Introduction to Nanotechnology

- Textbook：
  Nanophysics and Nanotechnology
  by:
  Edward L. Wolf

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Classroom: A209
Time: Thursday; 13:30-16:20 PM
Office hour: Thur., 10:00-11:30 AM or by appointment

Objective of the course

The course, Introduction to Nanotechnology (IN), will focus on understanding of the basic molecular structure principals of Nano-materials. It will address the molecular structures of various materials. The long term goal of this course is to teach molecular design of materials for a broad range of applications. A brief history of biological materials and its future perspective as well as its impact to the society will be also discussed.

Evaluation; Score: 100%:

Mid-term Exam: 30%
Final Exam: 30%
Scientific Activity: 40 % (Home work, Innovation Design)

Systematic of Making Things Smaller

The Nanoscience

The beginning of the end

Nano-Products

Nanobots

Nanomedicine

Nanostuff

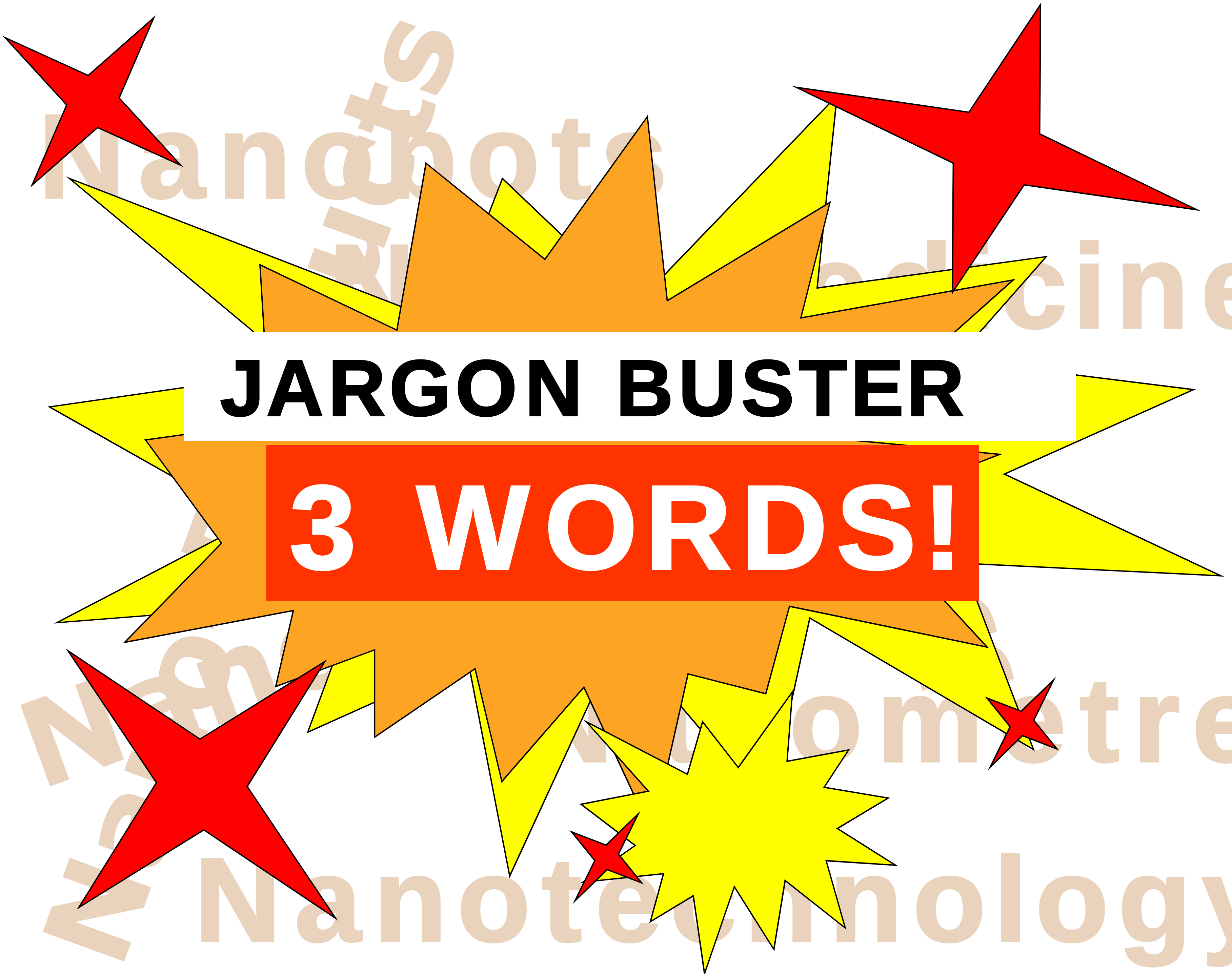
Nanos

Nanoscience

stuff

Nanometre

Nanotechnology

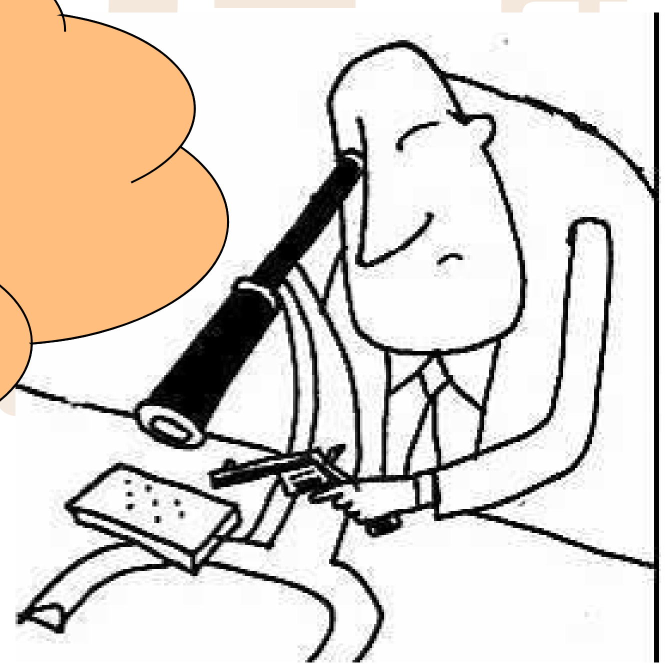


JARGON BUSTER
3 WORDS!
Nanobots
Nanotechnology

Nano:

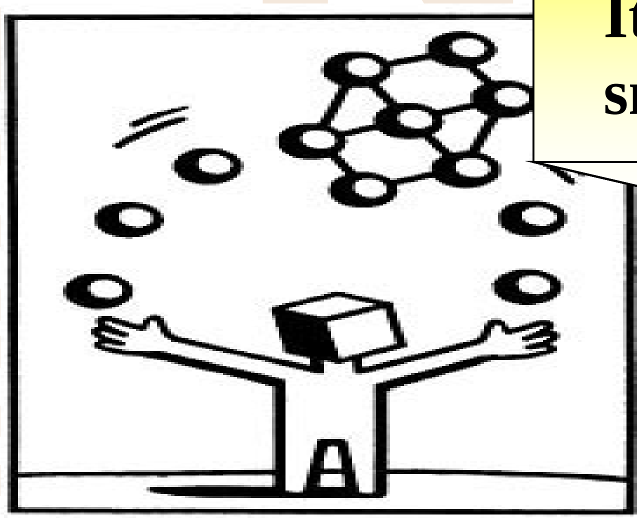
A prefix that means very, very, small.

The word nano is from the Greek.
word ‘Nanos’ meaning Dwarf.
It is a prefix used to describe "one billionth" of something, or 0.000000001.



Nanoscience

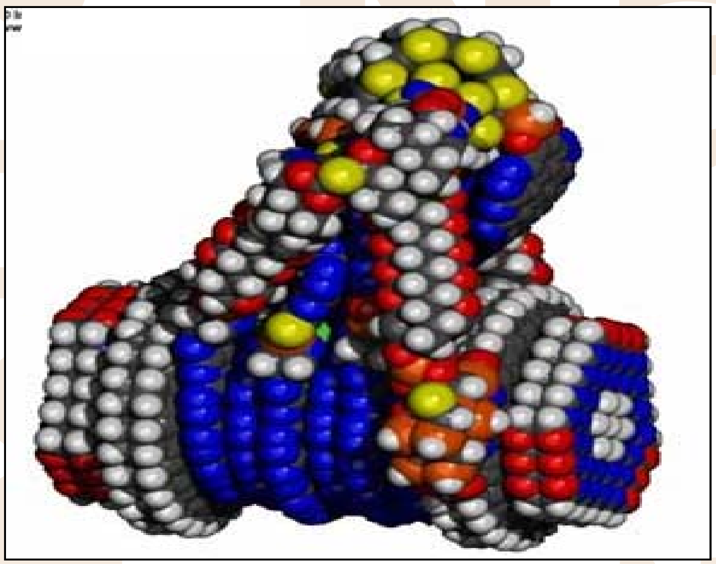
A part of science that studies small stuff.



It's not biology, physics or chemistry. It's all sciences that work with the very small.

Nanotechnology

The art and science of making useful stuff that does stuff on the nanometre length scale.



Includes advances in all industries, including the electronic, chemical, and pharmaceutical.

Understanding Size

- 1 metre

source: CERN http://microcosm.web.cern.ch/microcosm

Understanding Size

- 10 centimetres

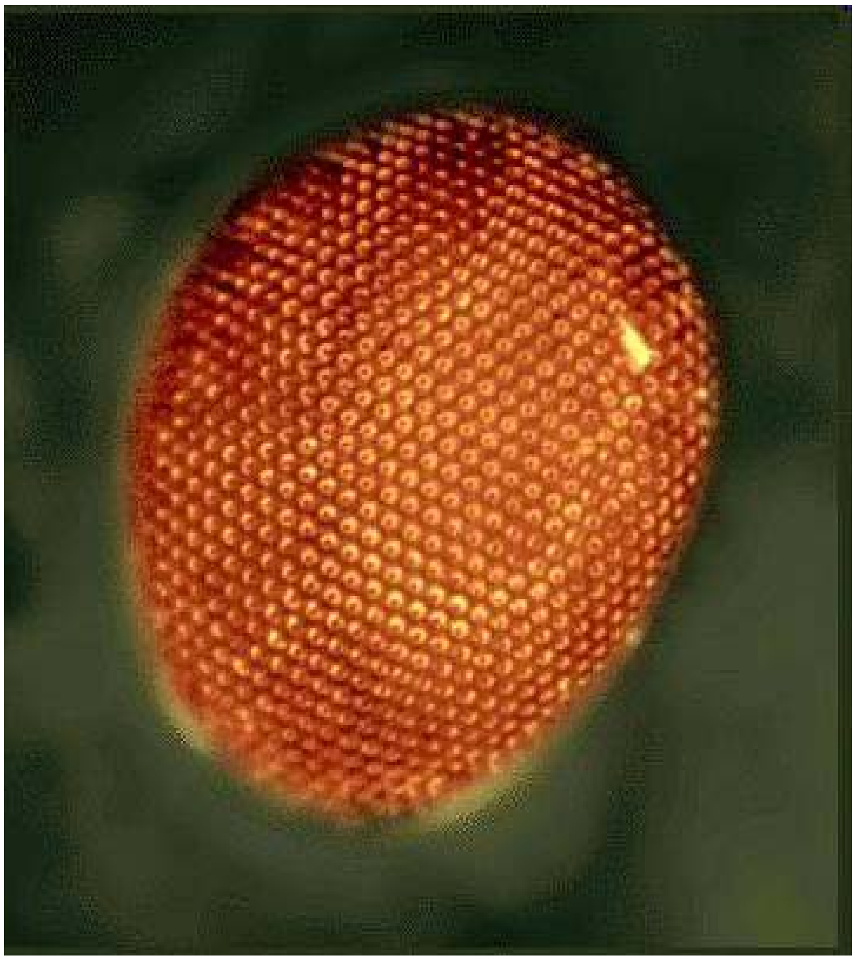
source: CERN http://microcosm.web.cern.ch/microcosm

Understanding Size

- 1 centimetre

source: CERN http://microcosm.web.cern.ch/microcosm

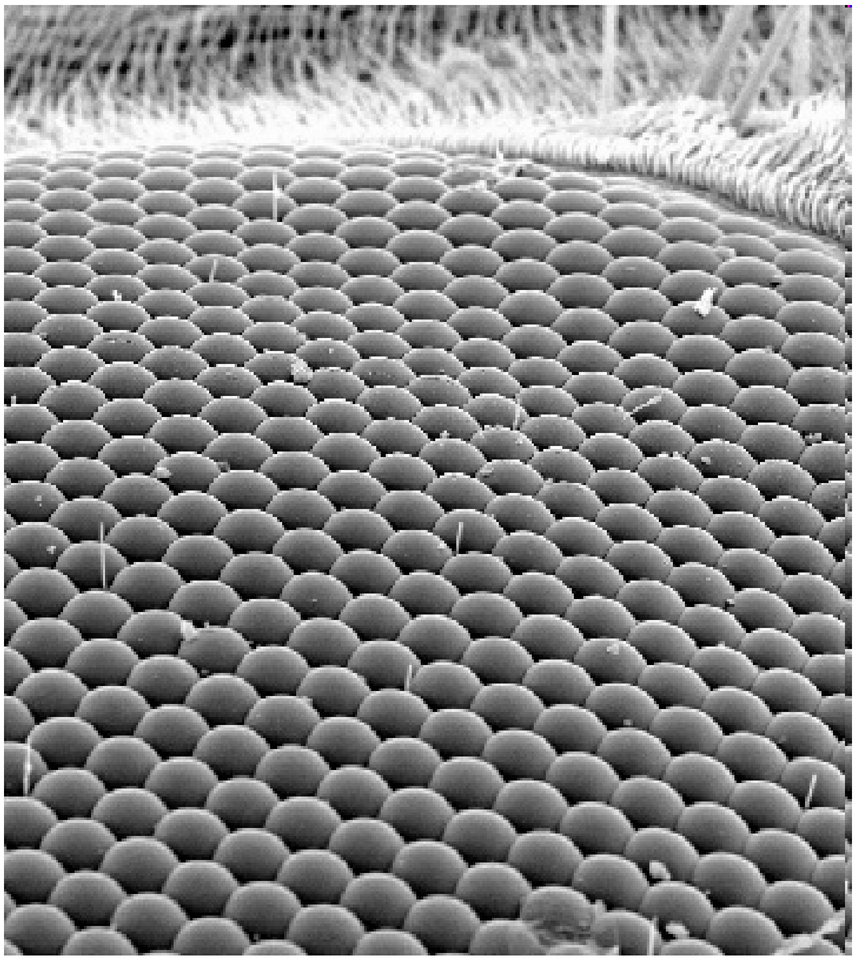
Understanding Size



- 100 micrometres

source: CERN http://microcosm.web.cern.ch/microcosm

Understanding Size



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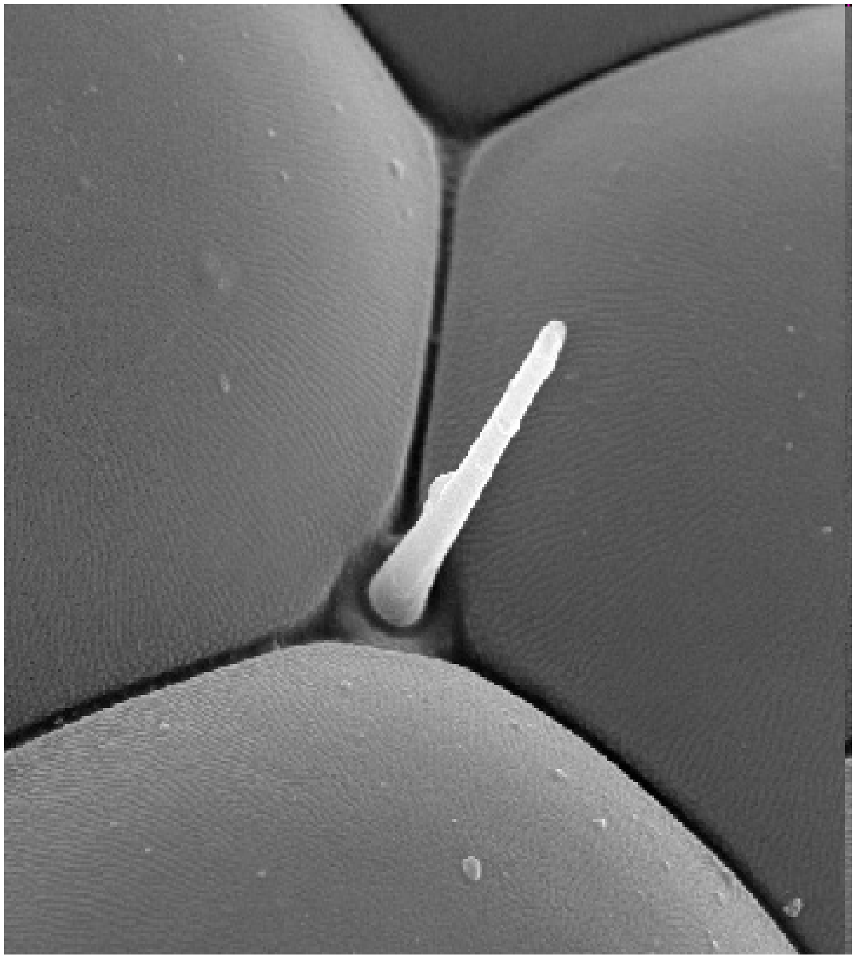
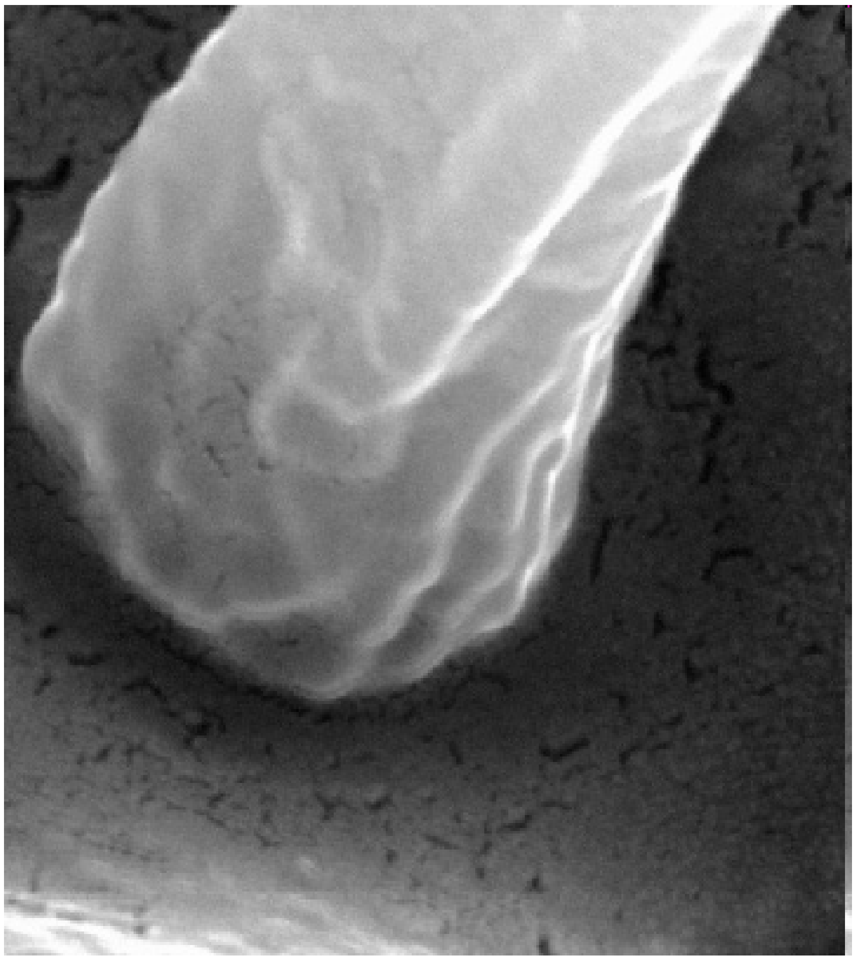
Understanding Size



- 1 micrometre

source: CERN http://microcosm.web.cern.ch/microcosm

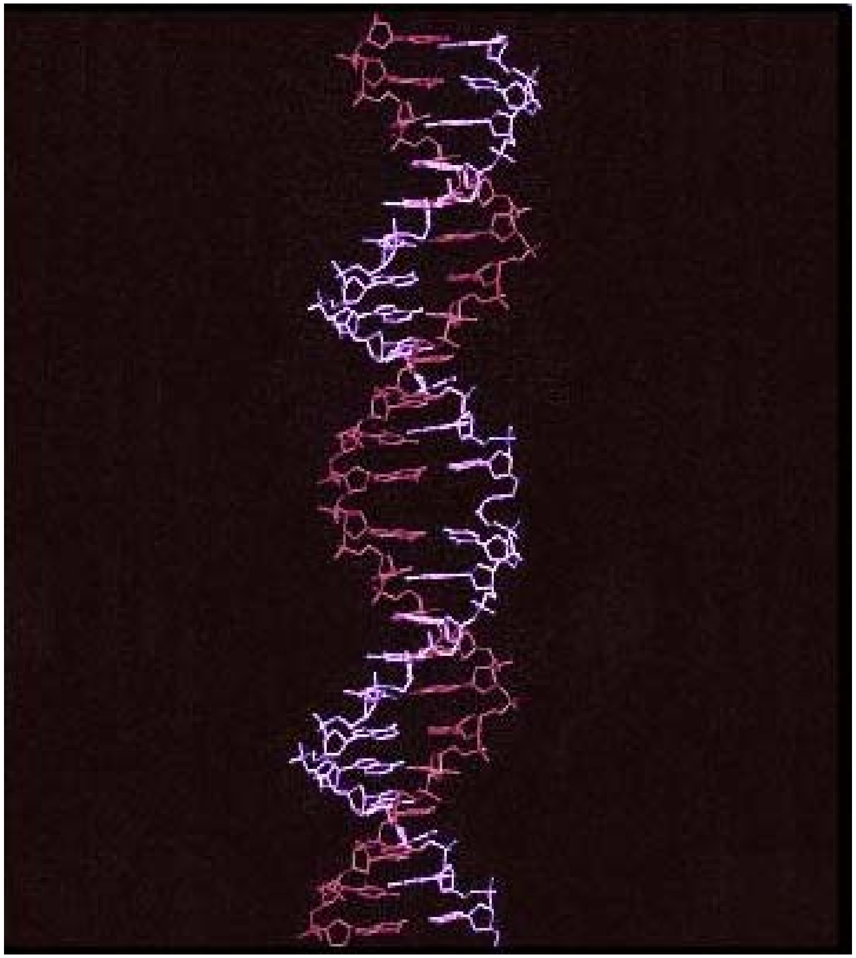
Understanding Size



- 100 nanometres

source: CERN http://microcosm.web.cern.ch/microcosm

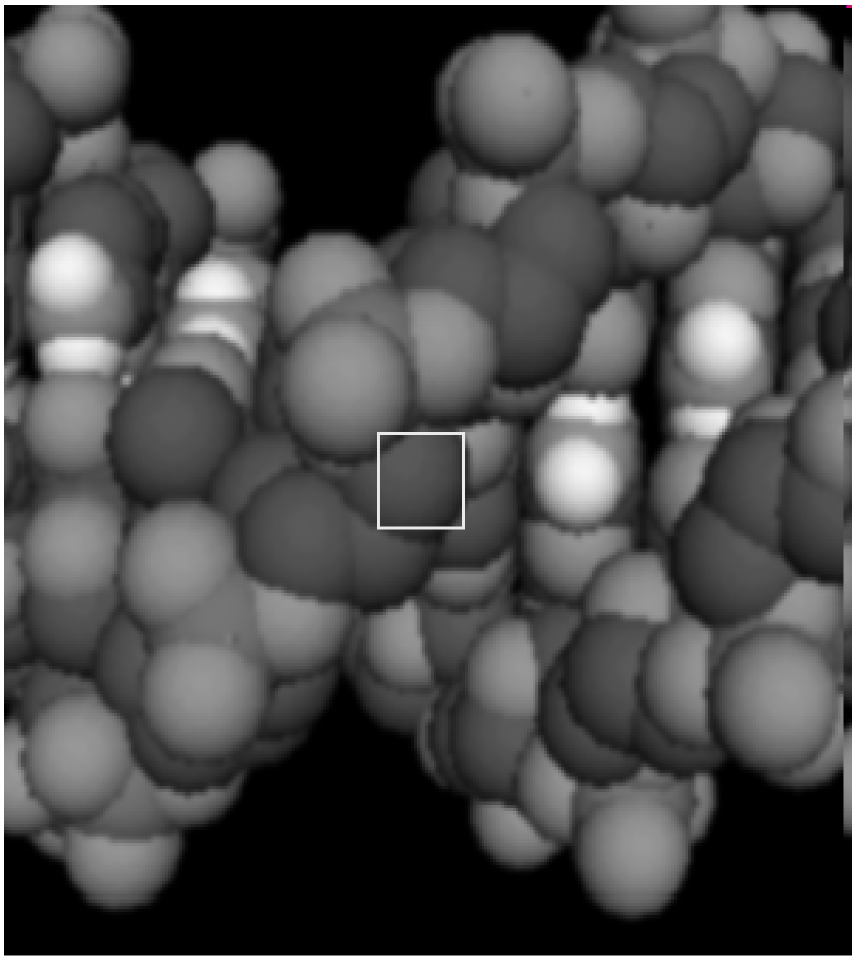
Understanding Size



- 10 nanometres

source: CERN http://microcosm.web.cern.ch/microcosm

Understanding Size

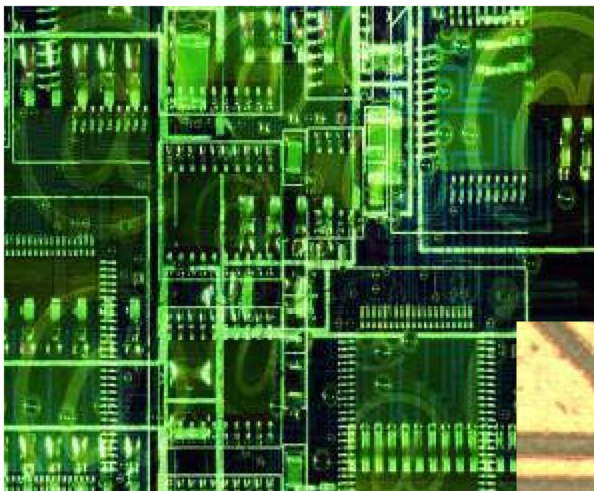


- 1 nanometre

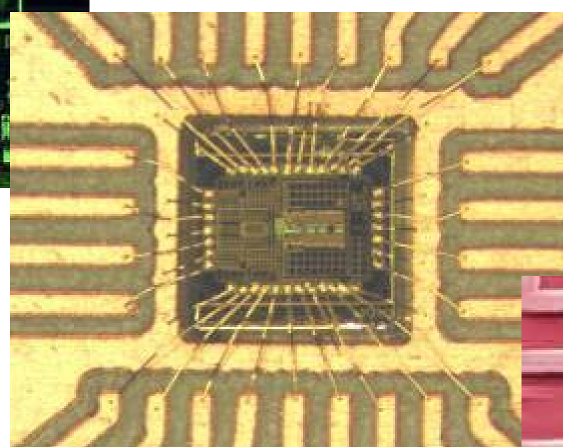
source: CERN http://microcosm.web.cern.ch/microcosm

Top-down

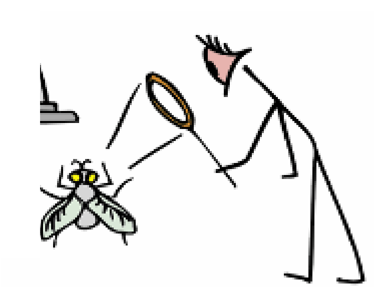
microelectronics



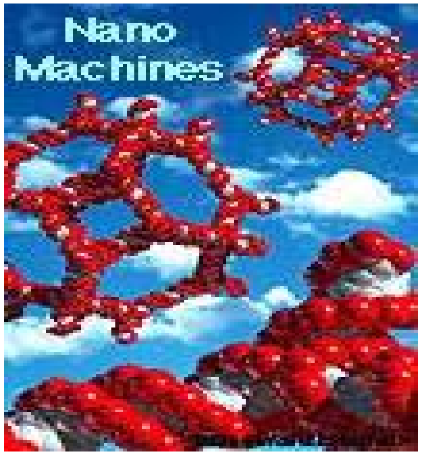
Nanotechnology is the next step after miniaturisation.

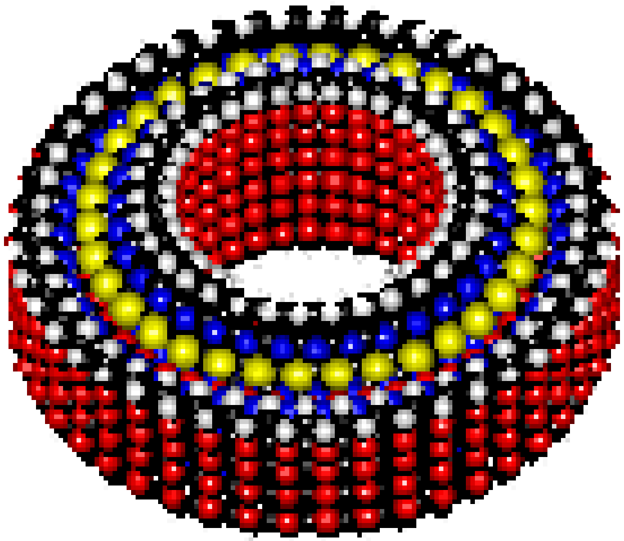


nanoelectronics



Bottom-up

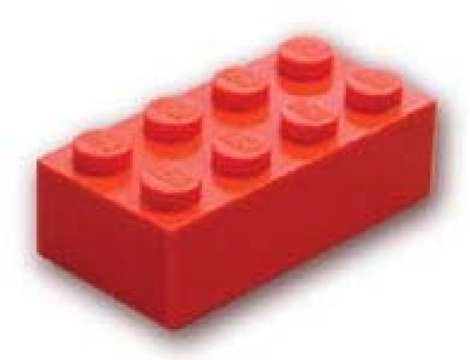




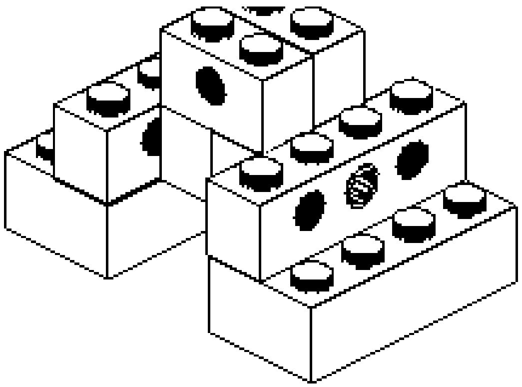
Arranged one way, atoms make up soil, air and water. Arranged another way they make up strawberries or smoke.

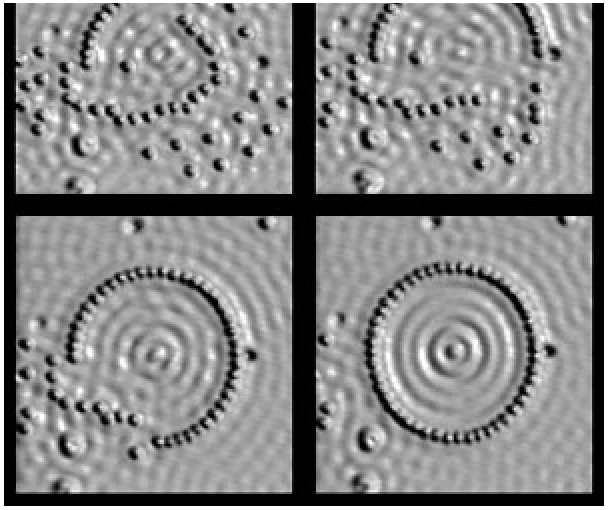
Ultimate Nanotechnology would be to build at the level of one atom at a time and to be able to do so with perfection.

Nature's Toy box.



ATOMIC LEGO
Molecular assembly is like a Lego set of 90 atoms that we can use to build anything from the bottom up! You just use every atom that you want. All of the elements in the periodic table can be mixed and matched,

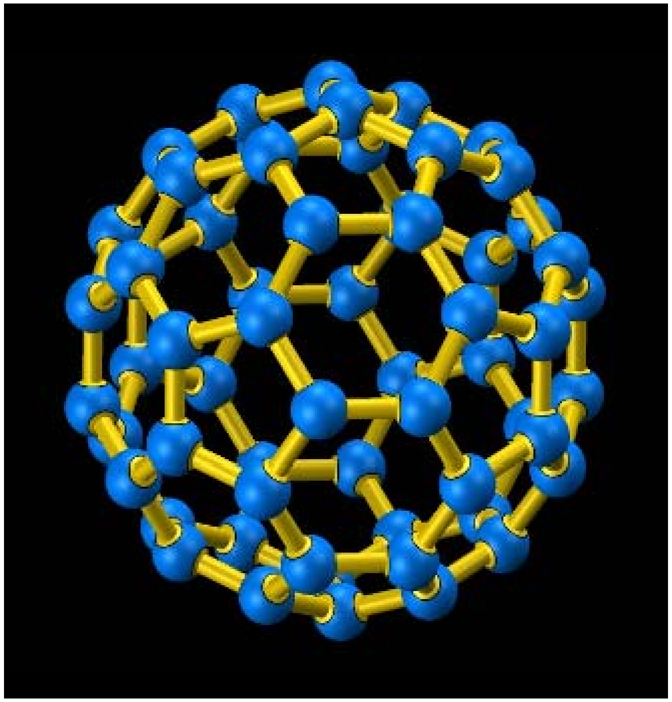


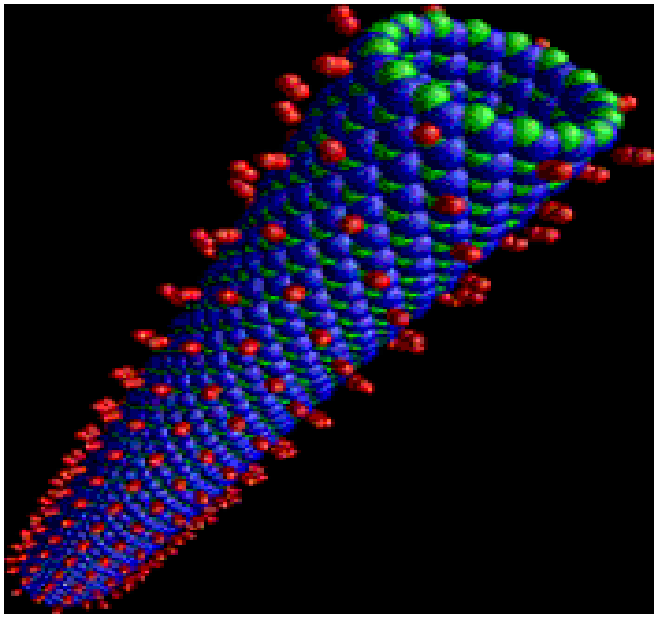


Nanoscience would probably be boring if small things were just like big things.

But they aren't. Pencil lead, for example takes on all sorts of shapes if kept from becoming a solid.

When carbon is a pure solid it is found as graphite or diamond. On the nano scale. Carbon takes on very different structures.



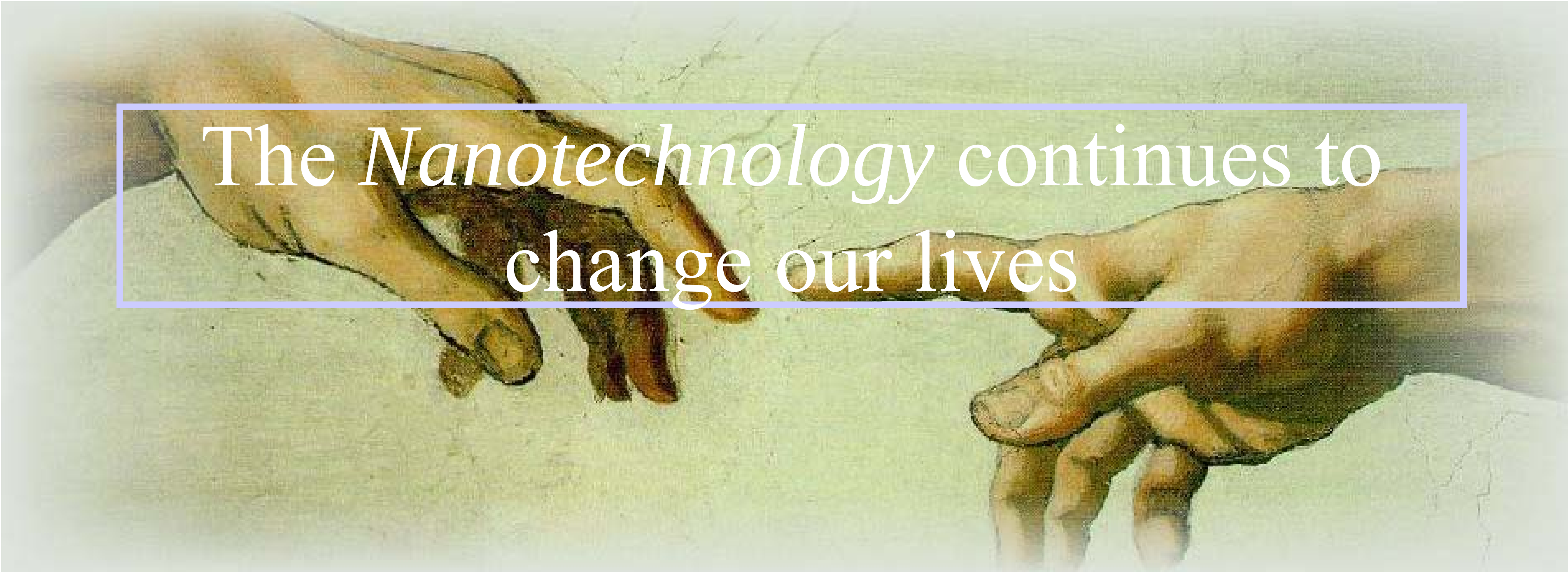


Size Matters

- It's not just how big you are
- It's what you can do with it

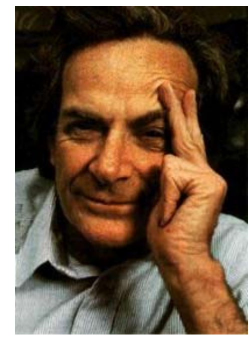
Early microscopes

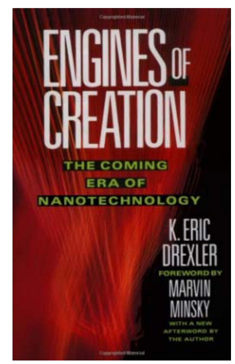
The *Nanotechnology* continues to change our lives

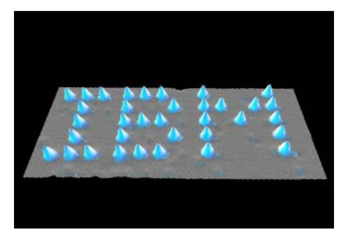


History of Nanotechnology

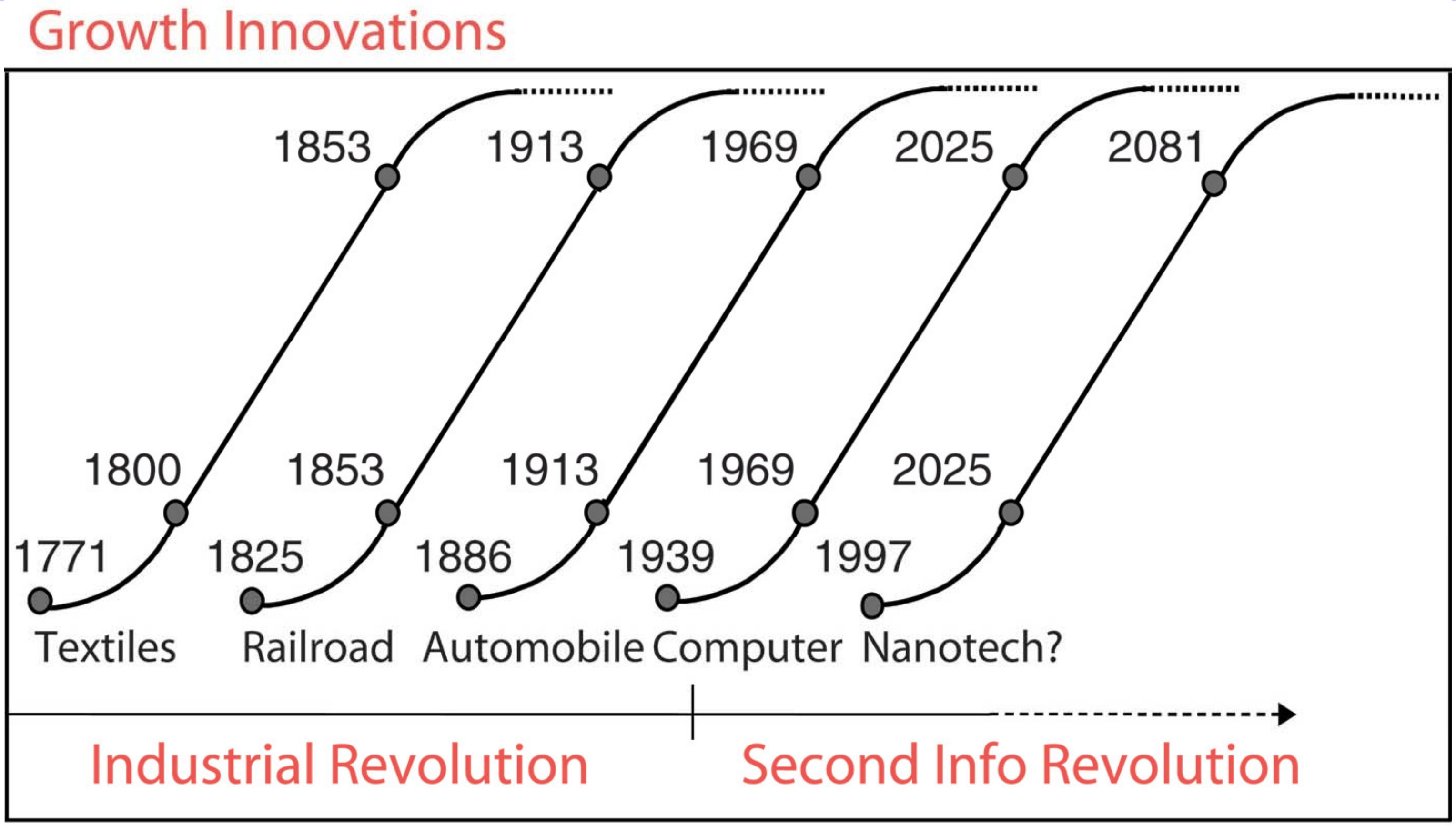
- **~ 2000 Years Ago** – Sulfide nanocrystals used by Greeks and Romans to dye hair
- **~ 1000 Years Ago (Middle Ages)** – Gold nanoparticles of different sizes used to produce different colors in stained glass windows
- **1959** – "There is plenty of room at the bottom" by R. Feynman
- **1974** – "Nanotechnology" - Taniguchi uses the term nanotechnology for the first time
- **1981** – IBM develops Scanning Tunneling Microscope
- **1985** – "Buckyball" - Scientists at Rice University and University of Sussex discover C_{60}
- **1986** – "Engines of Creation" - First book on nanotechnology by K. Eric Drexler. Atomic Force Microscope invented by Binnig, Quate and Gerbe
- **1989** – IBM logo made with individual atoms
- **1991** – Carbon nanotube discovered by S. Iijima
- **1999** – "Nanomedicine" – 1st nanomedicine book by R. Freitas
- **2000** – "National Nanotechnology Initiative" launched





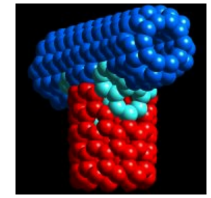


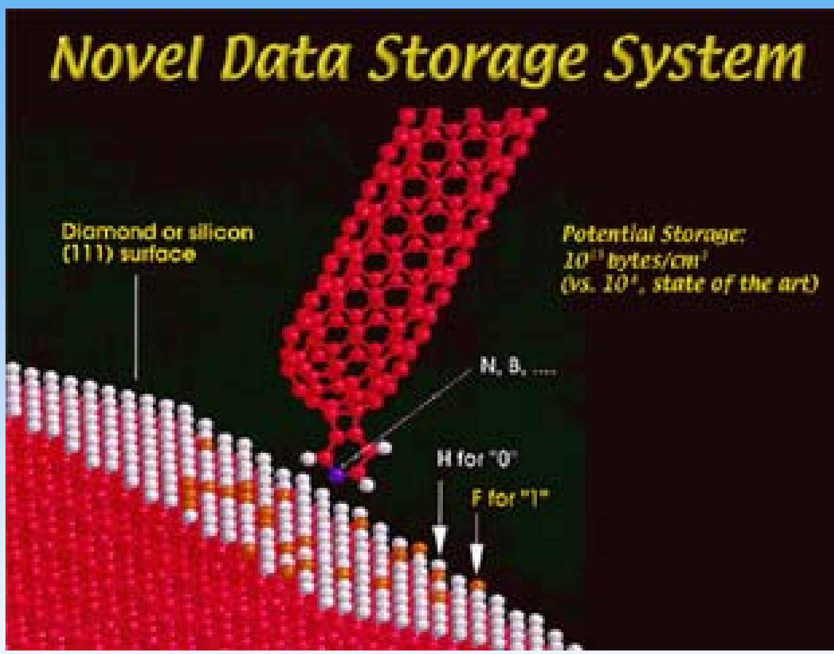
Nanotechnology Growth



Sources: Norman Poire, Merrill Lynch

Impact of Nanotechnology





- Computing and Data Storage
- Materials and Manufacturing
- Health and Medicine
- Energy and Environment
- Transportation
- National Security
- Space exploration

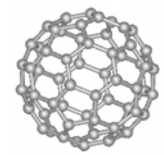
What is Nanoscale

ww.mathworks.com

12,756 Km

22 cm

Fullerenes C_{60}



0.7 nm

www.physics.ucr.edu

1.27 × 107 m **0.22 m** **0.7 × 10-9 m**

10 millions times smaller

1 billion times smaller

Nanoscale Size Effect

- Realization of miniaturized devices and systems while providing more functionality
- Attainment of high surface area to volume ratio
- Manifestation of novel phenomena and properties, including changes in:
  - Physical Properties (e.g. melting point)
  - Chemical Properties (e.g. reactivity)
  - Electrical Properties (e.g. conductivity)
  - Mechanical Properties (e.g. strength)
  - Optical Properties (e.g. light emission)

Nanotechnology Applications

Information Technology

- Smaller, faster, more energy efficient and powerful computing and other IT-based systems

Energy

- More efficient and cost effective technologies for energy production
  - Solar cells
  - Fuel cells
  - Batteries
  - Bio fuels

Medicine

- Cancer treatment
- Bone treatment
- Drug delivery
- Appetite control
- Drug development
- Medical tools
- Diagnostic tests
- Imaging

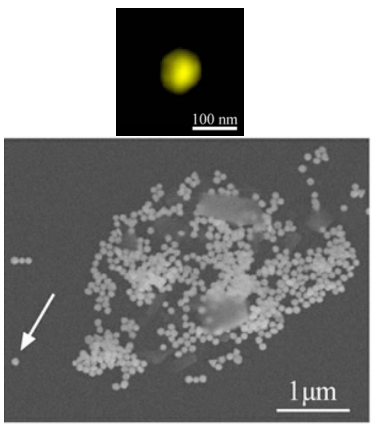
Consumer Goods

- Foods and beverages
  - Advanced packaging materials, sensors, and lab-on-chips for food quality testing
- Appliances and textiles
  - Stain proof, water proof and wrinkle free textiles
- Household and cosmetics
  - Self-cleaning and scratch free products, paints, and better cosmetics

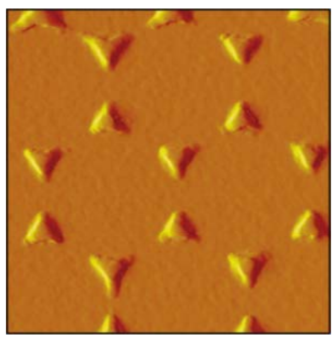
Nanoscale Materials

Nanoscale materials have feature size less than 100 nm – utilized in nanoscale structures, devices and systems

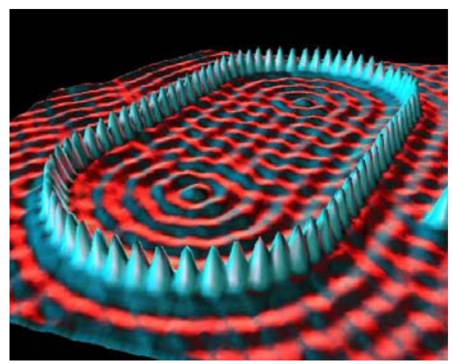
Nanoparticles and Structures



Gold nanoparticles
– TU Dresden/ESRF, 2008



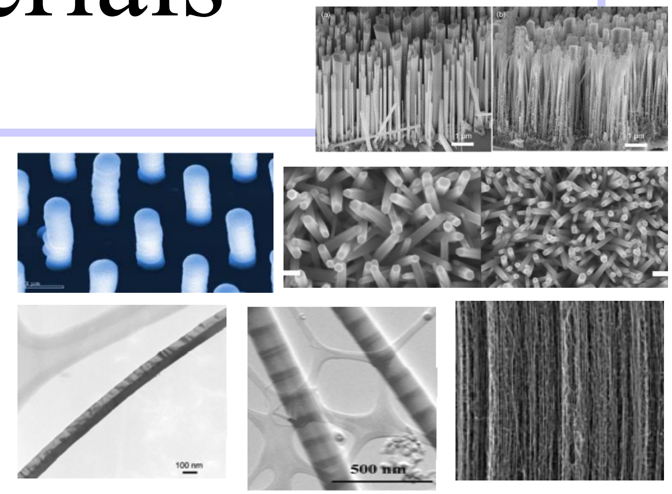
Silver nanoparticles *– Northwestern Univ., 2002*



A stadium shaped “quantum corral” made by positioning iron atoms on a copper surface *– IBM Corp., 1993.*

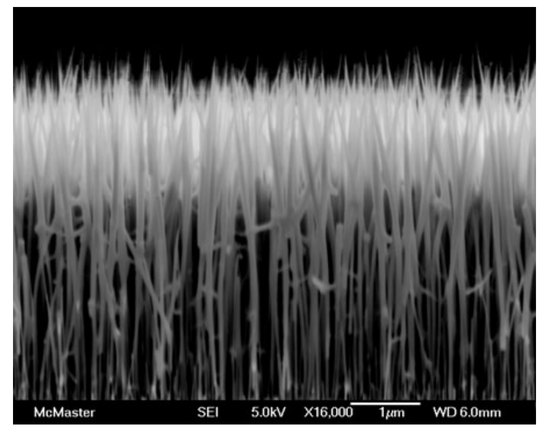
A 3-dimensional nanostructure grown by controlled nucleation of Silicon-carbide nanowires on Gallium catalyst particles
– Univ. of Cambridge, 2007

Nanoscale Materials



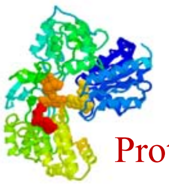
Nanowires and Nanotubes

- Lateral dimension: 1 – 100 nm
- Nanowires and nanotubes exhibit novel physical, electronic and optical properties due to
  - Two dimensional quantum confinement
  - Structural one dimensionality
  - High surface to volume ratio
- Potential application in wide range of nanodevices and systems
  - Nanoscale sensors and actuators
  - Photovoltaic devices – solar cells
  - Transistors, diodes and LASERs



Nanowire Solar Cell: The nanowires create a surface that is able to absorb more sunlight than a flat surface – *McMaster Univ., 2008*

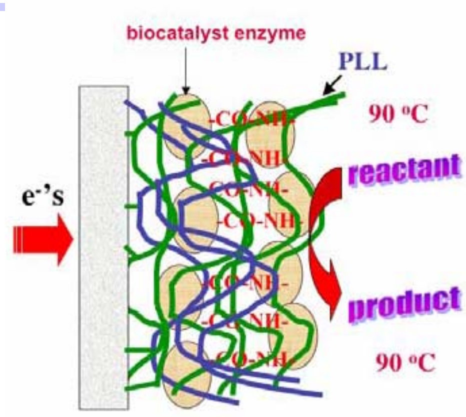
Nanoscale Materials



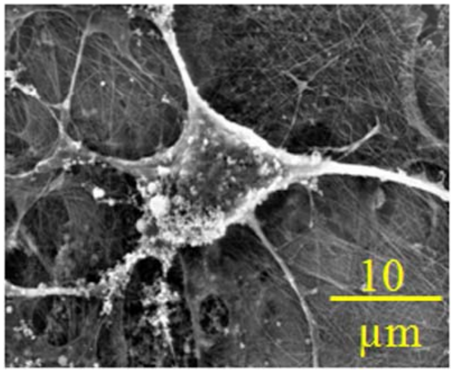
Protein

<u>Bionanomaterials</u>

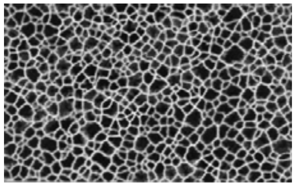
1. Biological materials utilized in nanotechnology
   - Proteins, enzymes, DNA, RNA, peptides
2. Synthetic nanomaterials utilized in biomedical applications
   - Polymers, porous silicon, carbon nan-otubes
   - Quantum Dots (range from 4~5 nm) (will be discussed in Biological application)



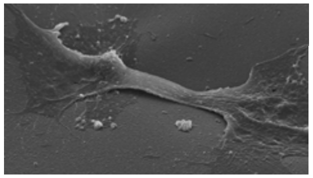
Cross-linked enzymes used as catalyst *– Univ. of Connecticut, Storrs , 2007*



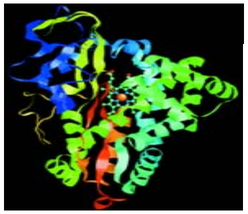
Bone cell on porous silicon – *Univ. of Rochester, 2007*



Porous silicon (PSi)

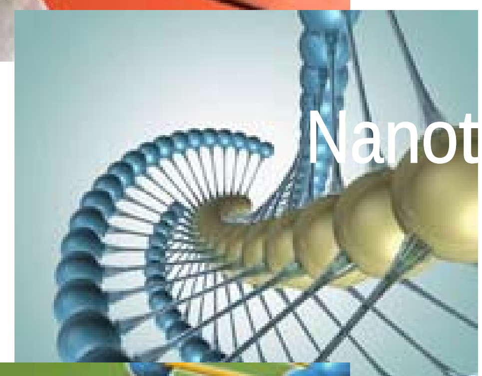


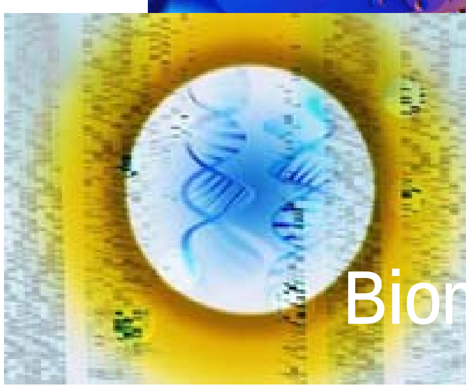
Human cell on PSi



Enzymes are used as oxidation catalysts

Technology is an accelerator





…so what's it going to take?

It's time to bust out

…and maximize use of all tools available to us to assume new and expanded roles

Systematic of Making Things Smaller-Pre-Quantum

1. Mechanical Frequencies increase in <u>Small System</u>

2. Thermal Time Constants and Temperature Differences *Decrease*

3. Viscous Forces Becomes Dominant for <u>Small Particles</u> in Fluid Media

4. Fractional Forces can <u>Disappear</u> in Symmetric <u>Molecular Scale</u> Systems

Thermal Time Constants and Temperature Differences *Decrease*

heat energy flow:
dq/dt: kAT/L

dq/dt : CVdT/dt

We can write:

$dT/T : -(kA/LCV)dt \longrightarrow T=T(0)\exp(-t/\tau_{th})$

$\tau_{th} : LCV/kA$

Thermal time constant decrease as the size is reduced.

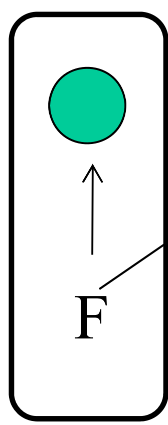
Viscous Forces Becomes Dominant for Small Particles in Fluid Media

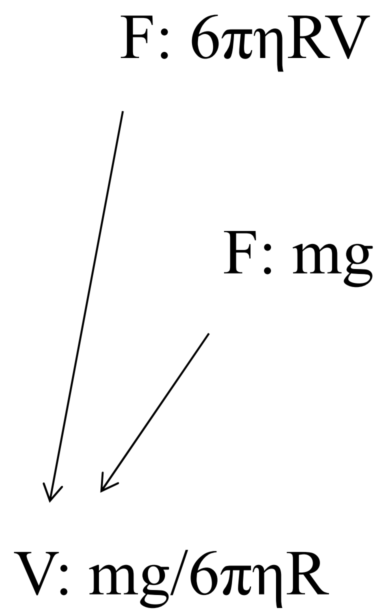
The force needed to move a sphere of radius R and velocity V

$F: 6\pi\eta RV$

Stokes's Law

Viscosity Index of the medium





Falling particle of mass of m
under gravity

A particle of 10 um radius and density 2000 kg/m3 falls
In air at V of 23 mm/s

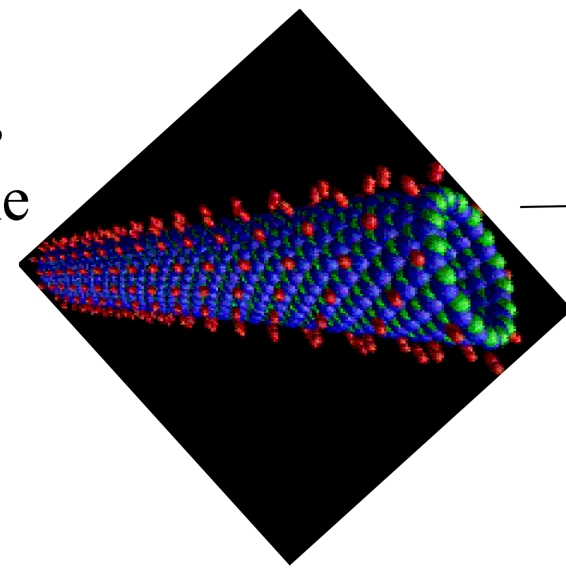
A particle of 15 nm and density 500 kg/m3 fall in air
At V of 13 nm/s.

Fractional Forces can Disappear in Symmetric Molecular Scale Systems

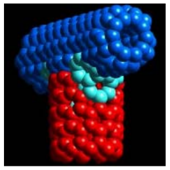
Viscous and Fractional forces are nearly "0" in nano-scale system.

Carbon nano-tubes:
They are rolled sheets of Graphite

There are no molecules at all between the layers of Graphite and the same In Nano-tubes.



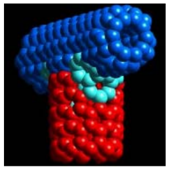
The medium between the very close space moving elements is vacuum

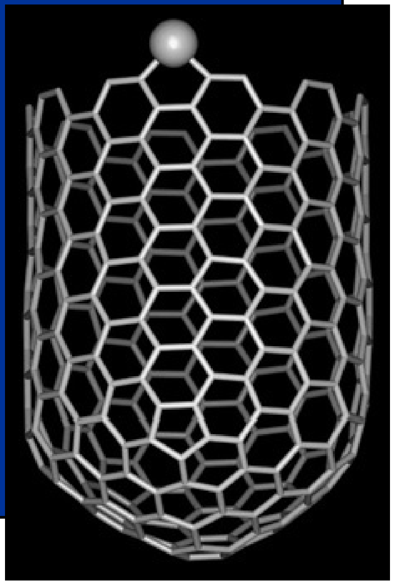


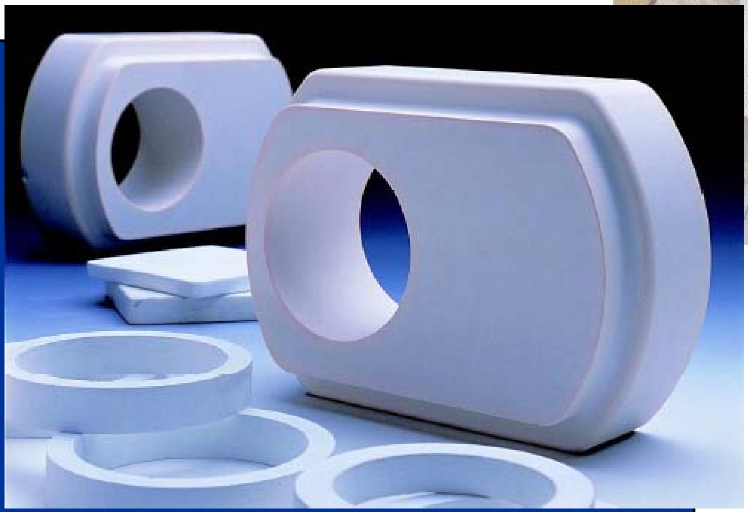
- Ability to synthesize nanoscale building blocks with control on size, composition etc. → further assembling into larger structures with designed properties will revolutionize materials manufacturing
  - Manufacturing metals, ceramics, polymers, etc. at exact shapes without machining
  - Lighter, stronger and programmable materials
  - Lower failure rates and reduced life-cycle costs
  - Bio-inspired materials
  - Multifunctional, adaptive materials
  - Self-healing materials

- Challenges ahead
  - Synthesis, large scale processing
  - Making useful, viable composites
  - Multiscale models with predictive capability
  - Analytical instrumentation

- Carbon Nanotubes
- Nanostructured Polymers
- Optical fiber preforms through sol-gel processing of nanoparticles
- Nanoparticles in imaging systems
- Nanostructured coatings
- Ceramic nanoparticles for netshapes



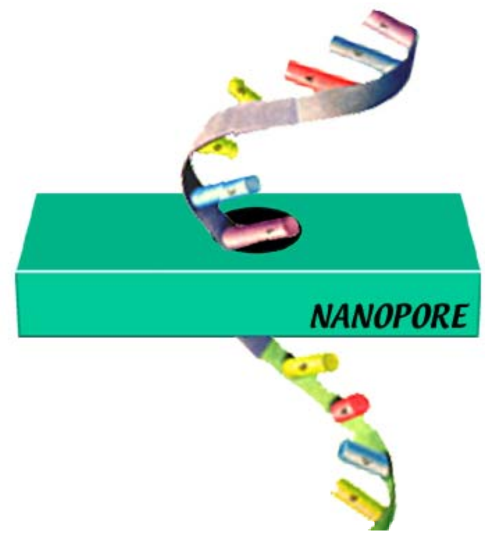


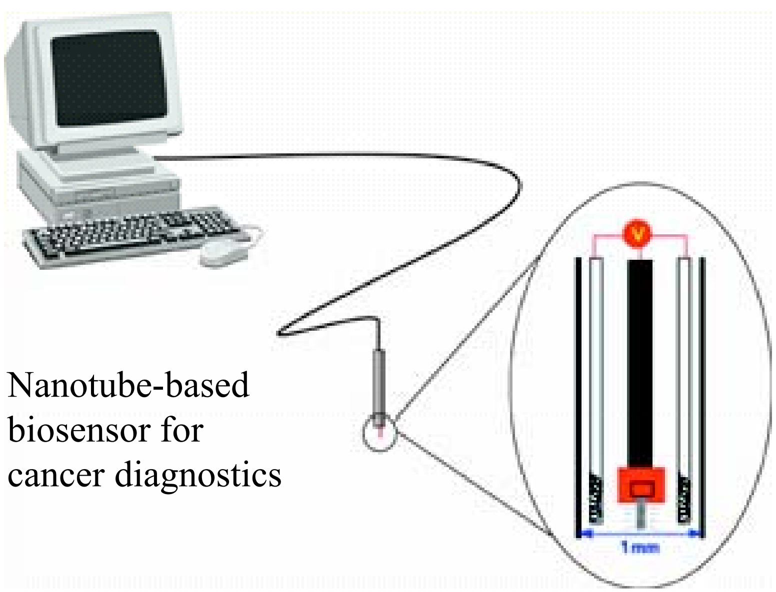


Sensors for the Automotive Industry

- Automotive electronics to grow to $30 Billion by 2005
- Pressure to keep cost of devices low is enormous
- Sensors in use now include monitoring wheel speed, pedal positions, oxygen sensors to check exhaust, accelerometers to detect sudden stops, pressure and temperature sensors
- Future systems
  - Collision avoidance
  - Break-by-wire, steer-by-wire systems (slowing the car and guiding electrically instead of manually)
  - Sensor systems when new fuel sources become common
- Challenges
  - High temperature survival of sensors
  - Withstanding mechanical shock, hostile environment
  - Conditions: sever swing in T; variable humidity; road salt; noxious gases; f ~ 10 g; ~ 10 year life-time
- MEMS made it in the airbag. But the car interior is a benign environment. Will MEMS work elsewhere in the car?

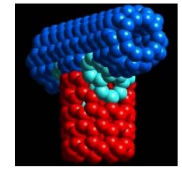
- Expanding ability to characterize genetic makeup will revolutionize the specificity of diagnostics and therapeutics
  - Nanodevices can make gene sequencing more efficient
- Effective and less expensive health care using remote and in-vivo devices



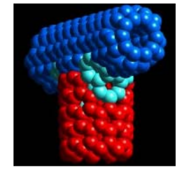


Nanotube-based biosensor for cancer diagnostics

- New formulations and routes for drug delivery, optimal drug usage
- More durable, rejection-resistant artificial tissues and organs
- Sensors for early detection and prevention



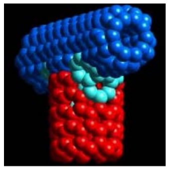
- Nanotechnology has the potential to impact energy efficiency, storage and production
- Materials of construction sensing changing conditions and in response altering their inner structure
- Monitoring and remediation of environmental problems; curbing emissions; development of environmental friendly processing technologies
- Some recent examples:
  - Crystalline materials as catalyst support, $300 b/year
  - Ordered mesoporous material by Mobil oil to remove ultrafine contaminants
  - Nano-particle reinforced polymers to replace metals in automobiles to reduce gasoline consumption



Some critical defense applications of nanotechnology include

- Continued information dominance: collection, transmission, and protection
- High performance, high strength, light weight military platforms while reducing failure rates and life cycle costs
- Chemical/biological/nuclear sensors; homeland protection
- Nano and micromechanical devices for control of nuclear and other defense systems
- Virtual reality systems based on nanoelectronics for effective training
- Increased use of automation and robotics

Summary of Issues and Challenges



- While there is an amazing amount of research activities across the world, only a limited number of viable ideas with commercial potential.
- Lots of ‘cool technology,’ but will they lead to ‘hot products’?
- In semiconductor, photonics and other recent technologies, most new start-ups were by people who left other large and small companies, those who knew what the potential customer wanted and had some expertise in manufacturing, quality control, reliability, etc…. This is not the case with nano startups; most of them are started by academics.
- Strong outside management and knowledgeable board (with people from industry) are critical to compensate for the ‘knowledge gap’ of the founder on ‘real world’issues.
- Recognize the nano-micro-macro hierarchy.
- So few engineers!
- Navigating the IP situation, during due-diligence process, is not easy as various groups across the world are working on same problems and pertinent information on IP information, priority dates etc. are not available.

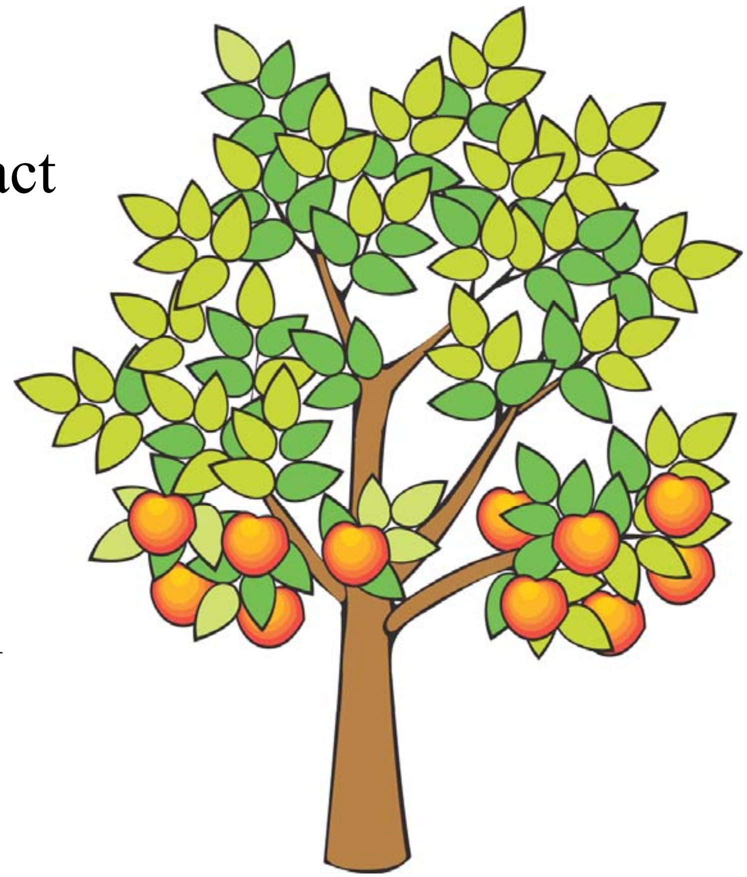
People do not buy technology, they buy products

Low Hanging Fruits

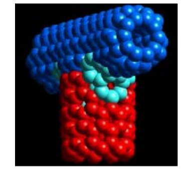
- Some opportunities are clearly very long term; one example is nanotube or molecule or DNA based computing; several others also in the ~ 15 year range.

- Nevertheless, even these appear to attract VC funding
  - Early access to IP in key future technologies?

- Rationale given is the attraction of ‘low-hanging fruits’ for the nearer term
  - Make sure they are edible!



Assessment of Opportunities

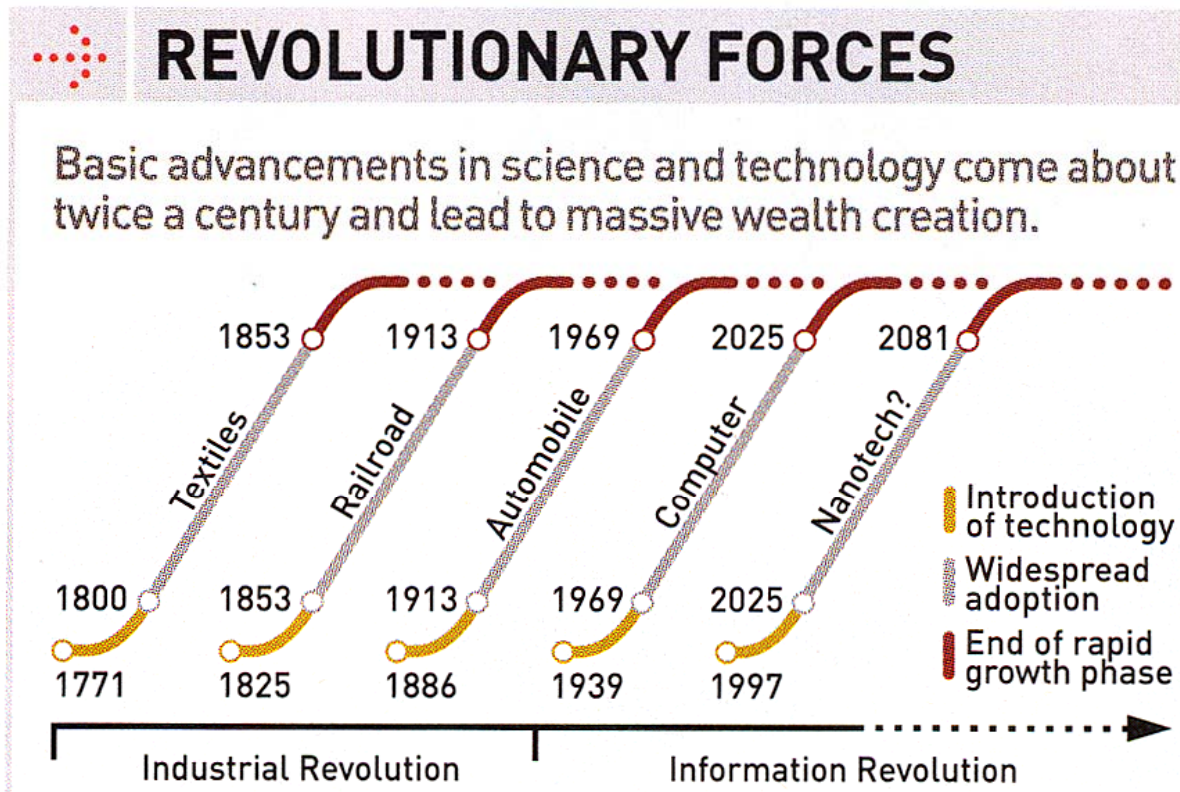


- Lots of nanoscience, little nanotechnology
- Short term (< 5 years)
  - CNT based displays
  - Nanoparticles
    - * Automotive industry (body moldings, timing belts, engine covers…)
    - * Packaging industry
  - CNT-based probes in semiconductor metrology
  - Coatings
  - Tools
  - Catalysts (extension of existing market)

Assessment of Opportunities (Cont.)

- Medium term (5-15 years)
  - Memory devices
  - Fuel cells, batteries
  - Biosensors (CNT, molecular, qD based)
  - Advances in gene sequencing
  - Advances in lighting
- Long term (> 15 years)
  - Nanoelectronics (CNT)
  - Molecular electronics
  - Routine use of new composites in Aerospace, automotive (risk-averse industries)

Revolutionary Technology Waves

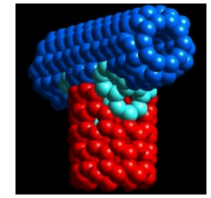


SOURCE: Norman Poire, Merrill Lynch

Red Herring, May 2002

Commonality: Railroad, auto, computer, nanotech all are enabling technologies

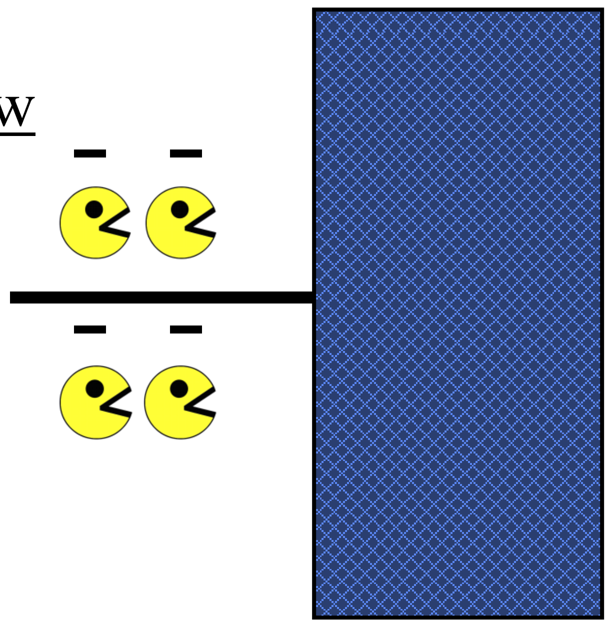
Mom, Are we There Yet?



- With previous technology waves, 28 years for maturing and gaining acceptance was no big deal.
- But, in the era of internet, 24/7 cable channels and mind-boggling number of trade magazines - all with insatiable appetite for news - evolution of this wave is different…
- Given the long period for starting - sustenance - maturation, some early disruption is unavoidable, but not much to worry about

<u>Barrier to electron flow</u> into SiO_2

- High bandgap, 9eV
- Thick oxide

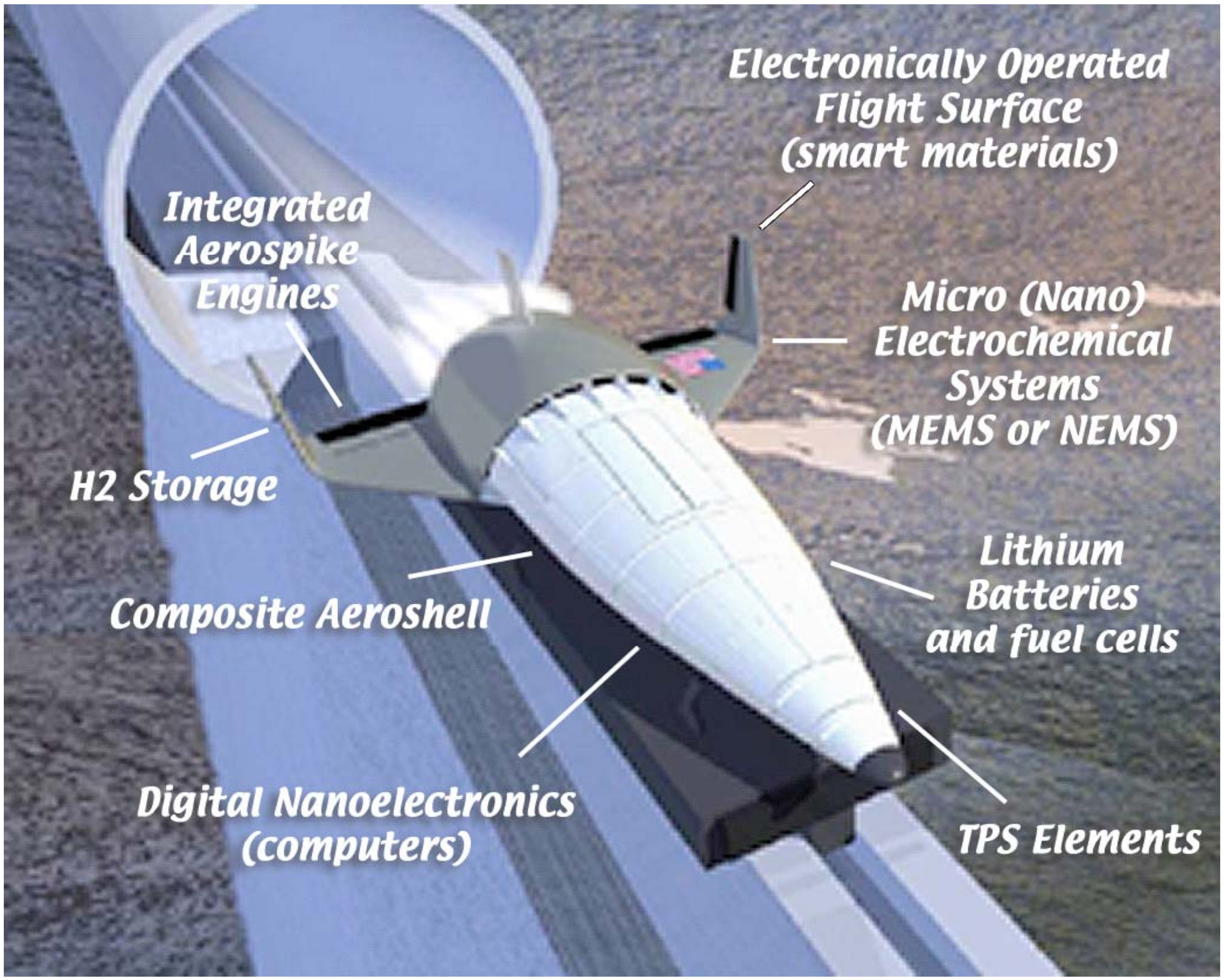


<u>Barrier to nanotech entry</u>

- Higher education (PhD)
- Big capital

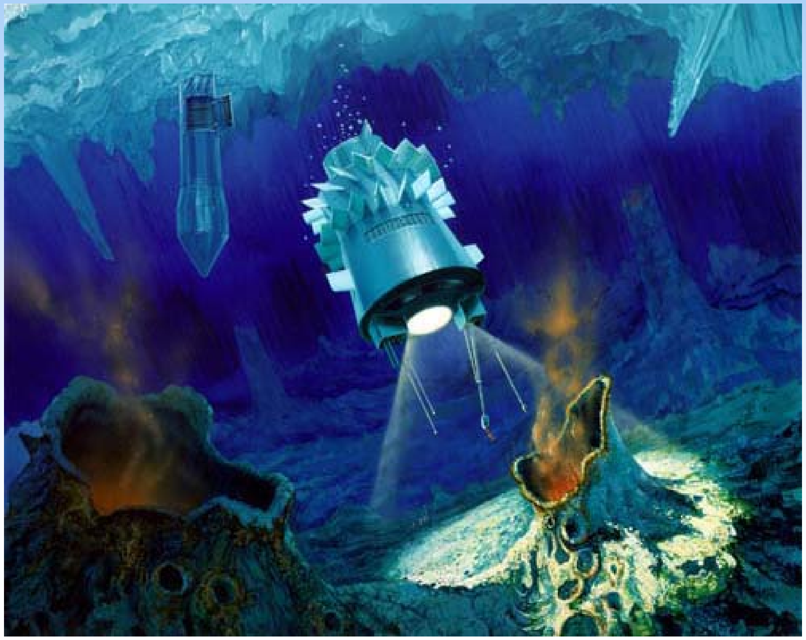
- Academia will play key role in development of nanoscience and technology
  - Promote interdisciplinary work involving multiple departments
  - Develop new educational programs
  - Technology transfer to industry
- Government Labs will conduct mission oriented nanotechnology research
  - Provide large scale facilities and infrastructure for nanotechnology research
  - Technology transfer to industry
- Government Funding Agencies will provide research funding to academia, small business, and industry through the NNI and other programs (SBIR, STIR, ATP…)
- Industry will invest only when products are within 3-5 years
  - Maintain in-house research, sponsor precompetitive research
  - Sponsor technology start-ups and spin-offs
- Venture Capital Community will identify ideas with market potential and help to launch start-ups
- Professional societies should establish interdisciplinary forum for exchange of information; reach out to international community; offer continuing education courses

Just one Material, so much Potential

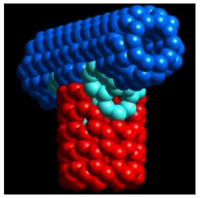


- Advanced miniaturization, a key thrust area to enable new science and exploration missions
  - Ultrasmall sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume and power consumption are needed
- Revolutions in electronics and computing will allow reconfigurable, autonomous, “thinking” spacecraft
- Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures
  - Networks of ultrasmall probes on planetary surfaces
  - Micro-rovers that drive, hop, fly, and burrow
  - Collection of microspacecraft making a variety of measurements

Europa Submarine



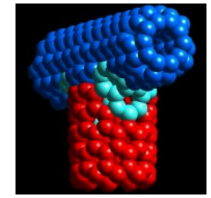
Nanotechnology Research Focus



* Carbon Nanotubes
  - Growth (CVD, PECVD)
  - Characterization
  - AFM tips
    - Metrology
    - Imaging of Mars Analog
    - Imaging Bio samples
  - Electrode development
  - Biosensor (cancer diagnostics)
  - Chemical sensor
  - Logic Circuits
  - Chemical functionalization
  - Gas Absorption
  - Device Fabrication
* Molecular Electronics
  - Synthesis of organic molecules
  - Characterization
  - Device fabrication
* Inorganic Nanowires
* Protein Nanotubes
  - Synthesis
  - Purification
  - Application Development
* Genomics
  - Nanopores in gene sequencing
  - Genechips development
* Computational Nanotechnology
  - CNT - Mechanical, thermal properties
  - CNT - Electronic properties
  - CNT based devices: physics, design
  - CNT based composites, BN nanotubes
  - CNT based sensors
  - DNA transport
  - Transport in nanopores
  - Nanowires: transport, thermoelectric effect
  - Transport: molecular electronics
  - Protein nanotube chemistry
* Quantum Computing
* Computational Quantum Electronics
  - Noneq. Green's Function based Device Simulator
* Computational Optoelectronics
* Computational Process Modeling

Ames Research Center

Summary



- There are incredible opportunities for nanotechnology to impact all aspects of the economic spectrum.
- It is very early in the game now. Jitters as well as hype are not uncommon at this stage.
- #1 on the wish-list: Need more engineers under the nano tent!
  - Nanoscience - discovery of novel ideas & concepts, lab demos
  - Nanotech - product, mfg., reliability, quality control
- # 2 on the wish-list: Some sanity in issuing patents
- Nano has no more ‘scary scenarios’ than any other technology since the stone ages.