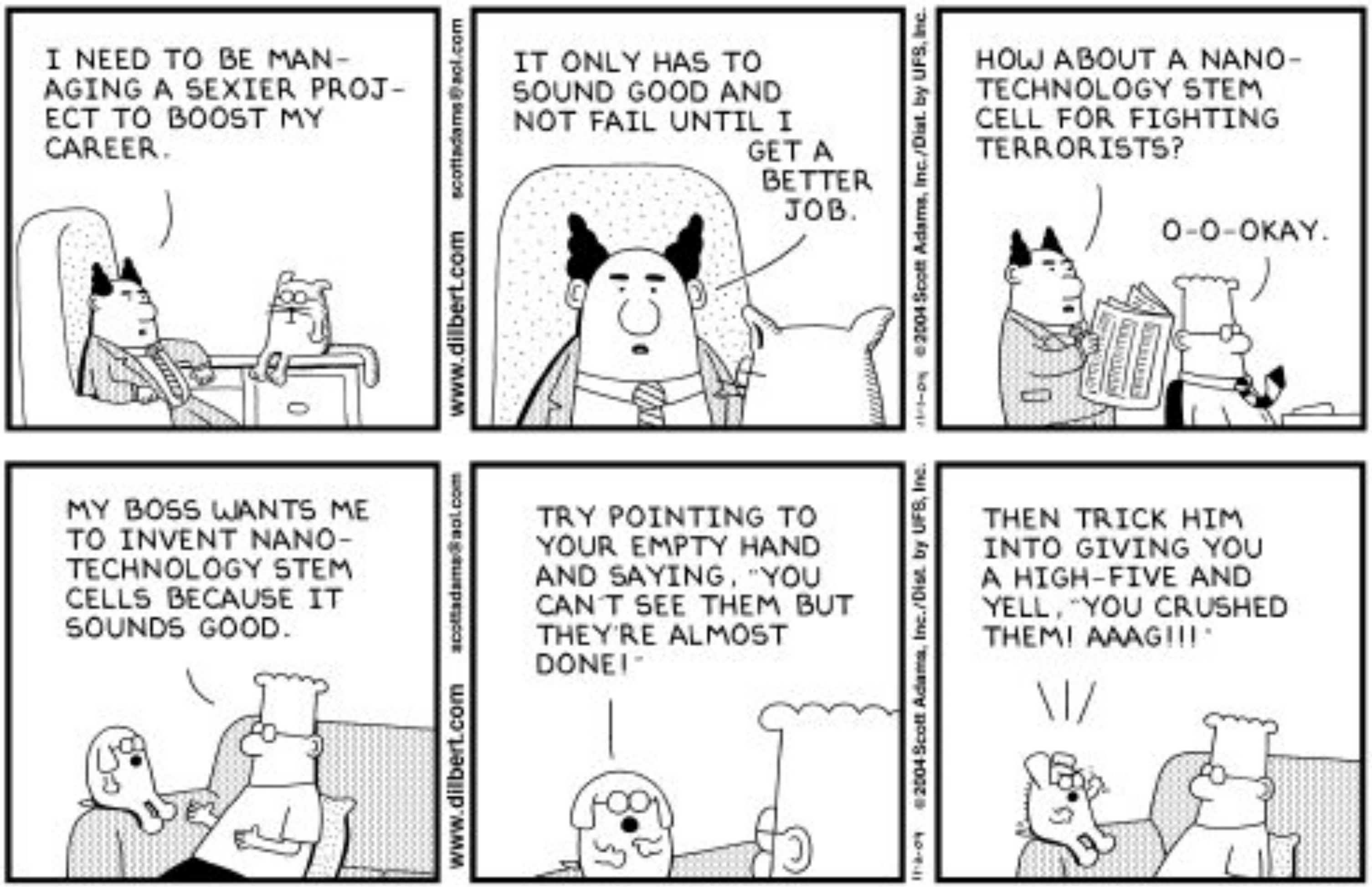
The nanotechnological evolution will lead to a total hybridism of mind-machine and art-science and new forms of personal interrelationship. The neuronal

ABSTRACT

Imagine that one could arrange atoms in any form one wanted: What would one create? 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.

J. Gimzewski, *Leonardo* 41(3):259-264, 2008.

Fun: **marketing**



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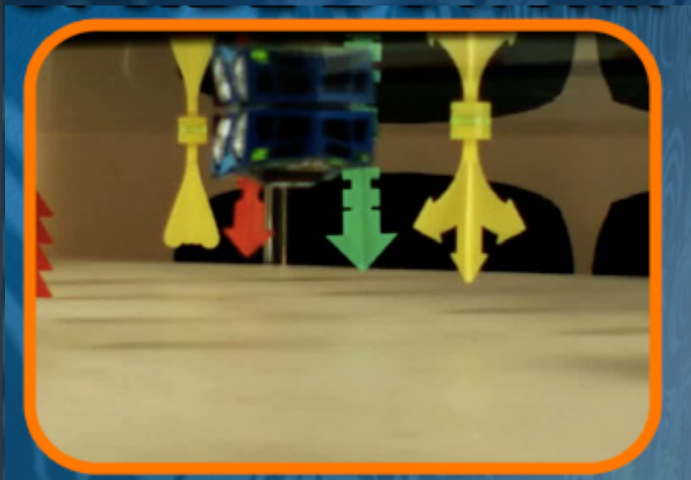

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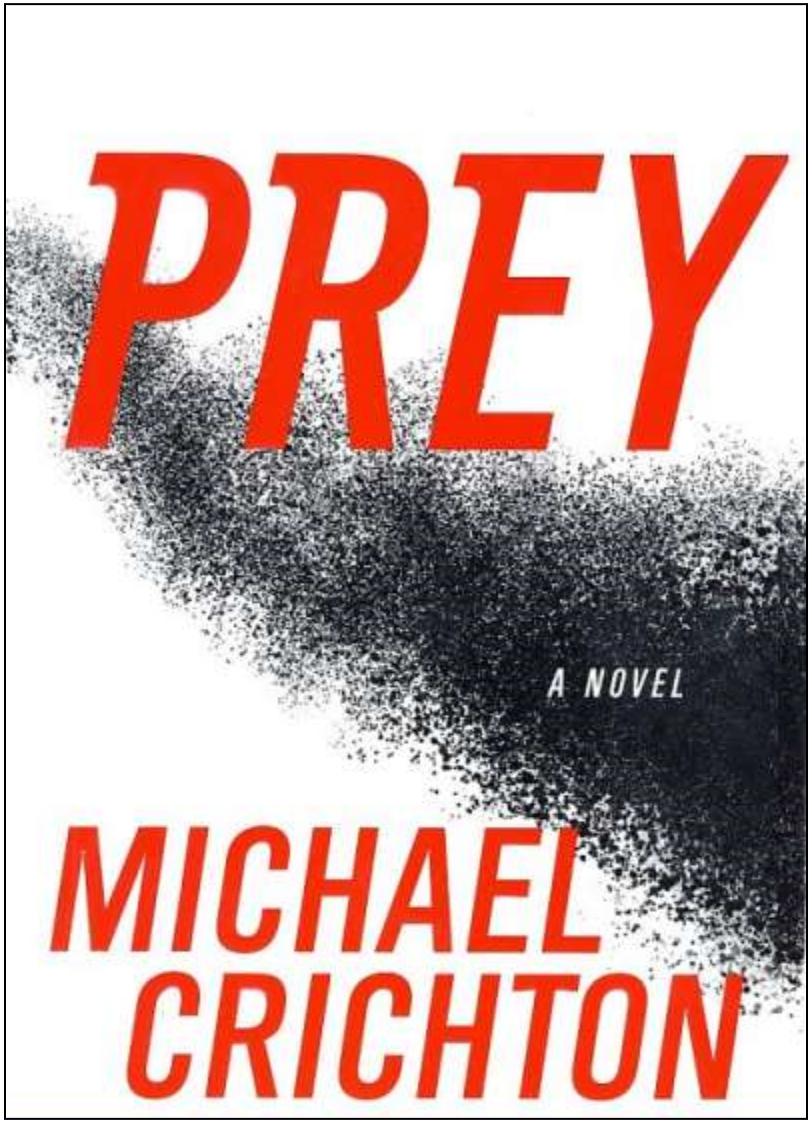
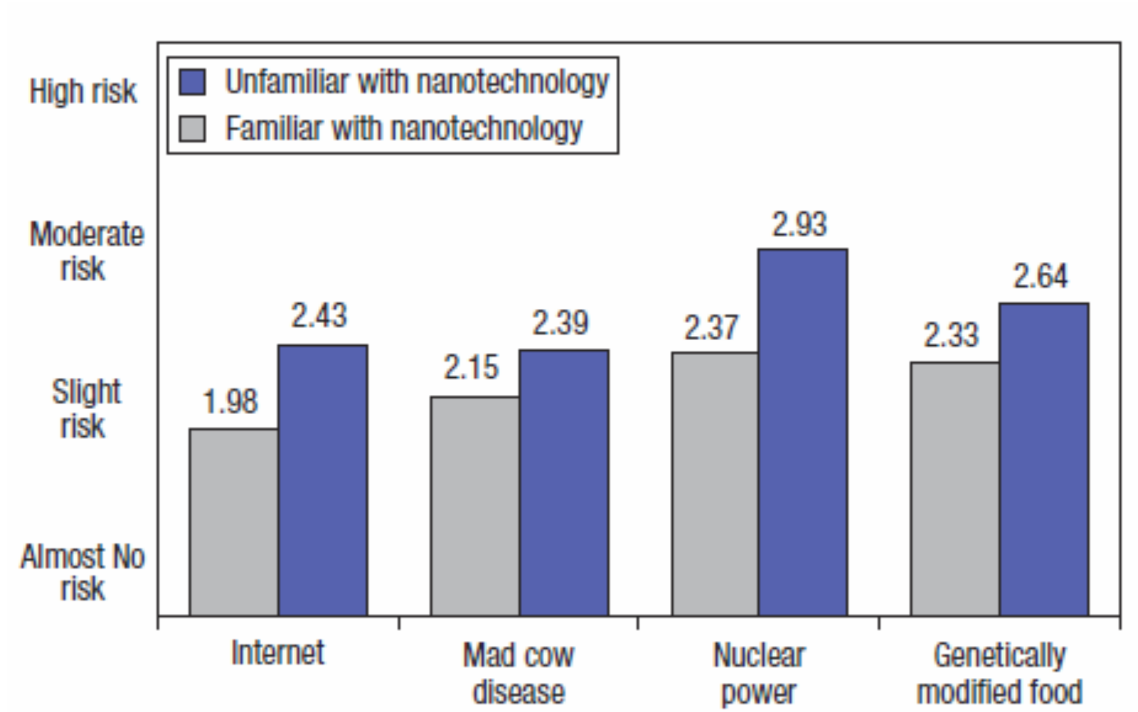

PREY
A NOVEL
MICHAEL
CRICHTON

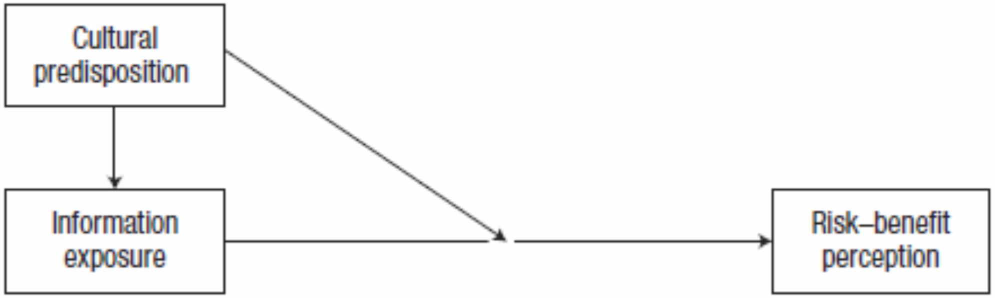
Imperative: **communication and outreach**

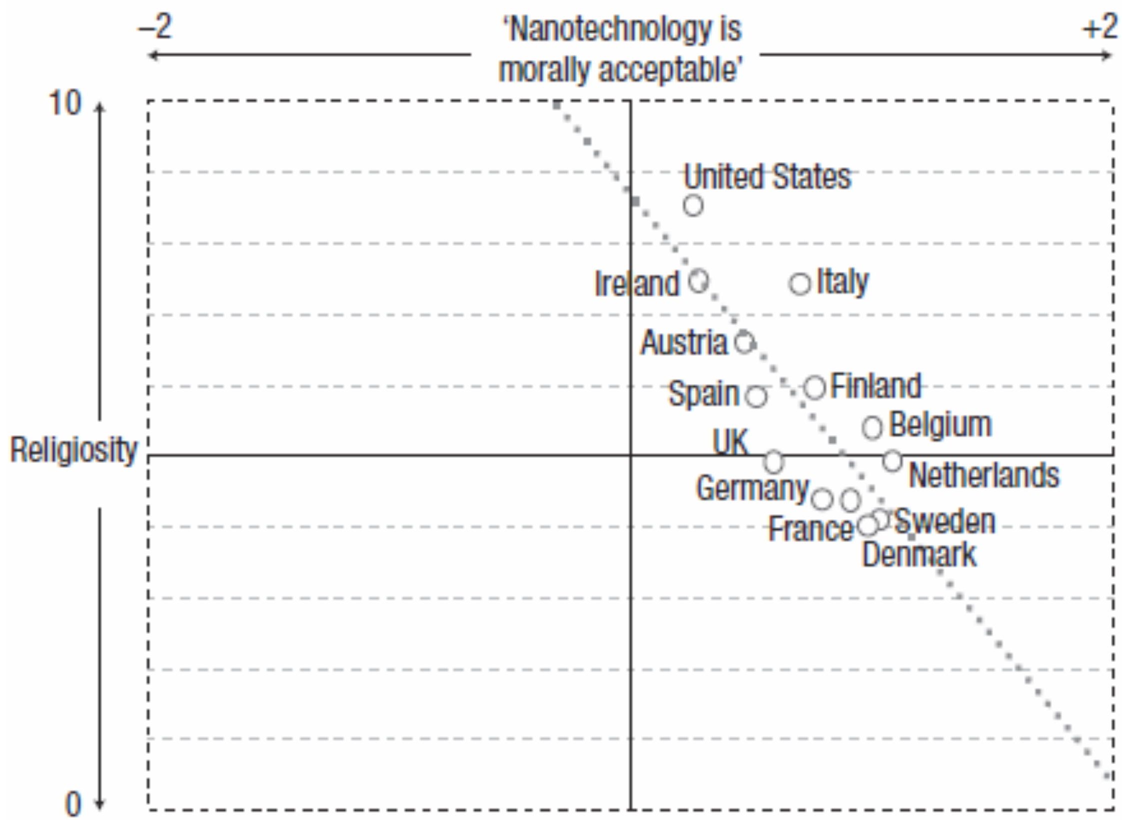
- 2008 – over 80% of Americans reported having heard 'just a little' (28%) or 'nothing at all' (54%) about nanotechnology.



Kahan et al., Nature Nanotechnology doi:10.1038/NNANO.2008.341

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

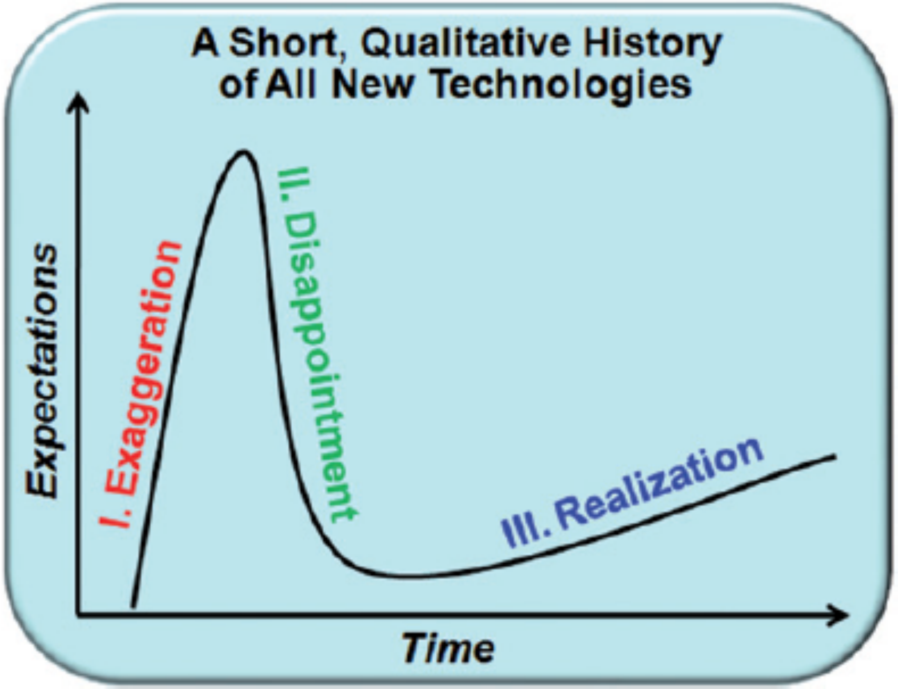
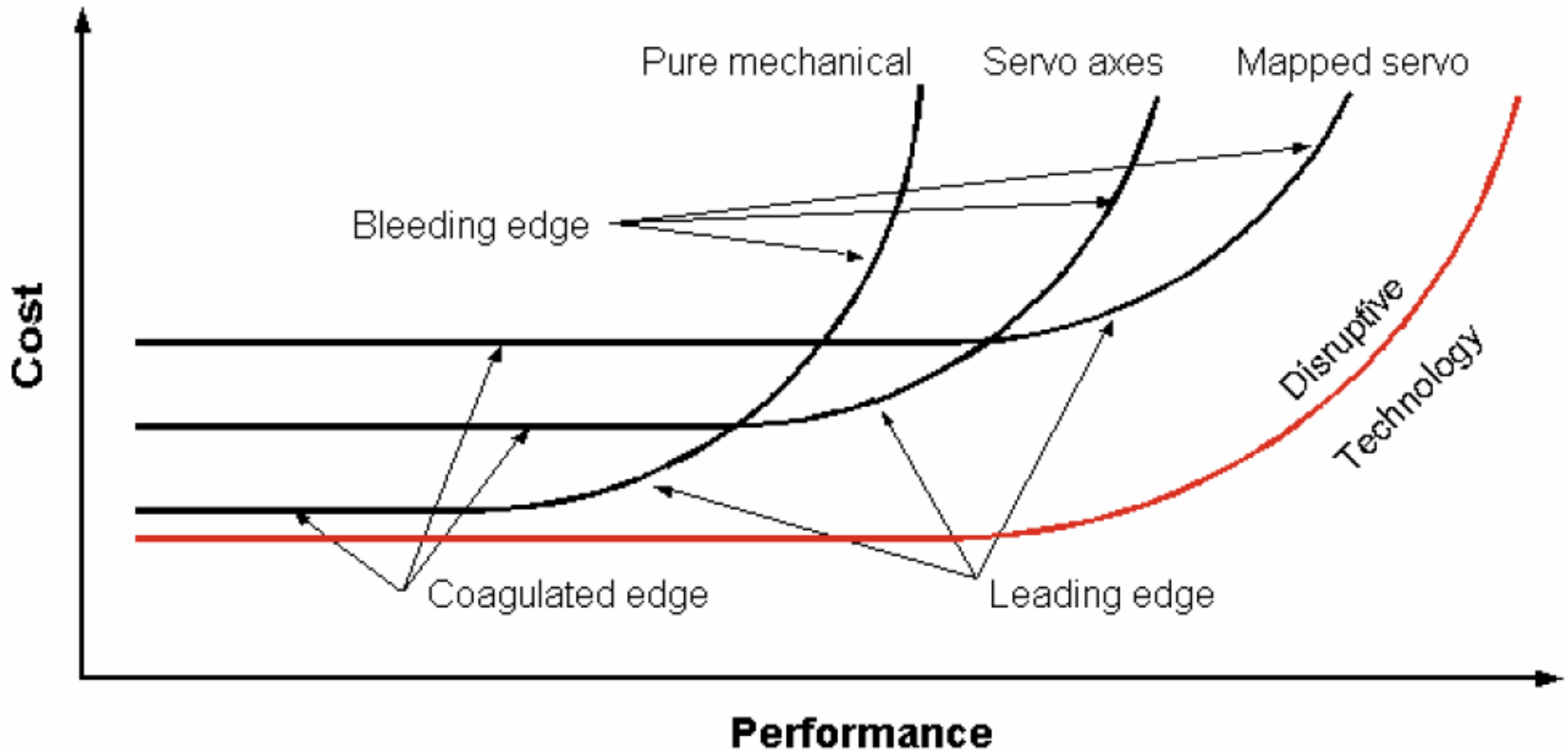


Fig. 1 The expectations of a new technology as a function of time. (I) In the beginning, there is a period of exaggerated expectations, during which exciting—but sometimes irreproducible—results and unrealistic claims are made. (II) When these high expectations go unmet, a period of disappointment sets 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.

G. Whitesides, *Faraday Discussions* 143:373-384, 2009.

Introductions

then closing advice



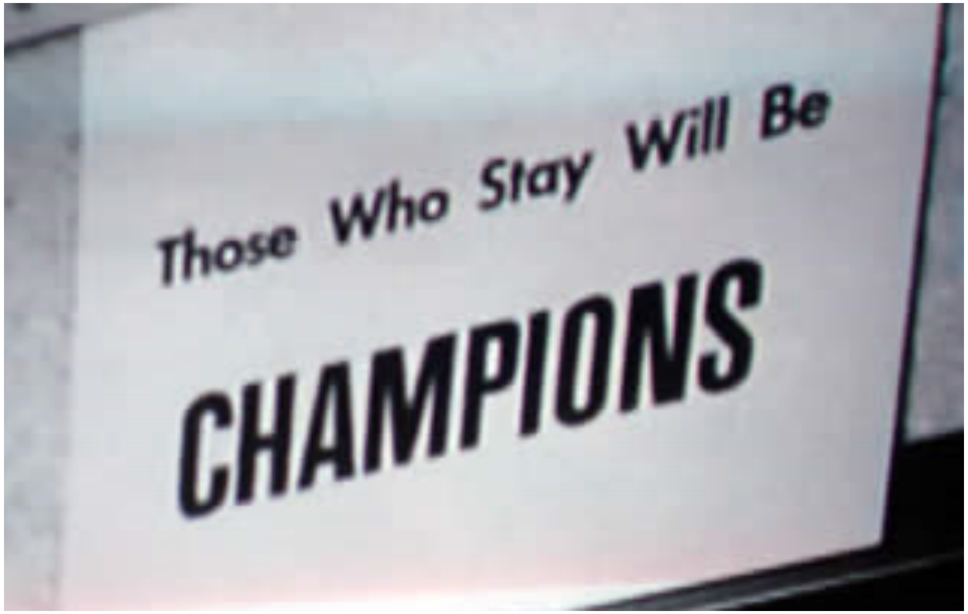
→ *Stay on the leading edge!*

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."

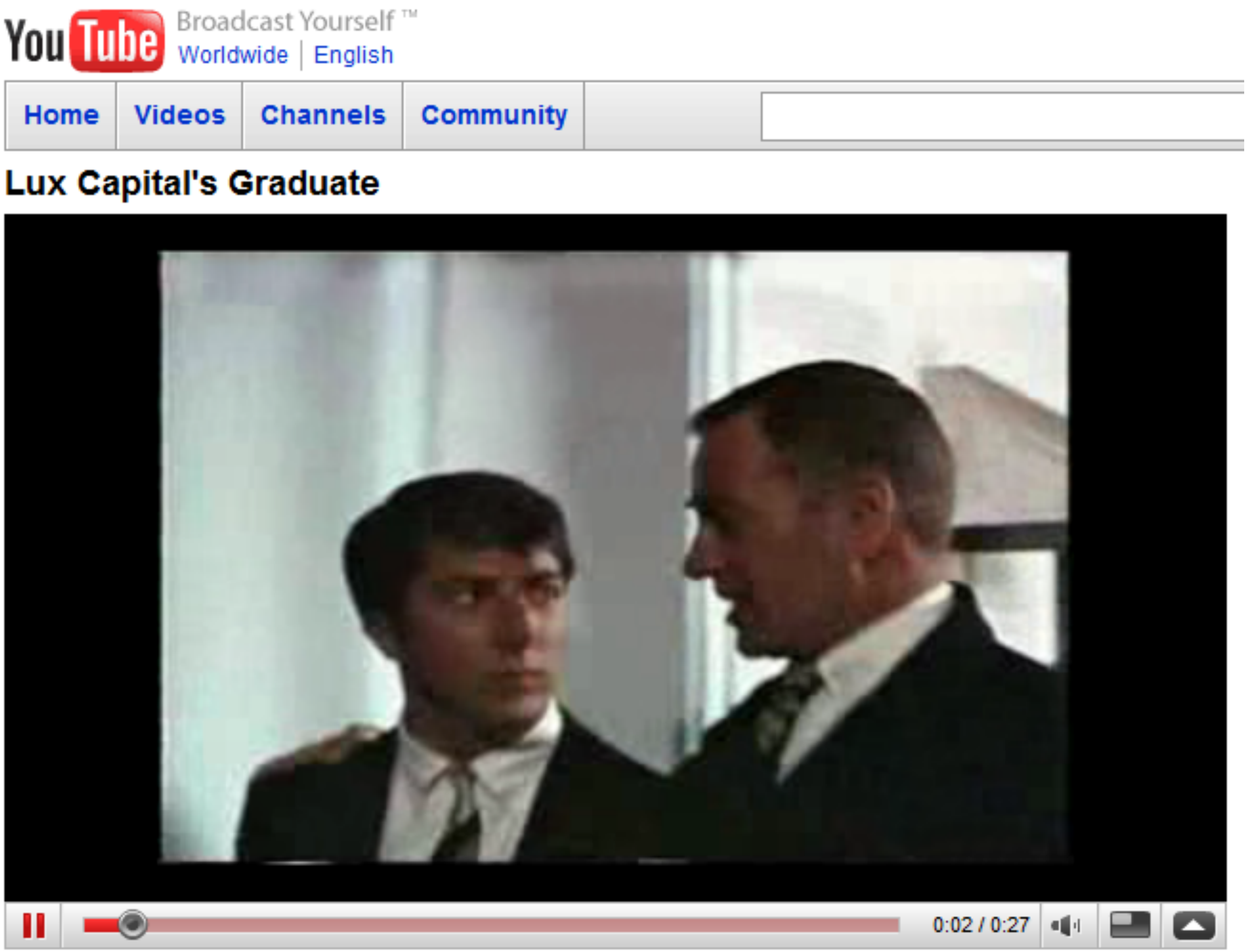
Dave "The Edge" Evans (U2), at Berklee College of Music Commencement, Boston, MA, May 2007.

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