PHYSICS FOR ENGINEERS

Course Code: PHY1701 Engineering Physics

Lecture : 3 per week L T P J C : 3 0 2 0 4

Theory

Mod 1: **Introduction to Modern Physics (6)**

Mod 2: **Applications of Quantum Physics (5)**

Mod 3: **Nanophysics (5)**

Mod 4: **Laser Principles and Engineering Applications (6)**

Mod 5: **Electromagnetic Theory and Applications (6)**

Mod 6: **Propagation of EM waves in Optical fibers (6)**

Mod 7: **Optoelectronic Devices & Applications of Optical fibers (6)**

Mod 8: **Special Theory of Relativity (5)**

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Module 3: **Nanophysics**

1. Introduction to Nano-materials.
2. Moore’s law.
3. Properties of Nano-materials.
4. Quantum confinement.
5. Quantum well, wire & dot.
6. Carbon Nano-tubes (CNT).
7. Applications of nanotechnology in industry.

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BOOKS:

The Essential Understandings of Nanoscience and Nanotechnology, J. Pradeep, Tata McGraw Hill, 2007

NANO

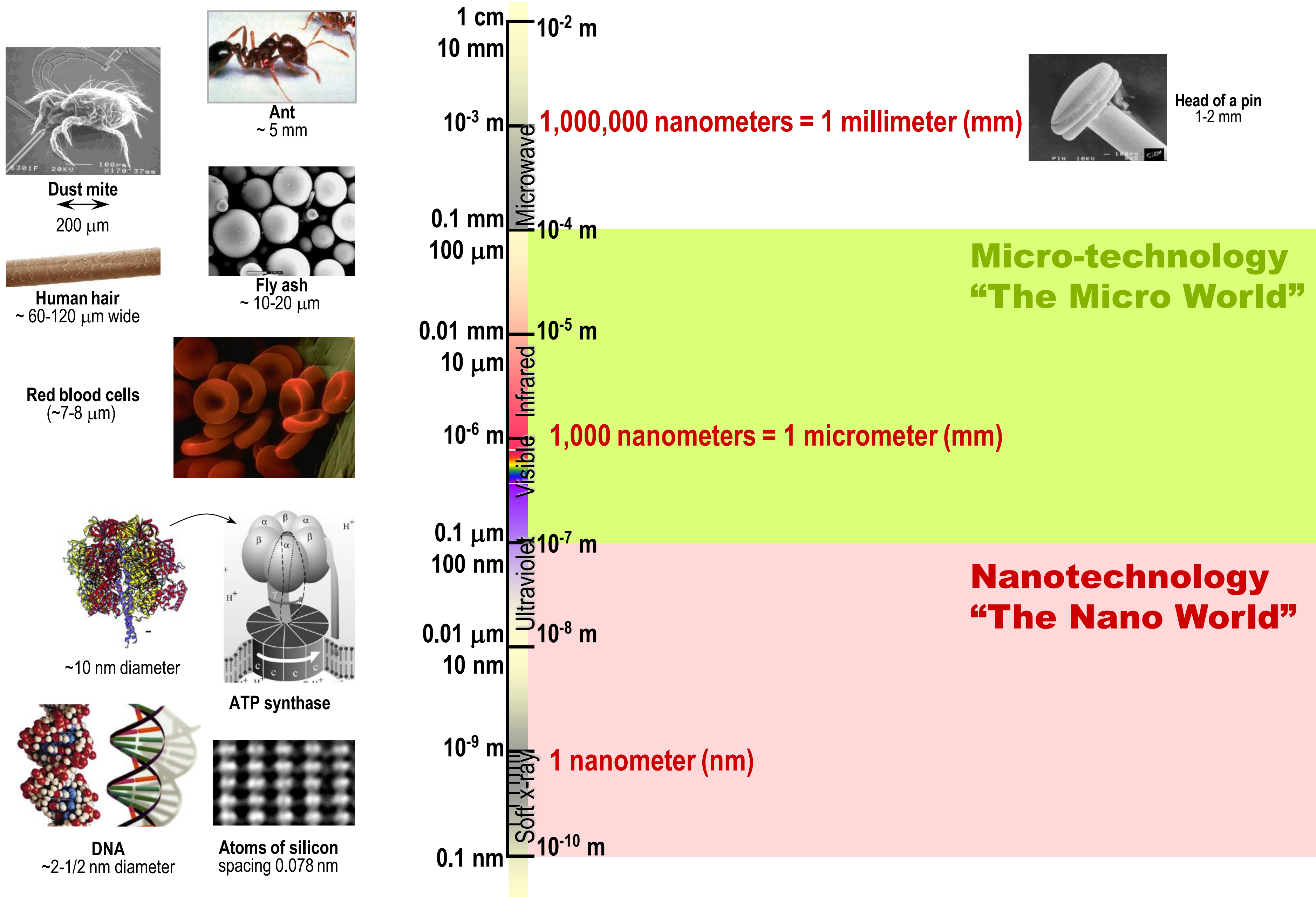
Nano

A prefix meaning 10^{-9} or one billionth

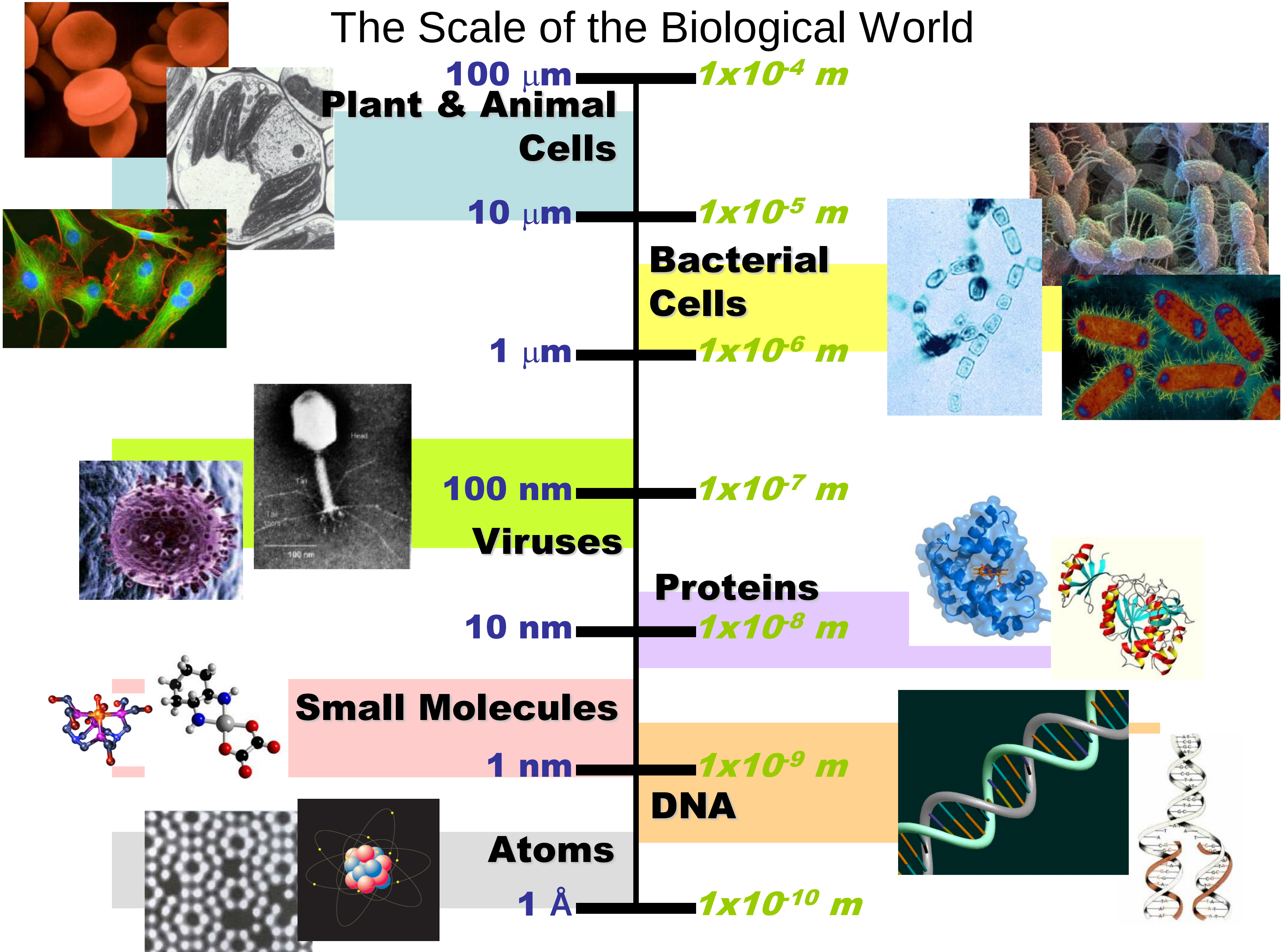
<u>Nanometer</u>

- One billionth (10^{-9}) of a meter
- Hydrogen atom 0.04 nm
- Proteins ~ 1-20 nm
- Feature size of computer chips 90 nm (in 2005)
- Diameter of human hair ~ 10 µm

The Scale of Things – Nanometers and More



The Scale of the Biological World



- Examples
  - Carbon Nanotubes
  - Proteins, DNA
  - Single electron transistors

- Not just size reduction but phenomena intrinsic to nanoscale
  - Size confinement
  - Dominance of interfacial phenomena
  - Quantum mechanics

- New behavior at nanoscale is not necessarily predictable from what we know at macroscales.

•Quantum size effects result in unique mechanical, electronic, photonic, and magnetic properties of nanoscale materials

•Chemical reactivity of nanoscale materials greatly different from more macroscopic form, e.g., gold

•Vastly increased surface area per unit mass, e.g., upwards of 1000 m^2 per gram

•New chemical forms of common chemical elements, e.g., fullerenes, nanotubes of carbon, titanium oxide, zinc oxide, other layered compounds

Atoms and molecules are generally less than a nm and we study them in chemistry. Condensed matter physics deals with solids with infinite array of bound atoms. Nanoscience deals with the in-between meso-world

- Quantum chemistry does not apply (although fundamental laws hold) and the systems are not large enough for classical laws of physics
- Size-dependent properties
- Surface to volume ratio
    - A 3 nm iron particle has 50% atoms on the surface
    - A 10 nm particle 20% on the surface
    - A 30 nm particle only 5% on the surface

1. **What novel quantum properties will be enabled by nanostructures (at room temp.)?**

2. How different from bulk behavior?

3. **What are the surface reconstructions and rearrangements of atoms in nanocrystals?**

4. Can carbon nanotubes of specified length and helicity be synthesized as pure species? Heterojunctions in 1-D?

5. **What new insights can we gain about polymer, biological…systems from the capability to examine single-molecule properties?**

6. How can one use parallel self-assembly techniques to control relative arrangements of nanoscale components according to predesigned sequence?

7. **Are there processes leading to economic preparation of nanostructures with control of size, shape… for applications?**

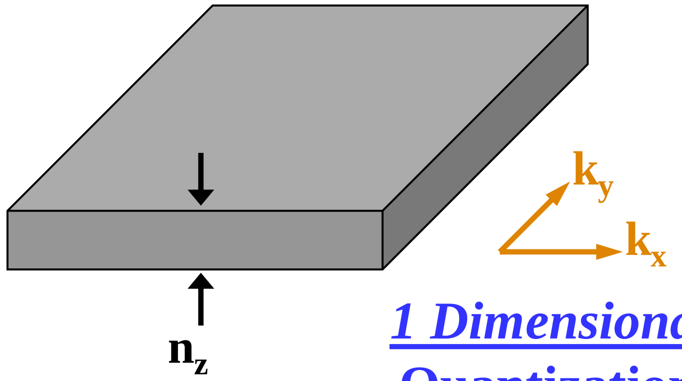
Quantum Confinement in Nanostructures: Overview

Electrons *Confined in 1 Direction*:

Quantum Wells (thin films):

⇒ **Electrons** can easily move in

***2 Dimensions*!**



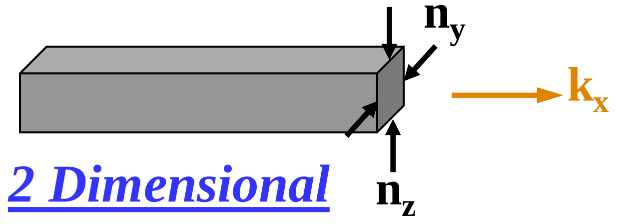
1 Dimensional
Quantization!

Electrons *Confined in 2 Directions*:

Quantum Wires:

⇒ **Electrons** can easily move in

***1 Dimension*!**



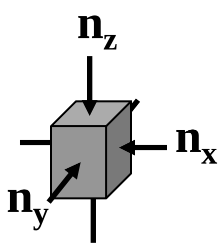
2 Dimensional
Quantization!

Electrons *Confined in 3 Directions*:

Quantum Dots:

⇒ **Electrons** can easily move in

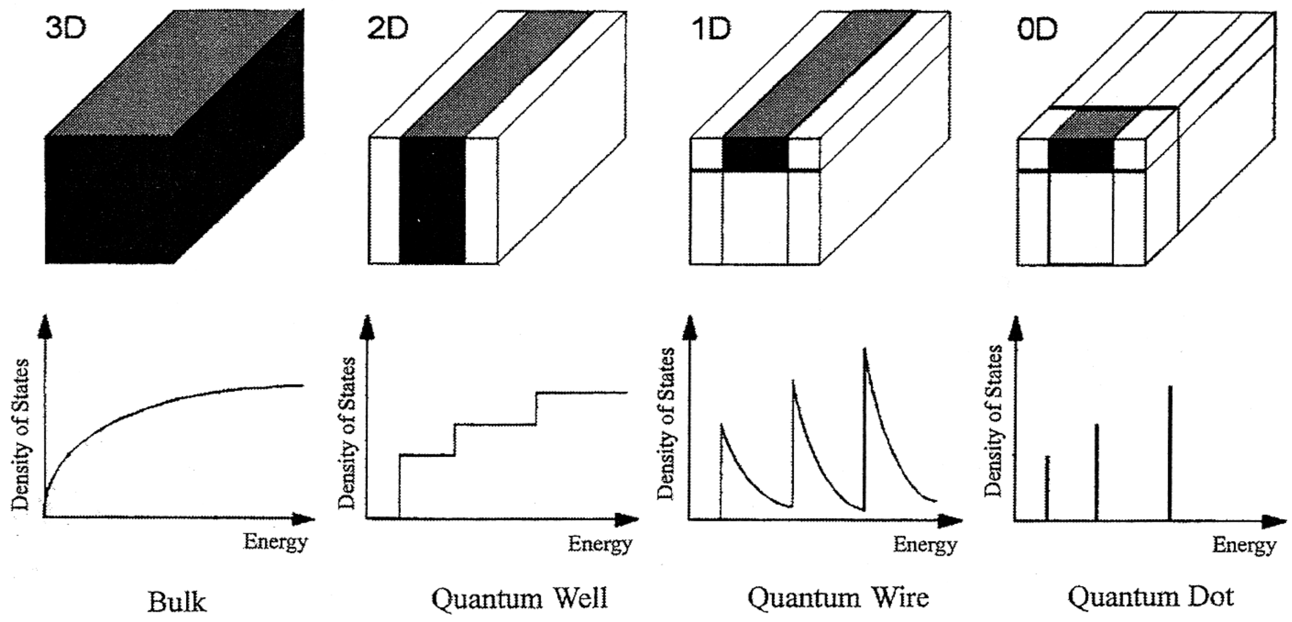
***0 Dimensions*!**



3 Dimensional
Quantization!

Each further confinement direction changes a continuous k component to a discrete component characterized by a quantum number n.

3D → 2D → 1D → 0D

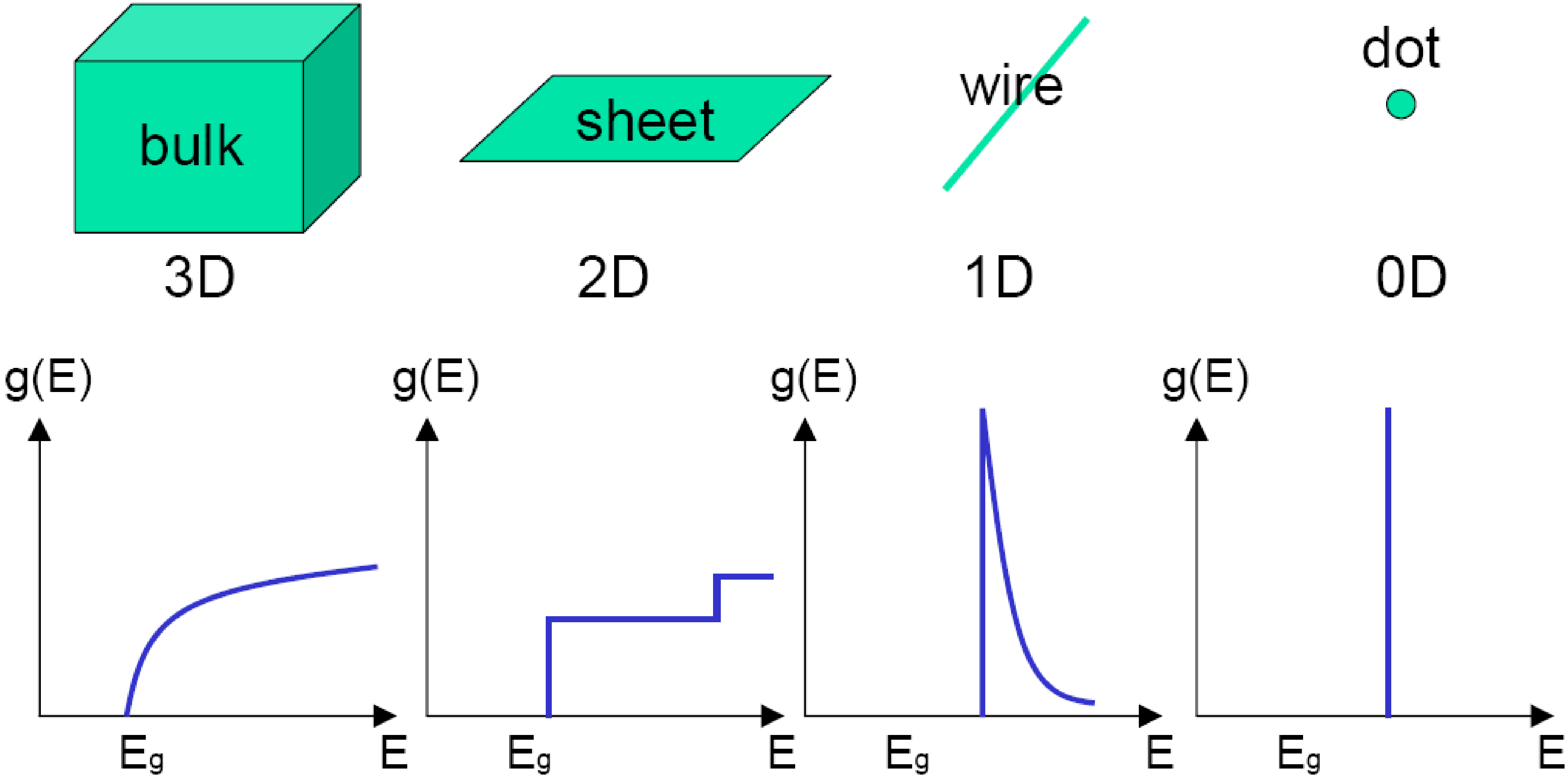


Source: Nanoscale Materials in Chemistry, Wiley, 2001

- If a bulk metal is made thinner and thinner, until the electrons can move only in two dimensions (instead of 3), then it is "2D quantum confinement."
- Next level is 'quantum wire
- Ultimately 'quantum dot'

Quantum confinement review

g(E) = Density of states



Some Basic Physics

- **Density of states** (DoS)

$$DoS = \frac{dN}{dE} = \frac{dN}{dk}\frac{dk}{dE}$$

in 3D:

$$N(k) = \frac{\text{k space vol}}{\text{vol per state}}$$

$$= \frac{4/3\,\pi k^3}{(2\pi)^3/V}$$

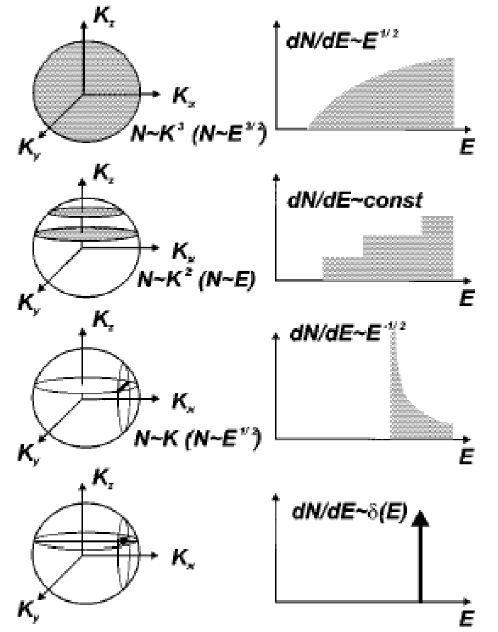
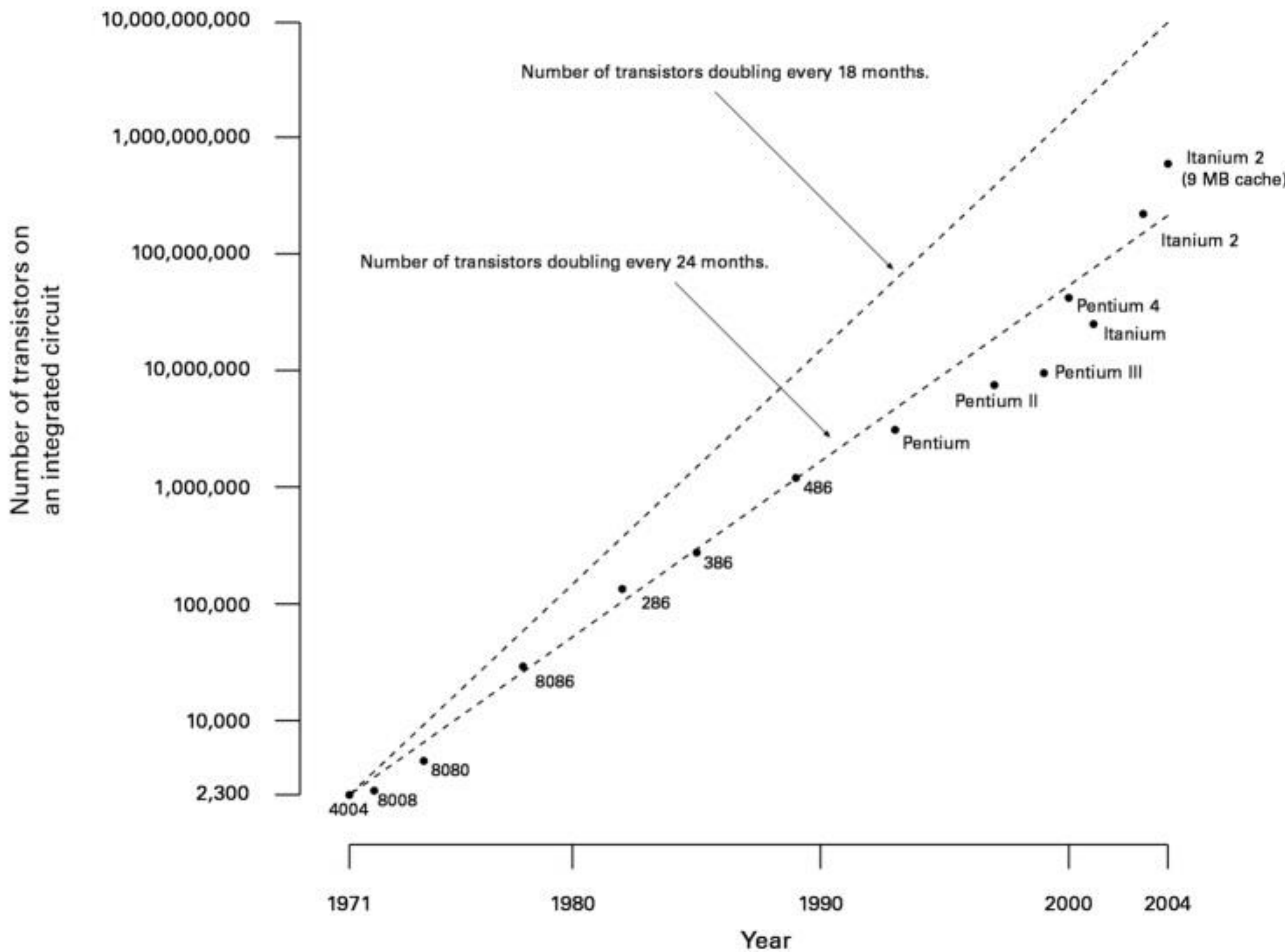


Fig. 1. Density of states for charge carriers in structures with different dimensionalities.

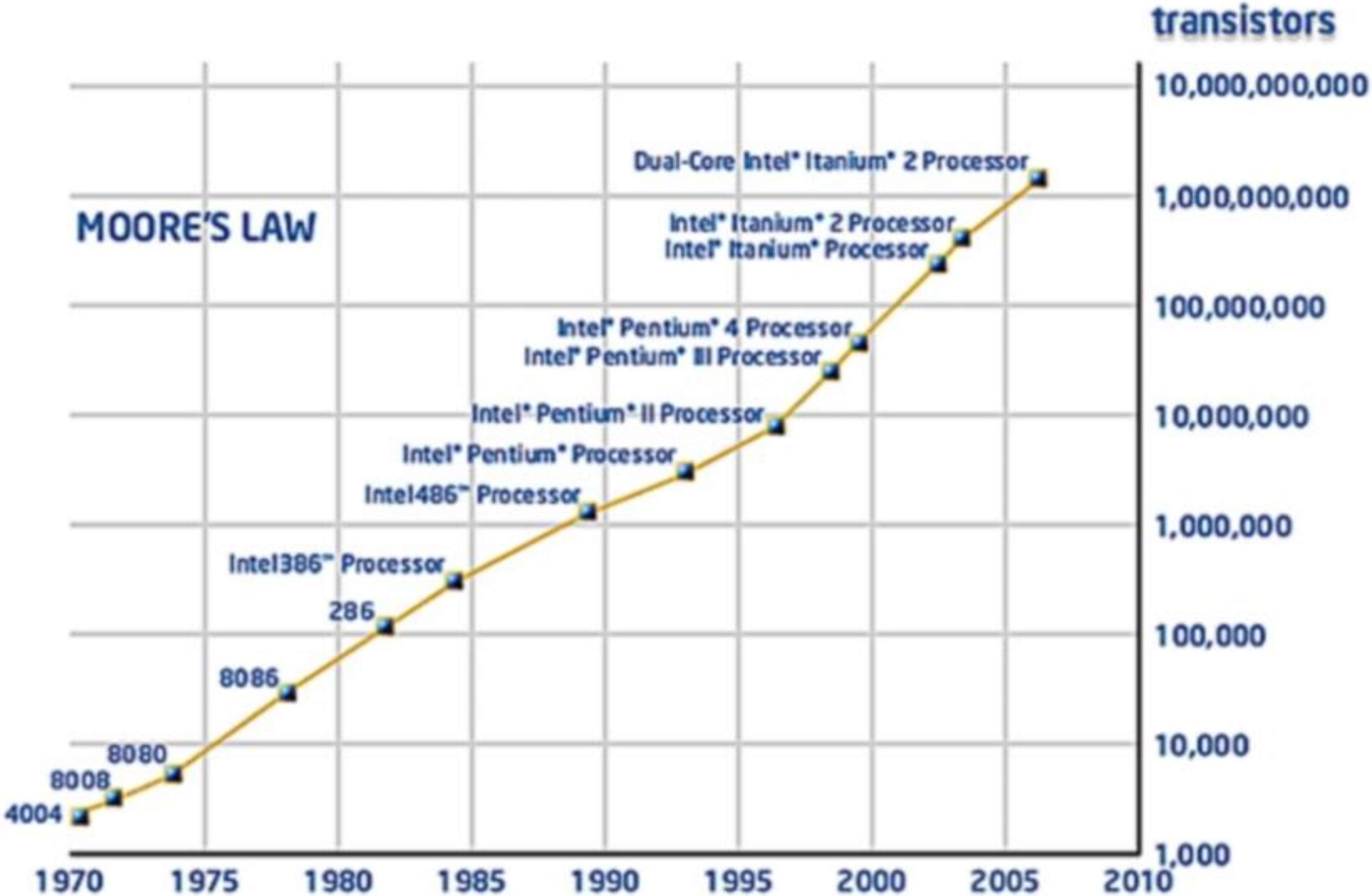
Structure	Degree of Confinement	$\frac{dN}{dE}$
Bulk Material	0D	$\sqrt{E}$
Quantum Well	1D	1
Quantum Wire	2D	$1/\sqrt{E}$
Quantum Dot	**3D**	**$\delta(E)$**

“Because of the recent rapid and radical progress in molecular electronics – where individual atoms and molecules replace lithographically drawn transistors – and related nanoscale technologies, we should be able to meet or exceed the Moore’s Law rate of progress for another 30 years.”

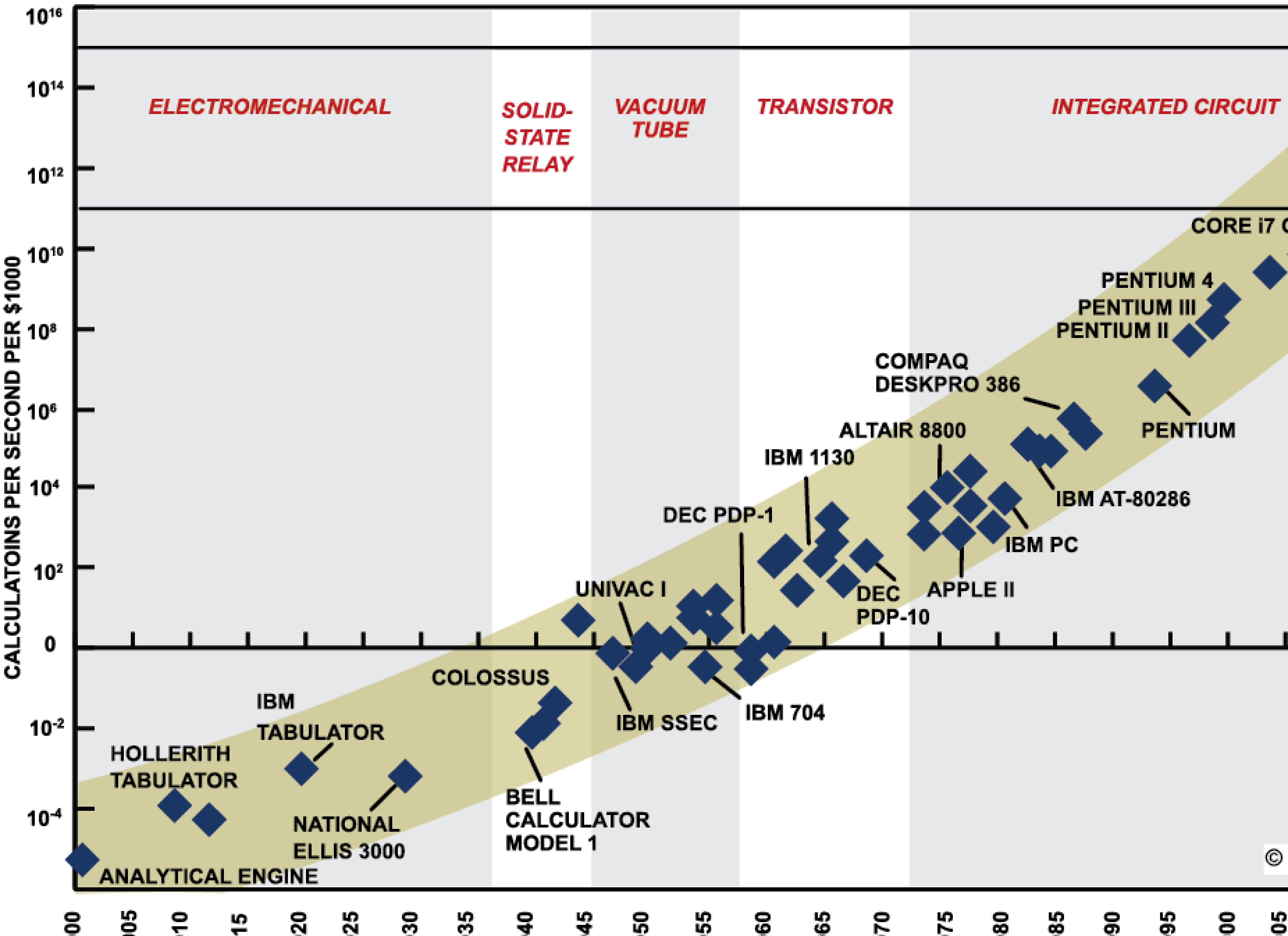
Moore's Law



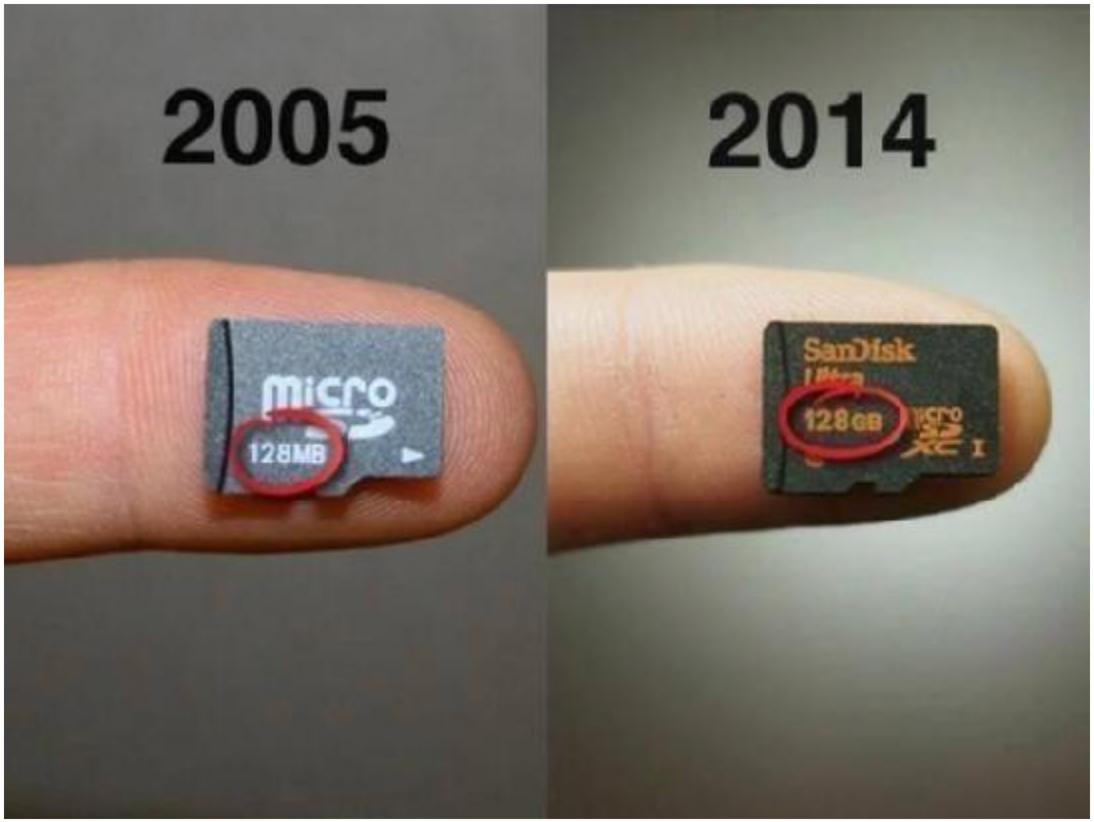
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
Number of transistors on an integrated circuit
Number of transistors doubling every 18 months.
Number of transistors doubling every 24 months.
Itanium 2 (9 MB cache)
Itanium 2
Pentium 4
Itanium
Pentium III
Pentium II
Pentium
486
386
286
8086
8080
8008
4004
1971
1980
1990
2000
2004
Year



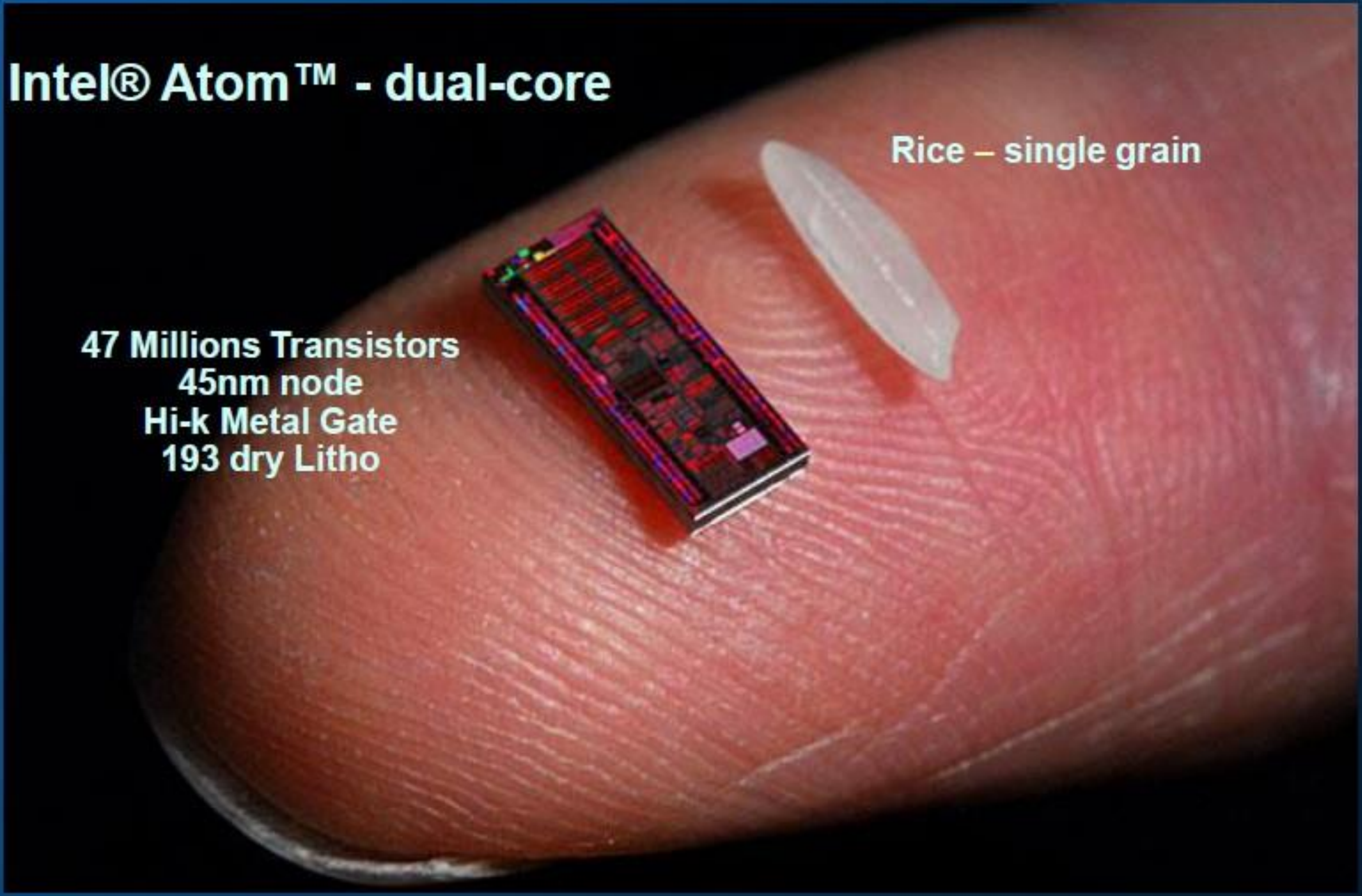
MOORE'S LAW
transistors
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
1970
1975
1980
1985
1990
1995
2000
2005
2010
Dual-Core Intel® Itanium® 2 Processor
Intel® Itanium® 2 Processor
Intel® Itanium® Processor
Intel® Pentium® 4 Processor
Intel® Pentium® III Processor
Intel® Pentium® II Processor
Intel® Pentium® Processor
Intel486™ Processor
Intel386™ Processor
286
8086
8080
8008
4004



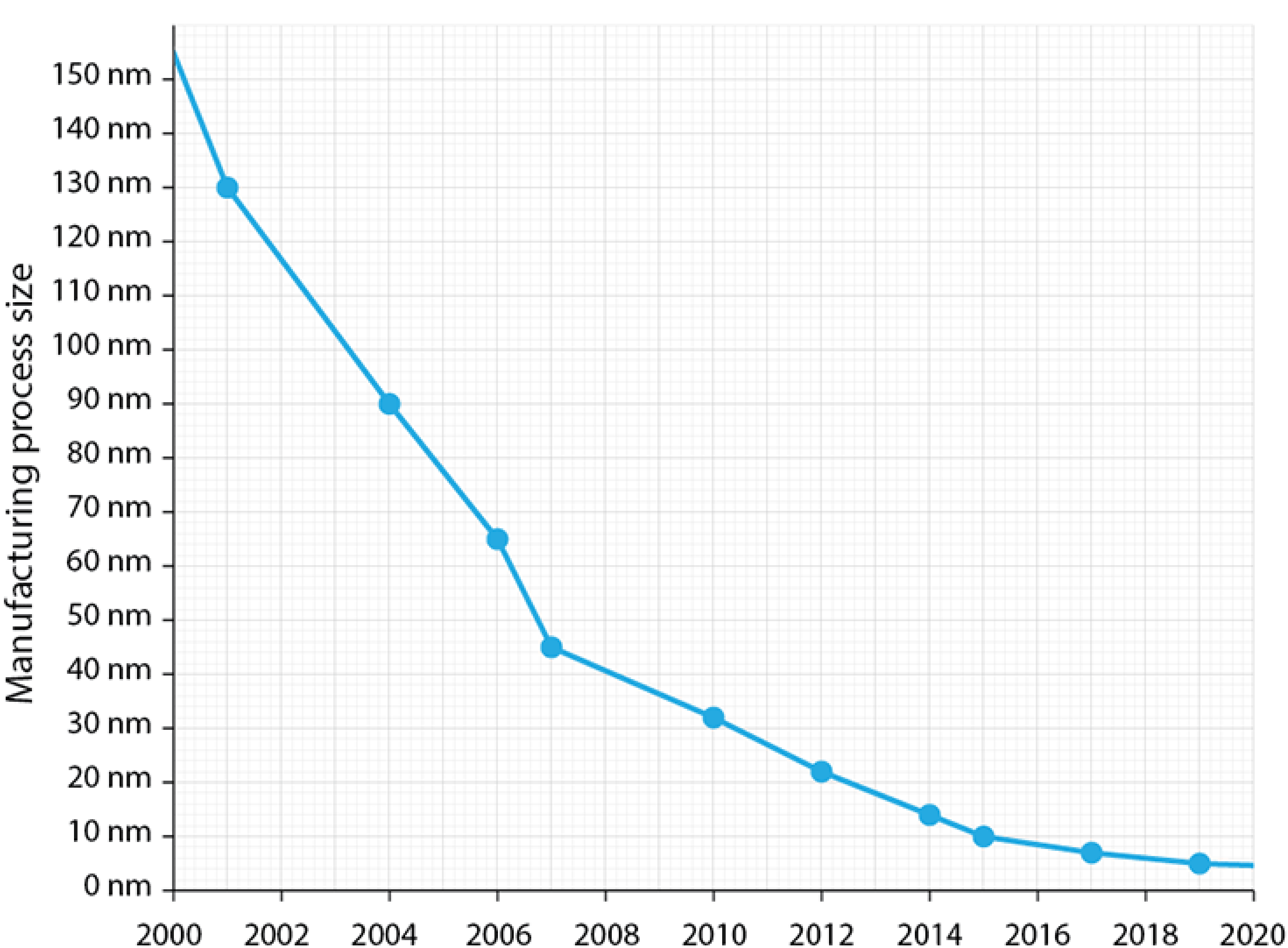
CALCULATOINS PER SECOND PER $1000
ELECTROMECHANICAL
SOLID-STATE RELAY
VACUUM TUBE
TRANSISTOR
INTEGRATED CIRCUIT
CORE i7
PENTIUM 4
PENTIUM III
PENTIUM II
PENTIUM
COMPAQ DESKPRO 386
IBM AT-80286
IBM PC
ALTAIR 8800
APPLE II
DEC PDP-10
IBM 1130
DEC PDP-1
UNIVAC I
IBM 704
IBM SSEC
COLOSSUS
BELL CALCULATOR MODEL 1
IBM TABULATOR
HOLLERITH TABULATOR
NATIONAL ELLIS 3000
ANALYTICAL ENGINE


2005
micro
128MB
2014
SanDisk
128GB

Moore's Law: circa 2008



In 2014, on 14nm technology, the above chip would be 1/8 the size
- Much smaller than the grain of rice!



Manufacturing process size
150 nm
140 nm
130 nm
120 nm
110 nm
100 nm
90 nm
80 nm
70 nm
60 nm
50 nm
40 nm
30 nm
20 nm
10 nm
0 nm
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

Electrical Conductivity

- For metals, conductivity is based on their band structure. If the conduction band is only partially occupied by electrons, they can move in all directions without resistance (provided there is a perfect metallic crystal lattice). They are not scattered by the regular building blocks, due to the wave character of the electrons.

$$\mu = \frac{e\lambda}{4\pi\varepsilon_o m_e v}$$

v = electron speed
ε_o = dielectric constant in vacuum

τ, mean time between collisions, is λ/v

- For Cu, $v = 1.6 \times 10^6$ m/s at room temp.; $\lambda = 43$ nm, $\tau = 2.7 \times 10^{-14}$ s

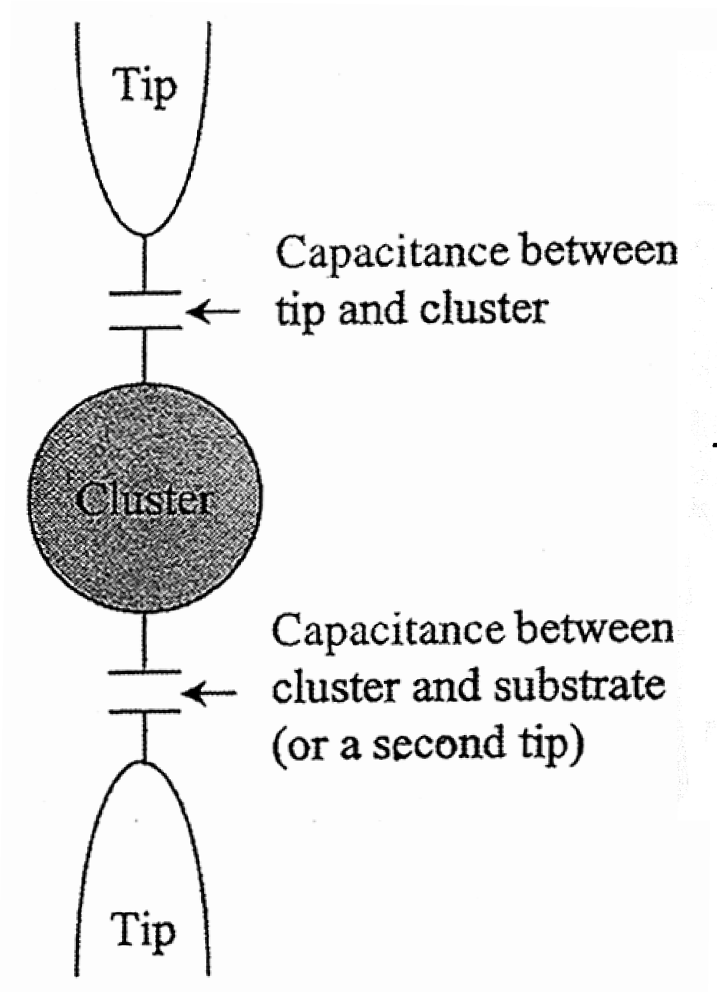
- Scattering mechanisms
  (1) By lattice defects (foreign atoms, vacancies, interstitial positions, grain boundaries, dislocations, stacking disorders)
  (2) Scattering at thermal vibration of the lattice (phonons)

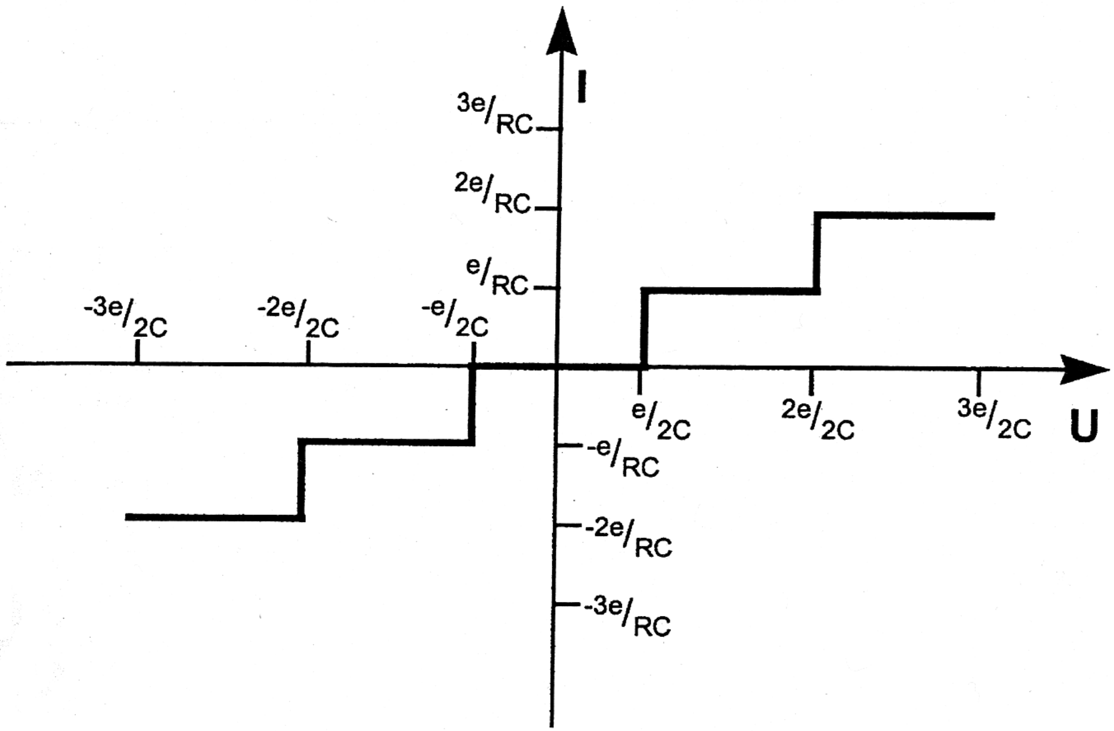
- Item (1) is more or less independent of temperature while item (2) is independent of lattice defects, but dependent on temperature.

- Electric current ➡ collective motion of electrons; in a bulk metal,
  Ohm's law: $V = RI$

- Band structure begins to change when metal particles become small. Discrete energy levels begin to dominate, and Ohm's law is no longer valid.

I-V of a Single Nanoparticle





Source: Nanoscale Materials in Chemistry, Wiley, 2001

I-V of a Single Nanoparticle

- Consider a single nanoparticle between two electrodes, but cushioned by a capacitance on each side
  - If an electron is transferred to the particle, its coulomb energy $\uparrow$ by
    $$E_c = e^2/2c$$
  - Thermal motion of the atoms in the particle can initiate a charge & E_c, leading to further electrons tunneling uncontrollably
  - So, $kT << e^2/2c$
  - Tunneling current $I = V/R_T$
  - Current begins at coulomb voltage $V_c = \pm\, e/2c$ which is called coulomb blockade
  - Further electron transfer happens if the coulomb energy of the 'quantum dot' is compensated by an external voltage $V_c = \pm\, ne/2c$ where n is an integer

- Repeated tunneling results in a 'staircase' with step height in current, e/Rc

- Possible to charge and discharge a quantum dot in a quantized manner $\Rightarrow$ principle behind some future computers

- Materials reduced to the nanoscale can show different properties compared to what they exhibit on a macroscale, enabling unique applications.

- **For instance, opaque substances become transparent (copper); stable materials turn combustible (aluminum); solids turn into liquids at room temperature (gold); insulators become conductors (silicon).**

- A material such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales. Much of the fascination with nanotechnology stems from these quantum and surface phenomena that matter exhibits at the nanoscale.

Chemistry: The Traditional Way

- Canon Ball Chemistry
- Carried out often under extreme conditions
- Irregular, amorphous structures are formed.

Feynman: "There is plenty of room at the bottom"

SELF Assembly

SELF-assembly involves the spontaneous and autonomous organization of disorganized interacting components into an organized pattern without direct human or mechanical interference

❖-common throughout nature and technology.

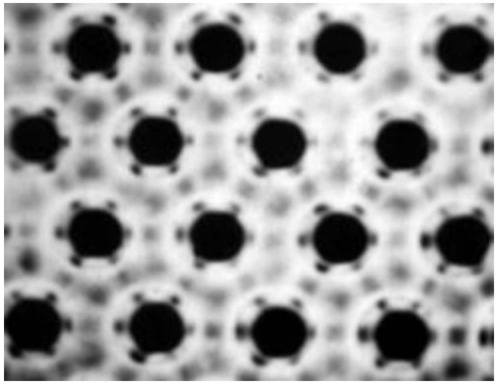
❖-involve components from the molecular (crystals) to the planetary (weather systems) scale and solar systems and many different kinds of interactions.

❖-In the natural world, self-assembly occurs over a wide range of size-scales to create structures that display new properties not present in the original components.

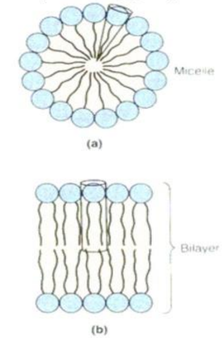
❖-In any living cell, nanoscale cellular machines spontaneously assemble themselves and drive the processes of life. Self-assembly occurs both in systems at equilibrium - such as the crystallization of proteins or colloids - and in systems far from equilibrium - such as cellular replication of DNA

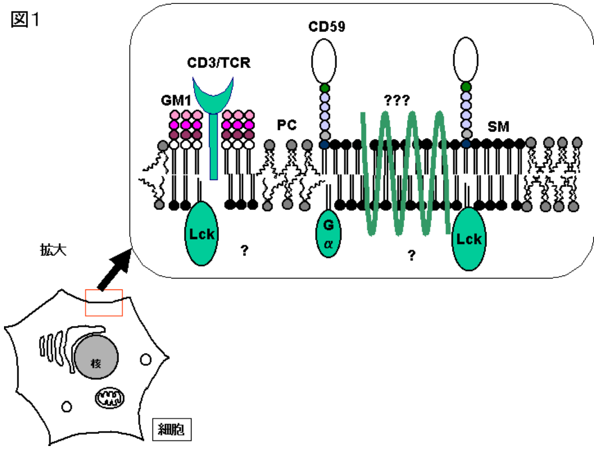
Nature’s Fabrication Technique: Self-assembly

- Self-aggregation of hydrophilic, lipophilic groups
- First layer creates template for growth of second layer
- Ions can be deposited on charged sites
- This kind of self-aggregation leads to ordered, heirarchical structures
- Techniques to study this atomic-scale morphology

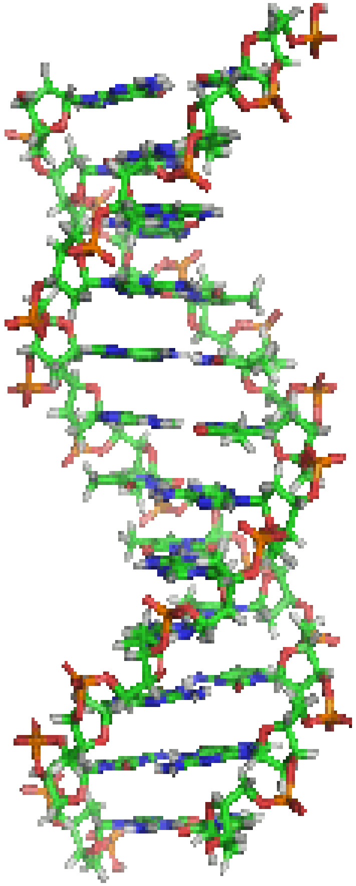


Fatty acid aggregation





DNA



- **<u>D</u>eoxyribo<u>n</u>ucleic <u>a</u>cid**
- DNA is a long <u>polymer</u> of simple units called nucleotides, which are held together by a backbone made of sugars and phosphate groups.

Why DNA?

Although research has shown improvement at creating nano-sized images, it is often a challenge to create desired patterns and details at the nanoscale level.

Nanoscientists are always looking for more accurate and consistent results.

programmed self assembly.

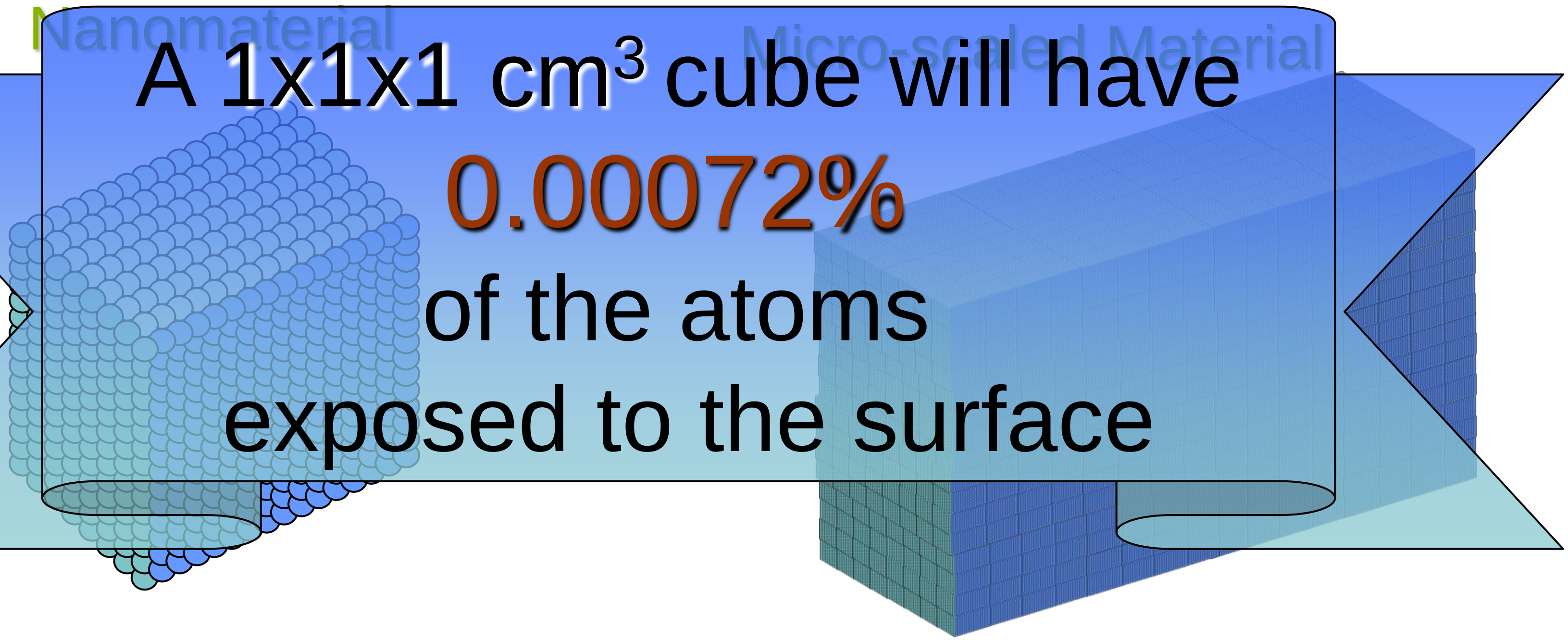
-DNA can be manipulated to create exact copies that are extremely accurate.

-DNA is predictable and programmable.

-DNA also has the ability to store enormous amounts of information

Nanomaterials Have More Atoms on the Surface

Materials of the micro ($1x10^{-6}$m) and especially nano ($1x10^{-9}$m) size have more atom exposed on the outside then inside



A 1x1x1 cm^3 cube will have

0.00072%

of the atoms

exposed to the surface

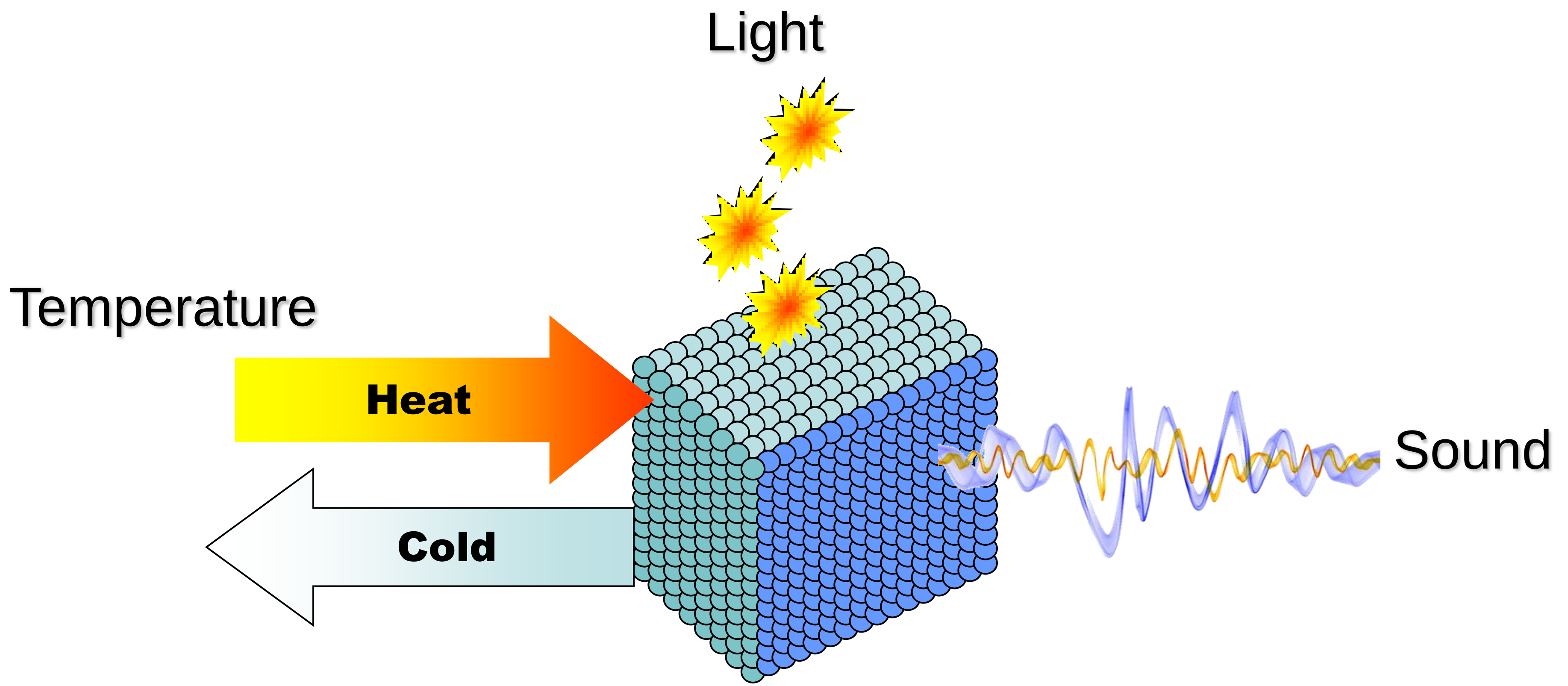
Volume = 18x19x1 nm^3 or 15x8x16 atoms = 1920 atoms total

976 or 51% of the atoms are at the surface

Volume = 3x3x0.7 μm^3 or ~4 million atoms total

976 or 4% of the atoms are at the surface

Surface Atoms Interact more with the Environment



The forms of energy that affect us in the environment can affect molecules.

Energy comes from the environment to affect molecular nature. Since more molecules are on the surface, the affect is more pronounced.

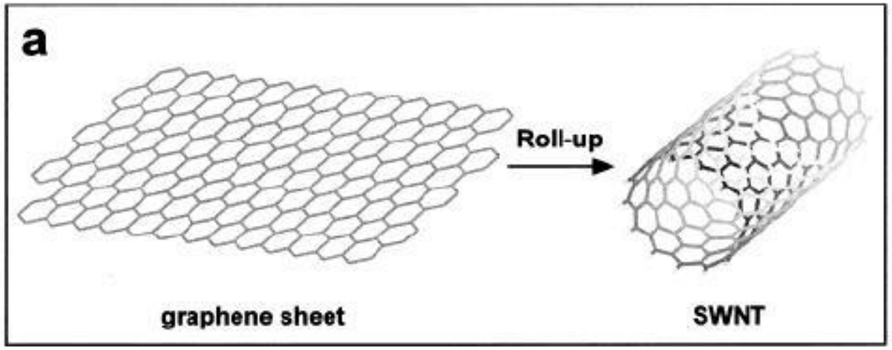
Definition:
Carbon Nanotube and Carbon fiber

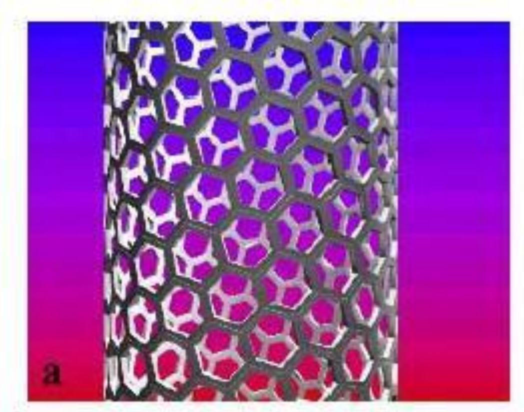
- The history of carbon fiber goes way back…

- The history of carbon nanotube starts from 1991

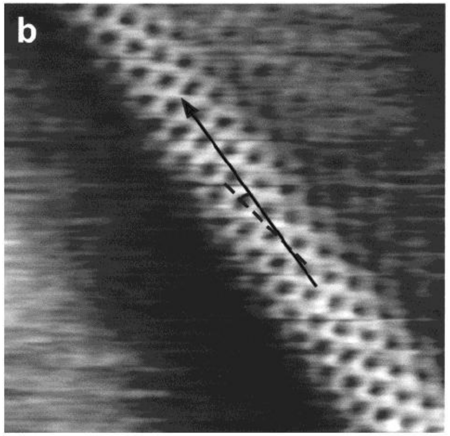
Carbon nanotube

CNT: Rolling-up a graphene sheet to form a tube

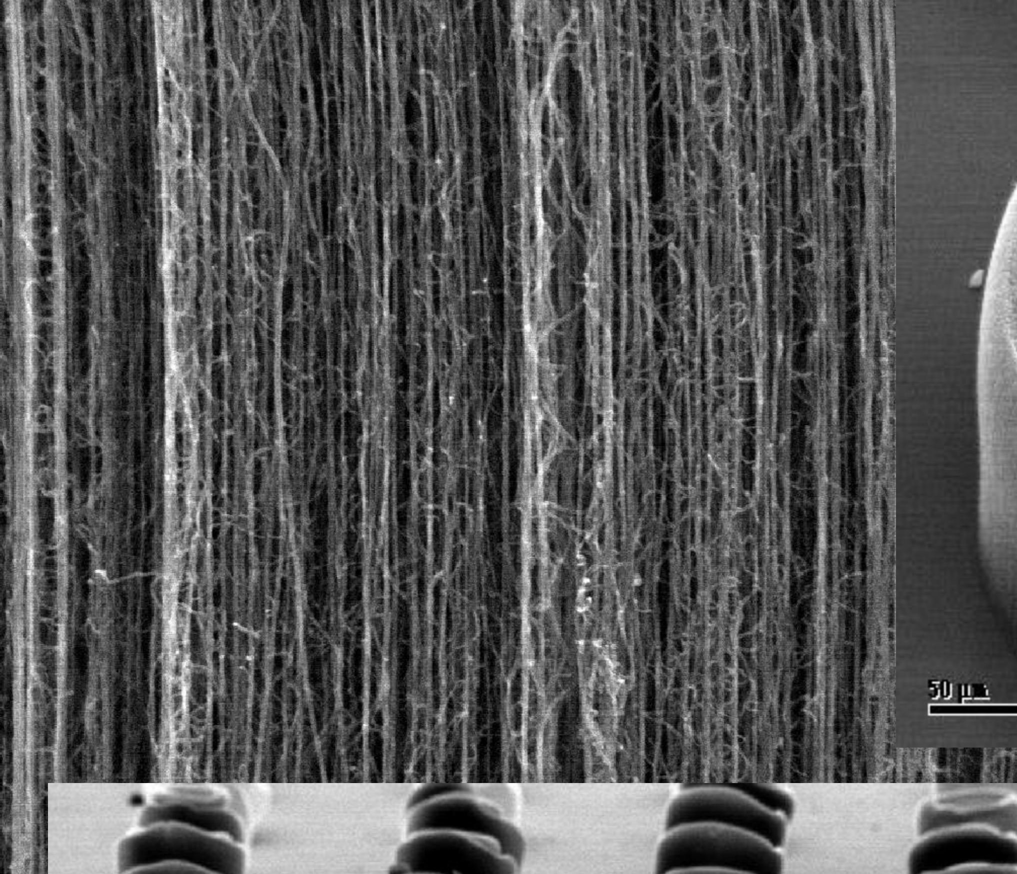


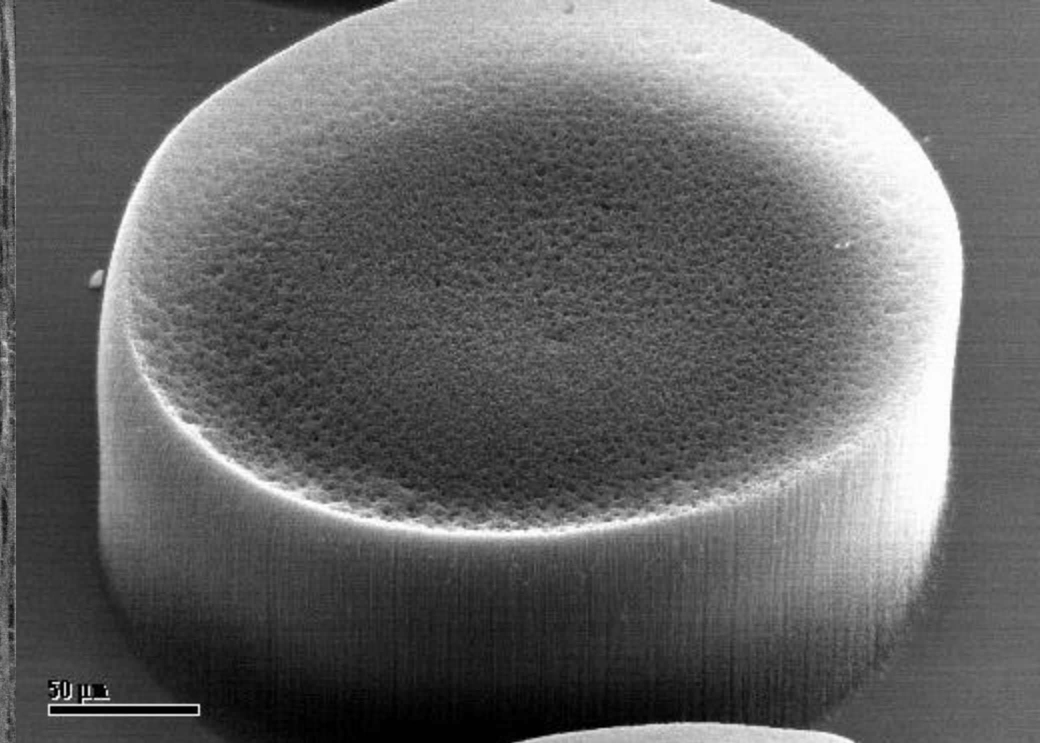


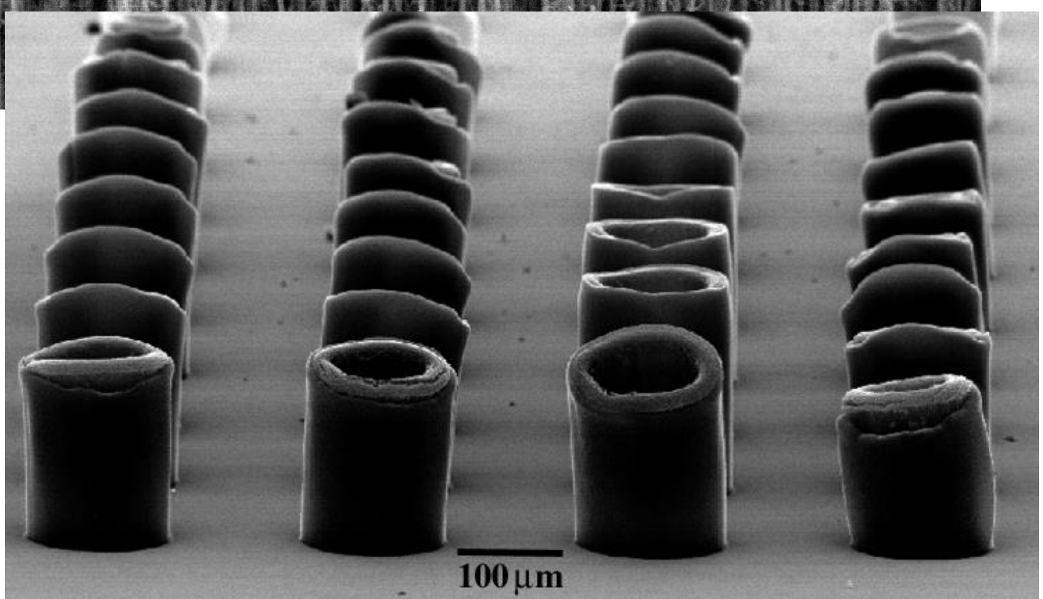
Schematic of a CNT



STM image of CNT







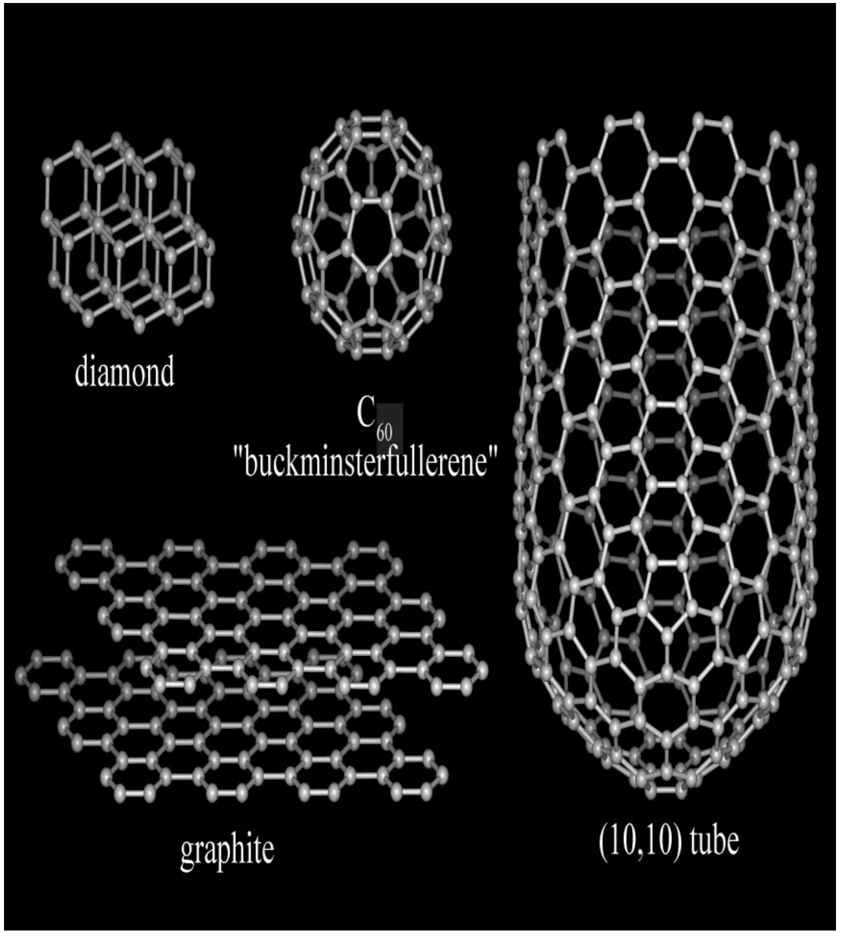
Carbon Nanotubes - SEM Images

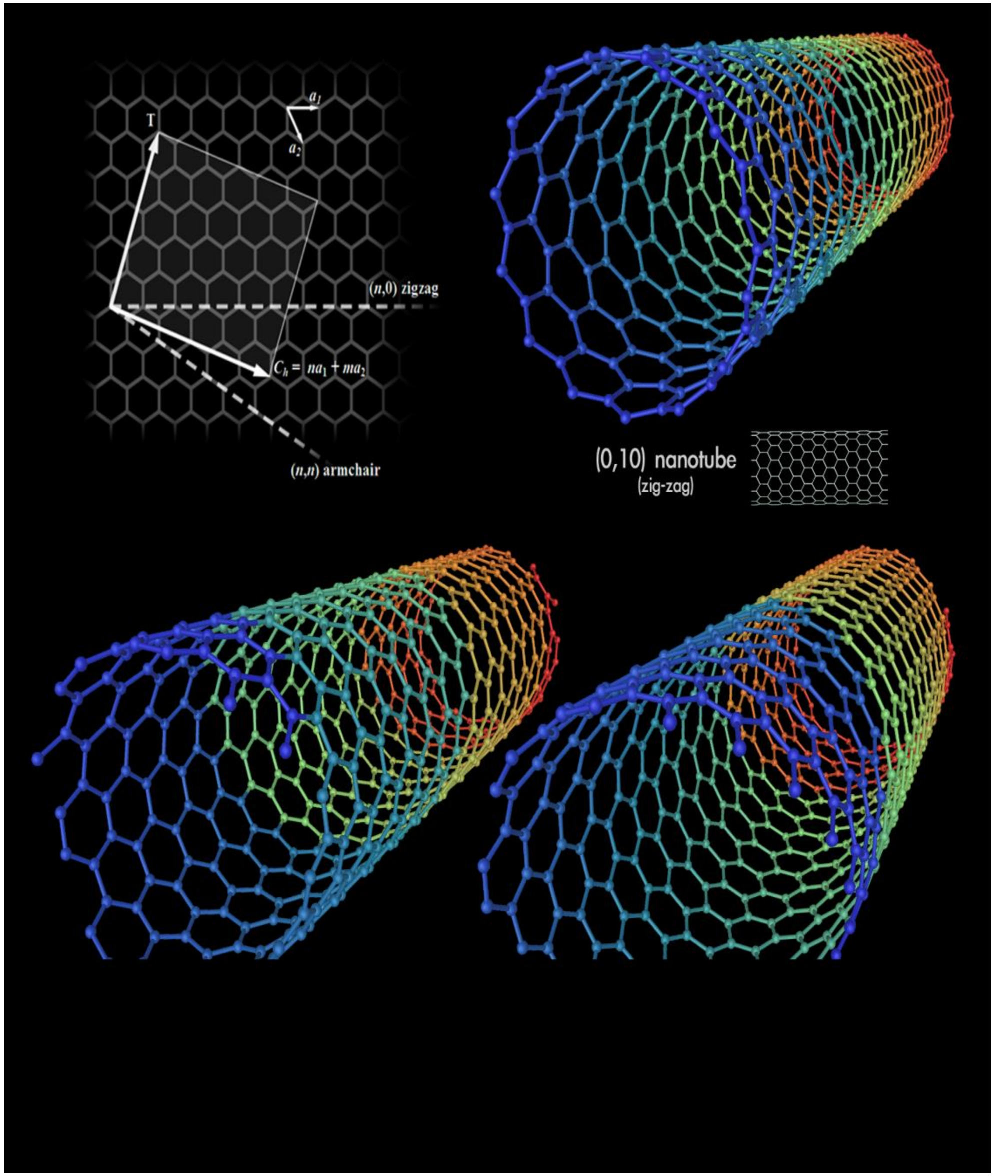
Carbon Nanotubes

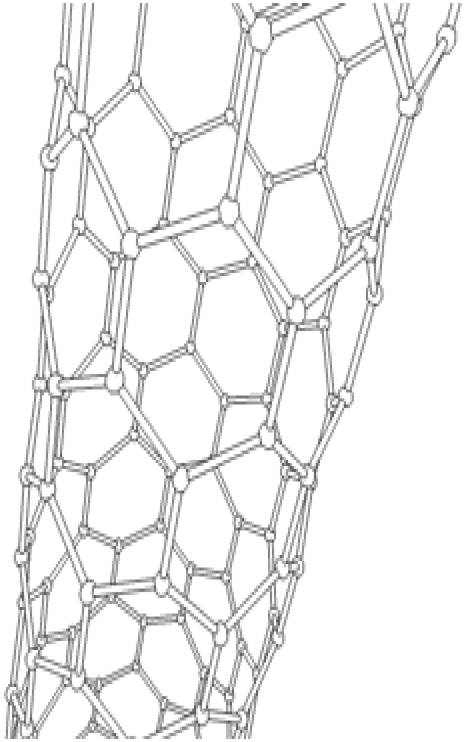
- What are they?
- They are single sheet of carbon atoms rolled together. They are very small objects and exhibit many different structures and properties.
- There are 4 different types of carbon nanotubes.
    - Single walled - one atom thick layer of graphite.
    - Multi walled – multiple layers of graphite.
    - Fullerite- solid state manifestation of fullerene
    - Torus – donut shaped.

CNT Background Info

- Discovered by S. Ijima in 1991
- Tubular hexagonal arrays of graphene sheets
- Can be single-walled or multi-walled (~2 nm SWNT diameter)
- Have metallic or semiconducting properties
- Nanoelectronic Applications

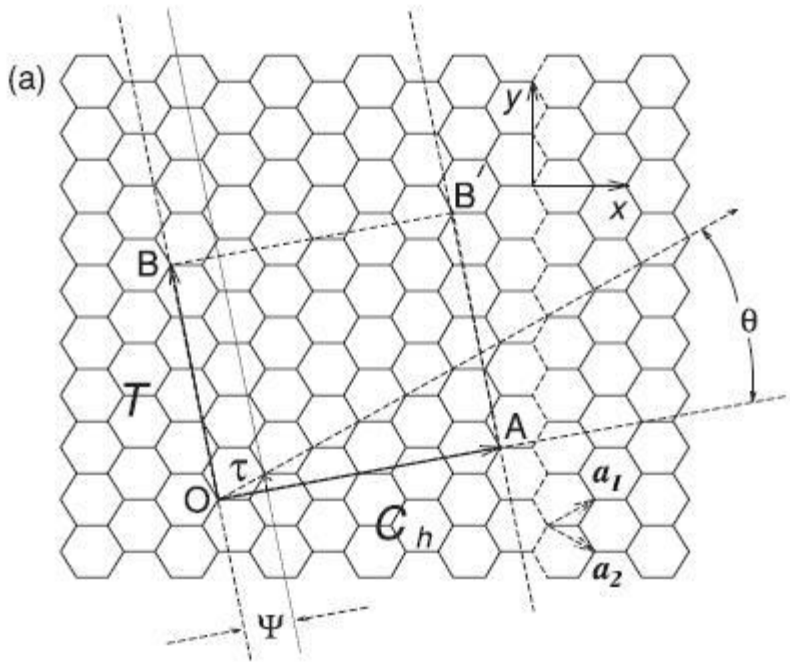



T
a_1
a_2
(n,0) zigzag
$C_h = na_1 + ma_2$
(n,n) armchair
(0,10) nanotube
(zig-zag)



Carbon nanotube

Properties depending on how it is rolled up.



a_1, a_2 are the graphene vectors.
OB/AB' overlaps after rolling up.
OA is the rolling up vector.

$$OA = na_1 + ma_2$$

Carbon nanotube properties: Electronic

Electronic band structure is determined by symmetry:

- n=m: Metal
- n-m=3j (j non-zero integer): Tiny band-gap semiconductor
- Else: Large band-gap semiconductor.

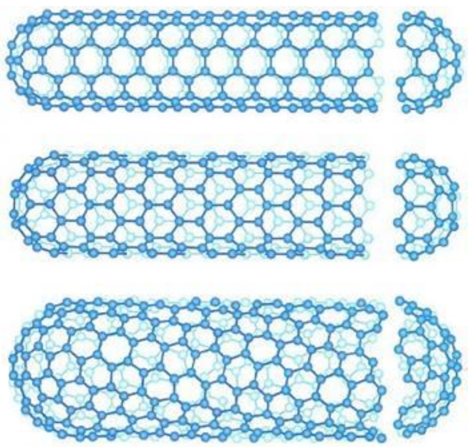
Band-gap is determined by the diameter of the tube:

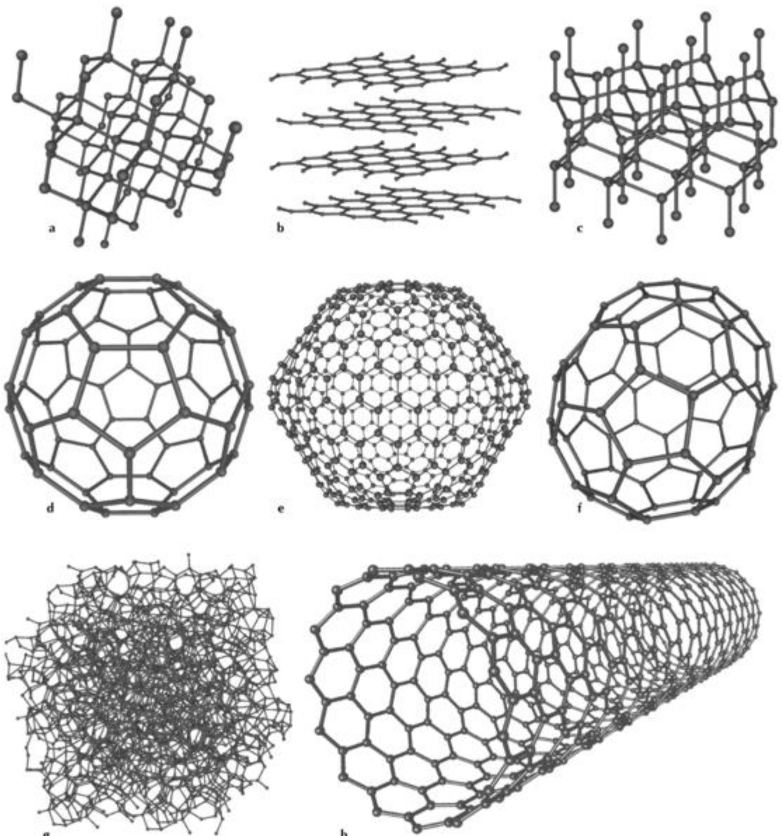
- For tiny band-gap tube: $E_g \propto 1/R^2$
- For large band-gap tube: $E_g \propto 1/R$

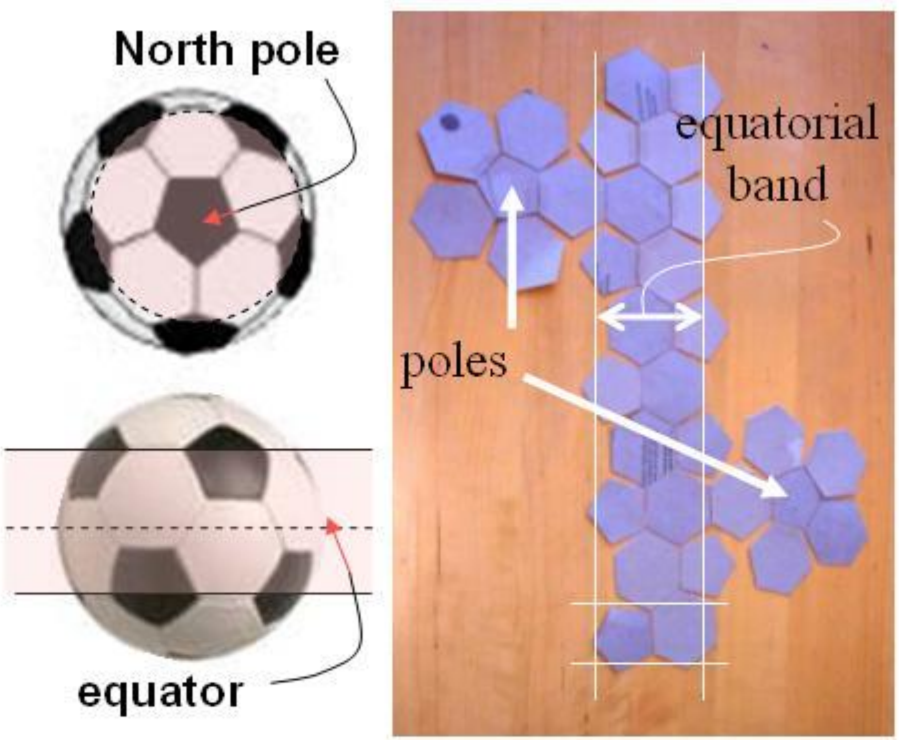
A Stretched Out Buckey Ball Becomes a Nanotube

Fullerenes (aka buckyballs)

- Discovered in 1985 at the University of Sussex and Rice University,







Carbon nanotube properties: Mechanical

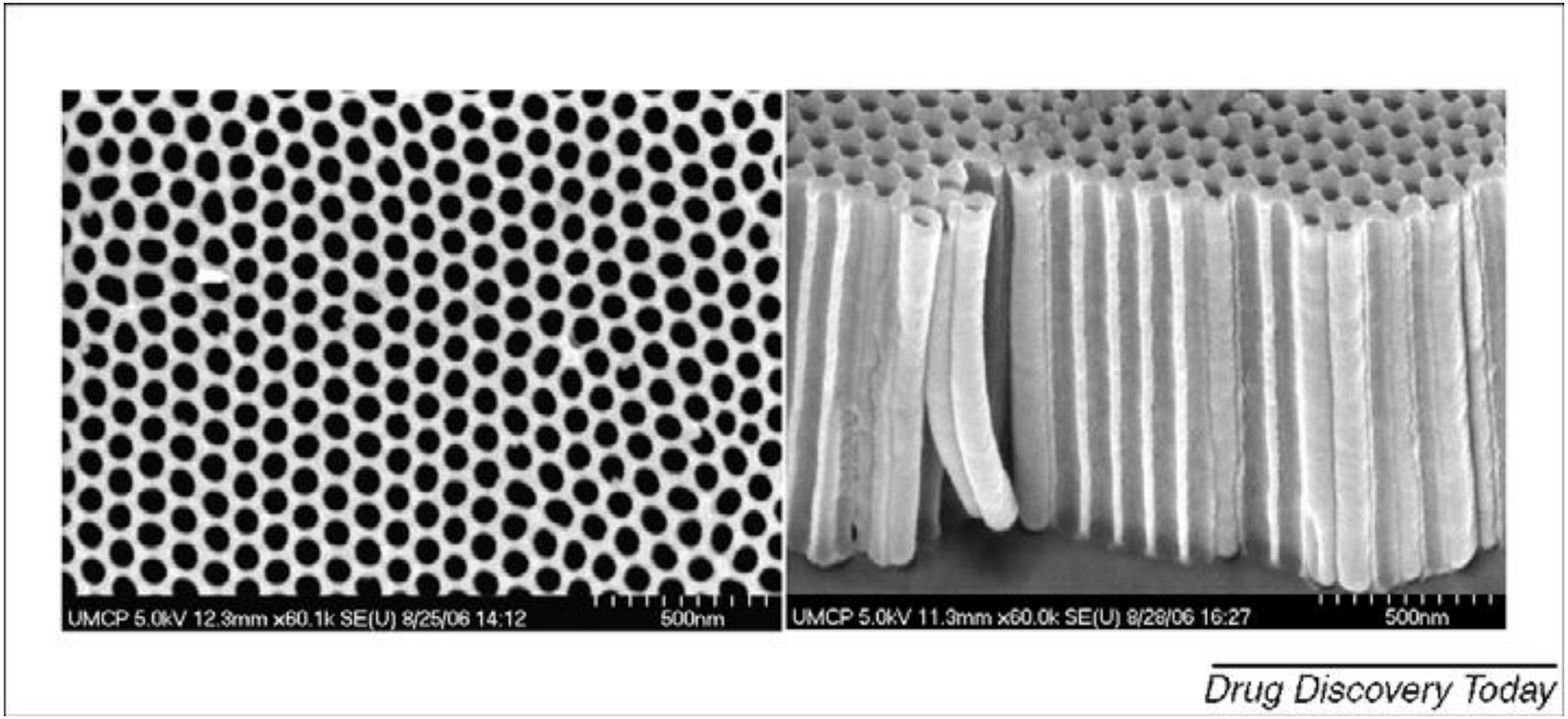
- Carbon-carbon bonds are one of the strongest bond in nature
- Carbon nanotube is composed of perfect arrangement of these bonds
- Extremely high Young’s modulus

Material	Young’s modulus (GPa)
Steel	190-210
SWNT	1,000+
Diamond	1,050-1,200

Applications

- Electrical
  1. Field emission in vacuum electronics
  2. Building block for next generation of VLSI
  3. Nano lithography
- Energy storage
  1. Lithium batteries
  2. Hydrogen storage
- Biological
  1. Bio-sensors
  2. Functional AFM tips
  3. DNA sequencing

Nanotubes in practice



Field emission scanning electron micrographs (FESEM) of a home-made alumina template (60-nm diameter) after silica ‘‘surface sol–gel’’ template synthesis; top-viewed (left) and cross-sectional viewed image (right). The cross-sectionally viewed image reveals that silica nanotubes were synthesized within the pores of the template.

Son, S., Bai, X., Lee, S., 2007. Inorganic Hollow Nanoparticles and Nanotubes in Nanomedicine: Part 1. Drug/Gene deliver applications. Drug Discovery Today. Vol 12, No. 15/16, pp 650-656.

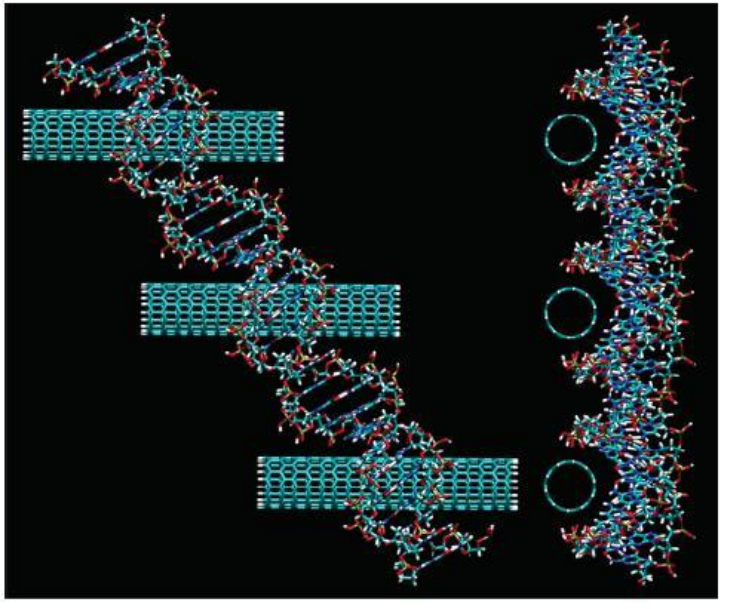
Biological applications: Bio-sensing

- Many spherical nano-particles have been fabricated for biological applications.
- Nanotubes offer some advantages relative to nanoparticles by the following aspects:

1. Larger inner volumes – can be filled with chemical or biological species.
2. Open mouths of nanotubes make the inner surface accessible.
3. Distinct inner and outer surface can be modified separately.

Biological applications: DNA sequencing

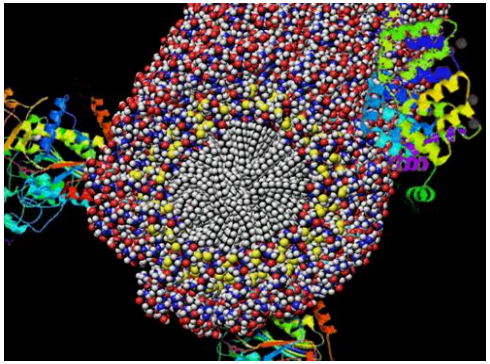
- Nanotube fits into the major grove of the DNA strand
- Apply bias voltage across CNT, different DNA base-pairs give rise to different current signals
- With multiple CNT, it is possible to do parallel fast DNA sequencing

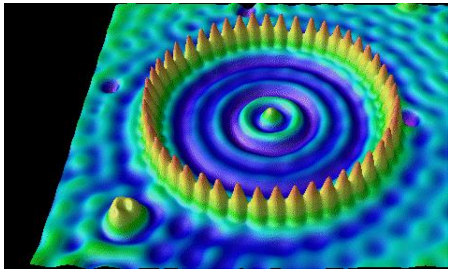


Top view and side view of the assembled CNT-DNA system

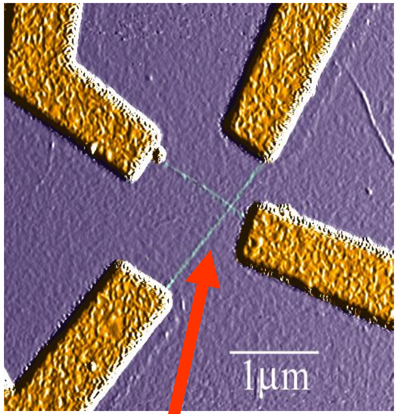
Nanotechnology has mechanical applications

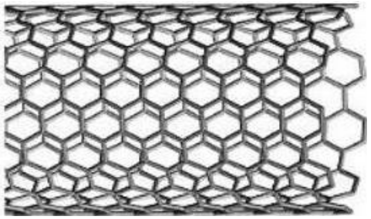
Self-assembled,
Nature-inspired structure
Many 10s of nm





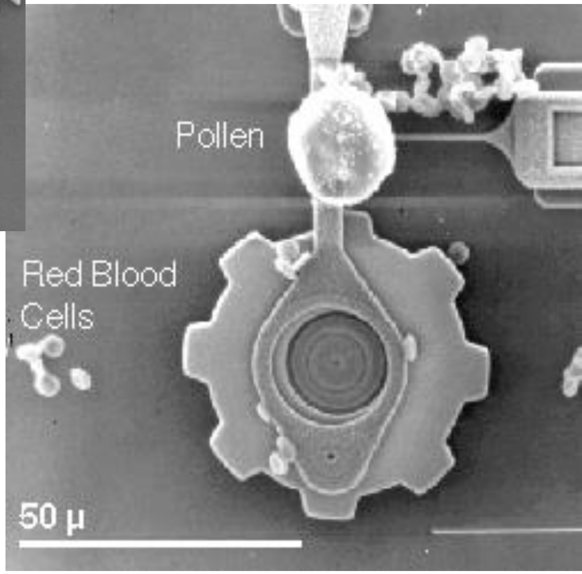
Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip
Corral diameter 14 nm



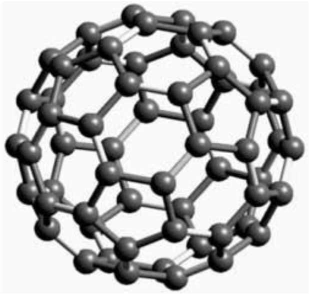


Carbon nanotube
~1.3 nm diameter

MicroElectroMechanical (MEMS) devices
10 -100 μm wide

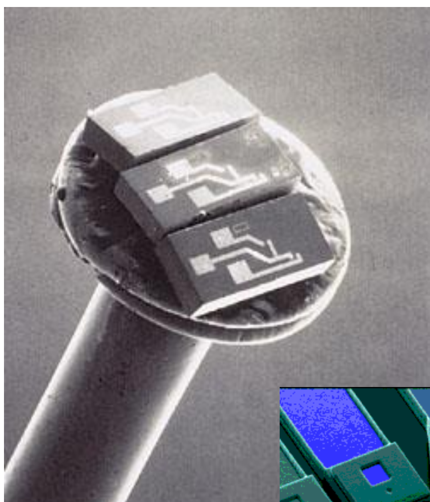


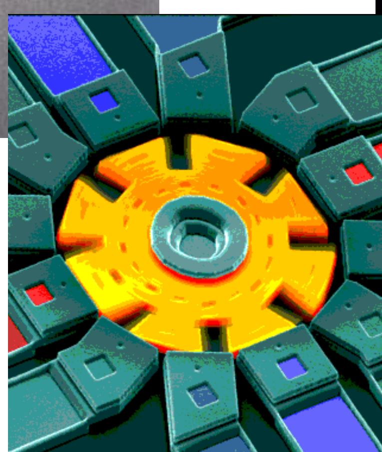
Carbon buckyball
~1 nm diameter

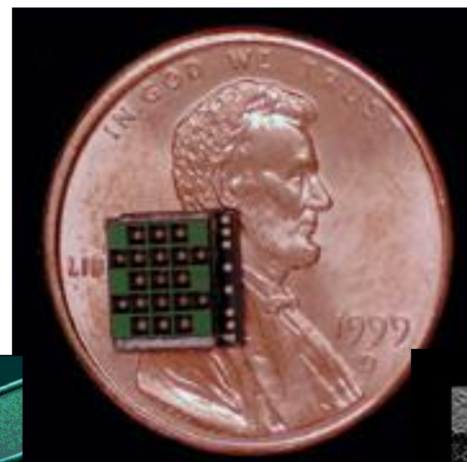


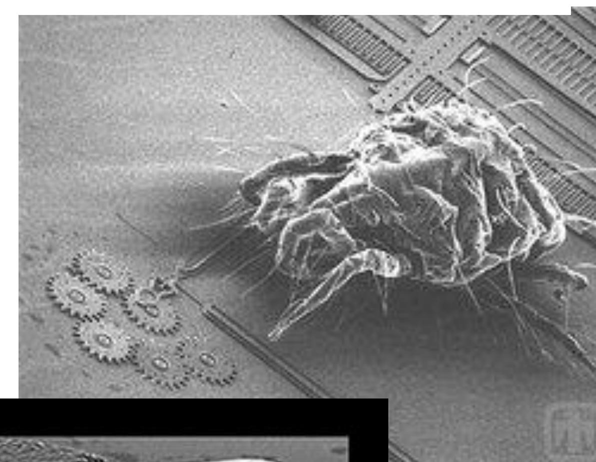
MEMs: MicroElectroMechanical Systems

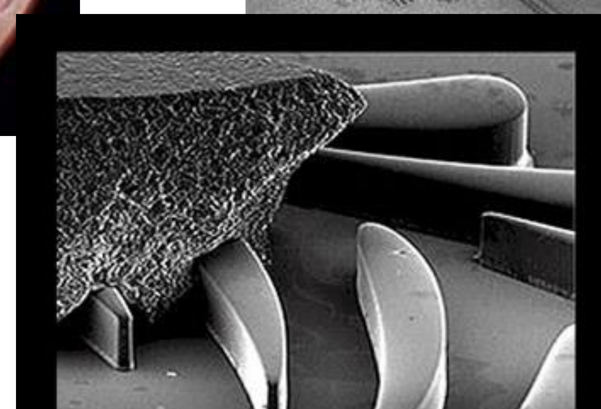
- High proportion of atom on the surface changes characteristics
  - electrostatics (static electricity)
  - wetting







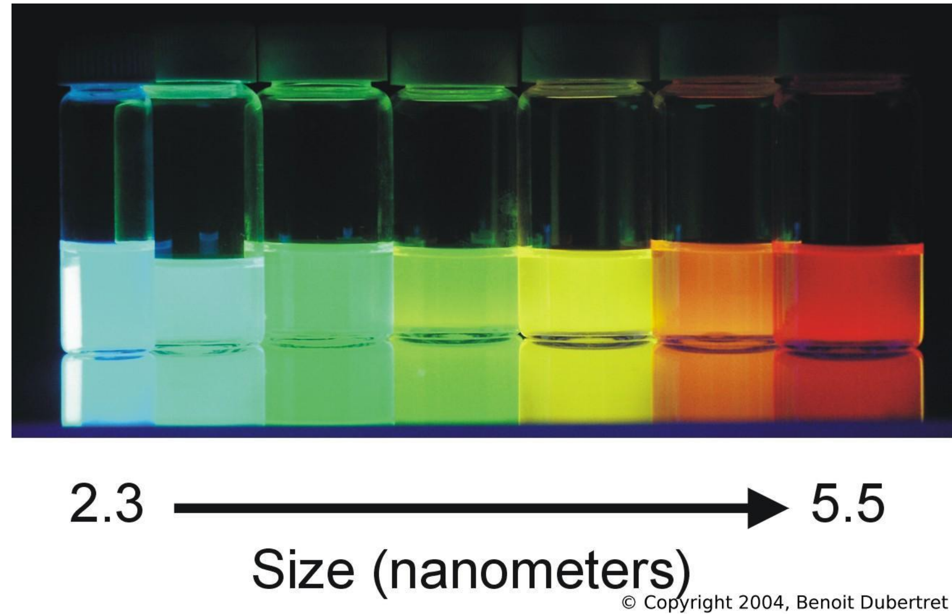


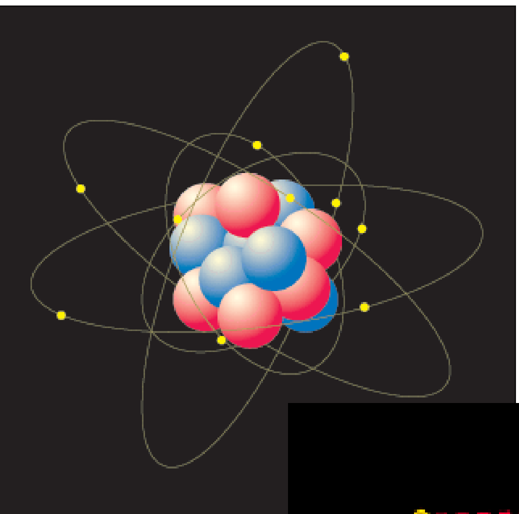


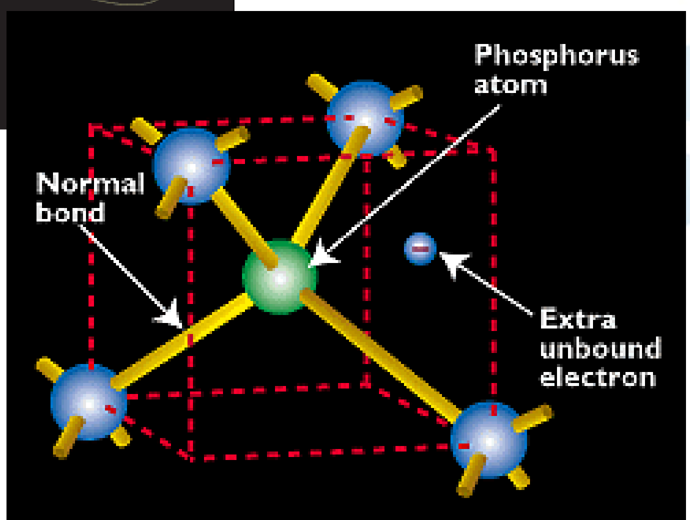
Processing of SiC Microengine Rotor and Blades

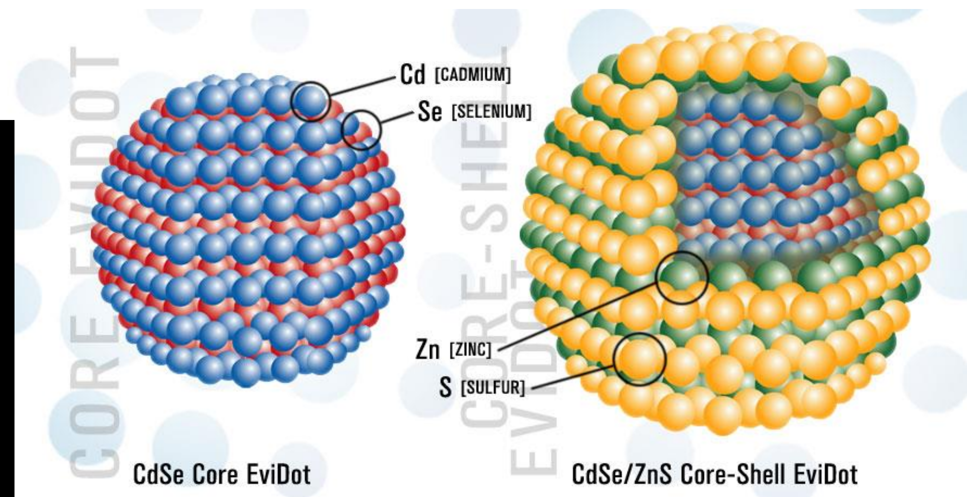
Quantum Dot Colors Vary with Size

- Semiconductor based material





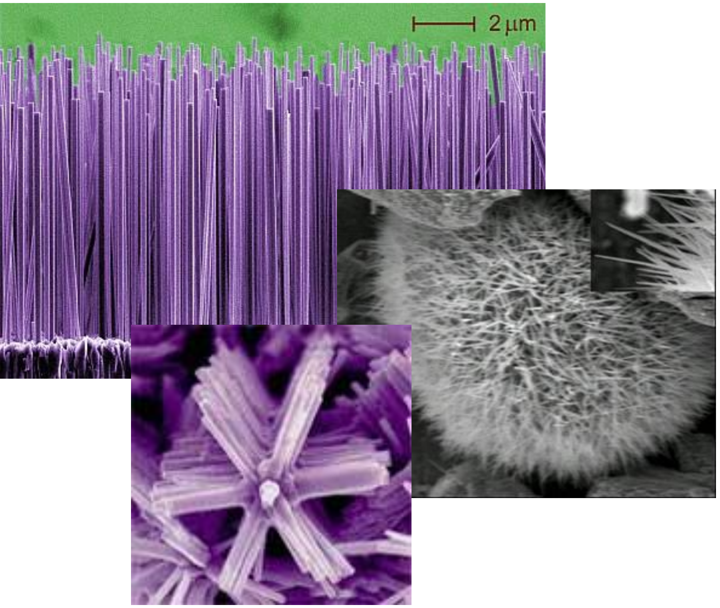




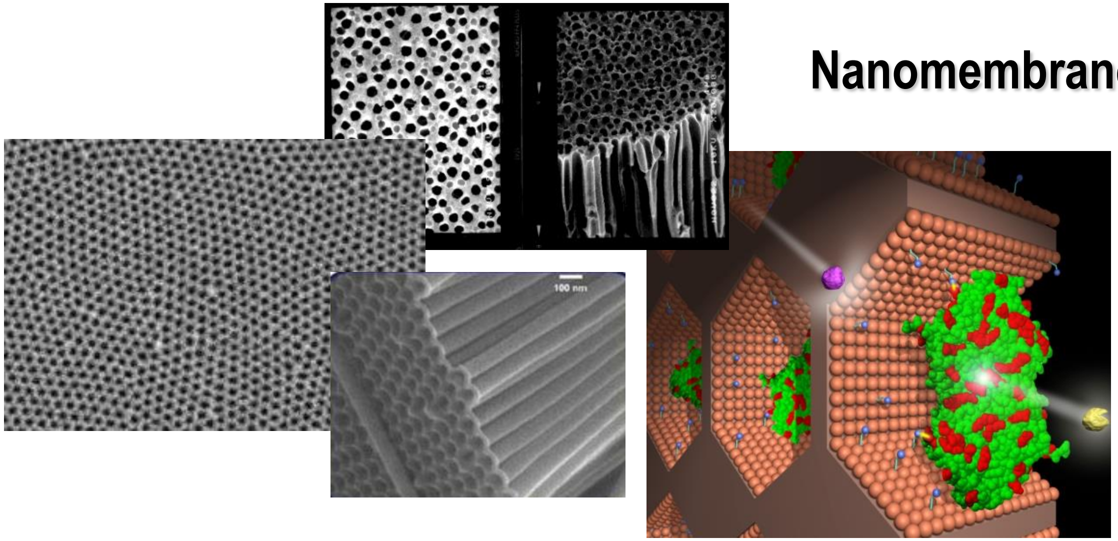
Nanotechnology Includes Nanomaterials

- Any material that has nano-scale features are termed a nanomaterial

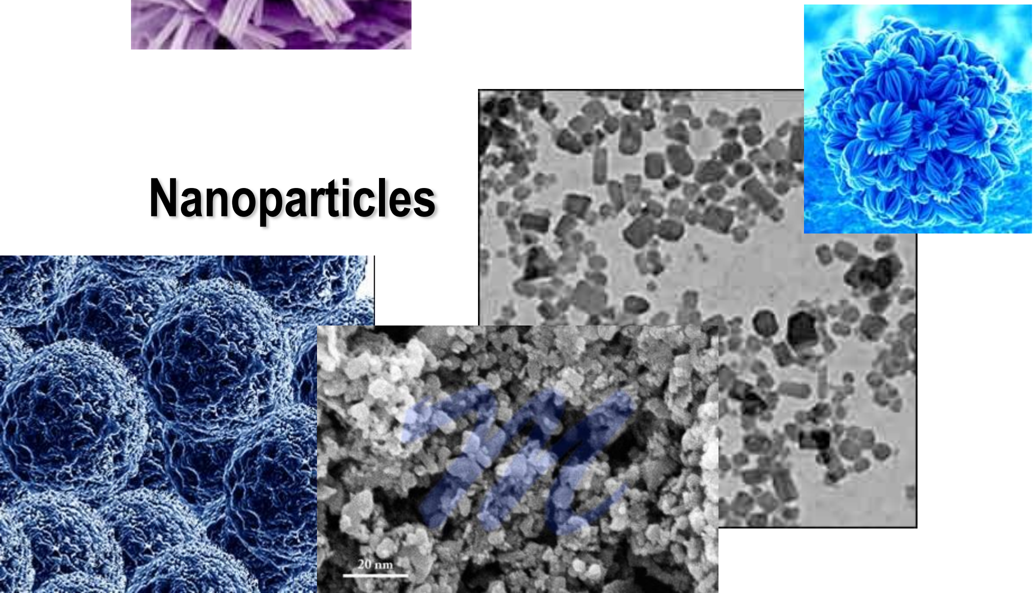
Nanowires



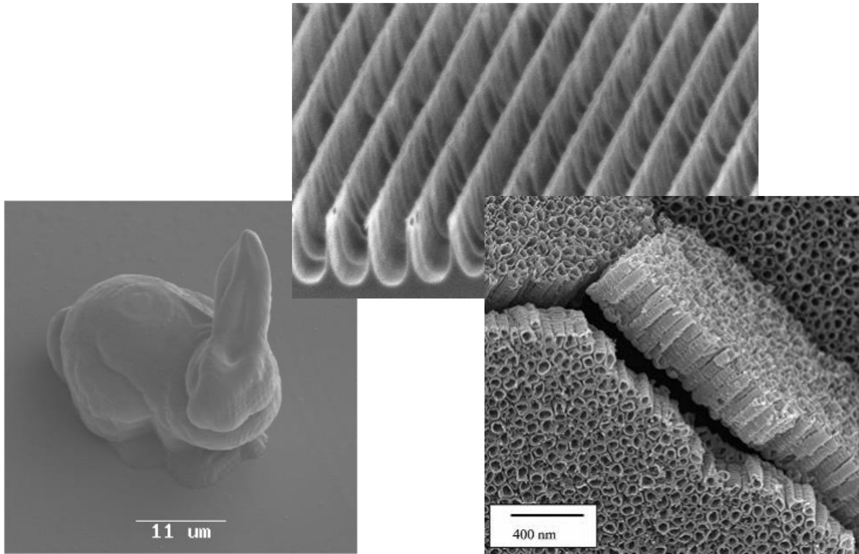
Nanomembranes



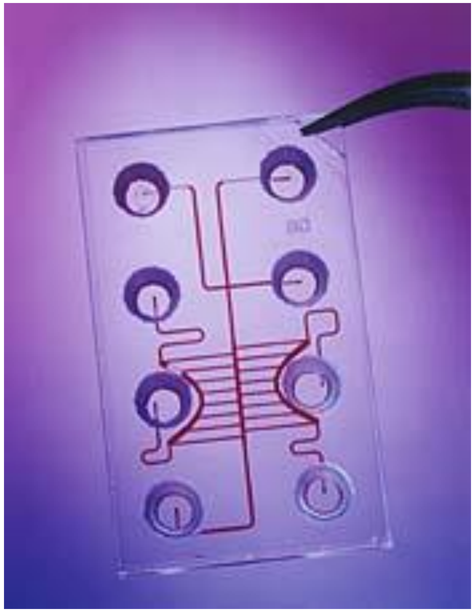
Nanoparticles



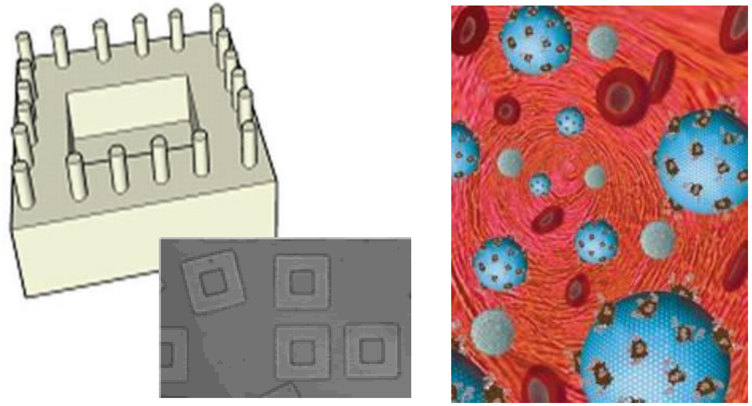
Nano-others



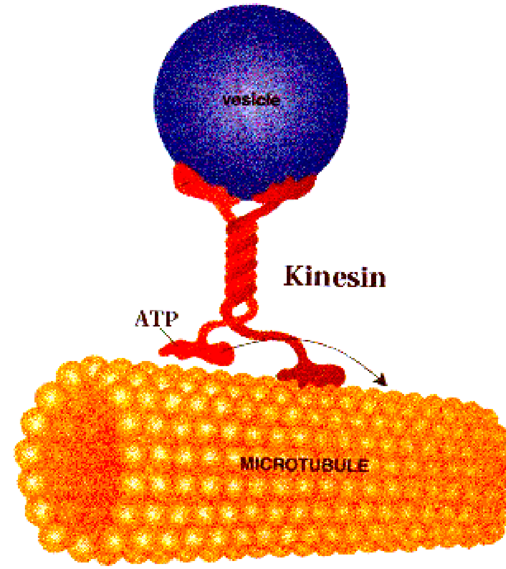
Nanotechnology has biomedical applications



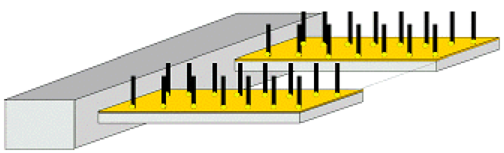
Lab on a Chip
Technology on the micron scale

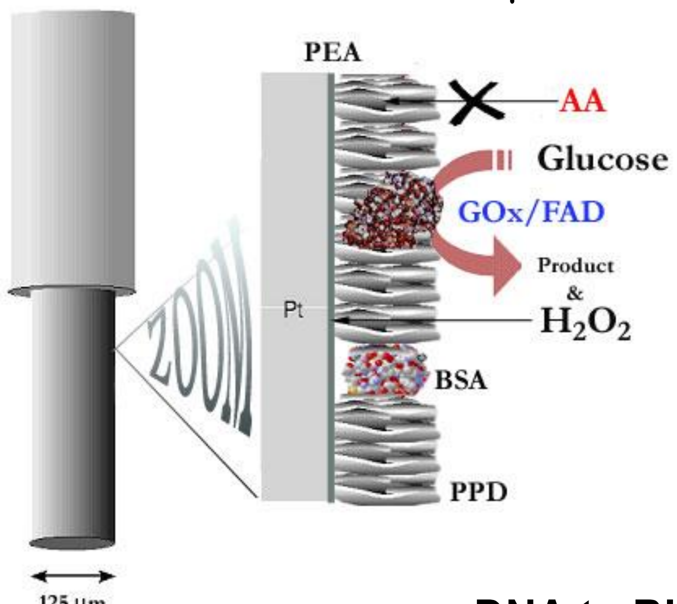


Therapeutic Drug Delivery Devices
10nm-100 μm

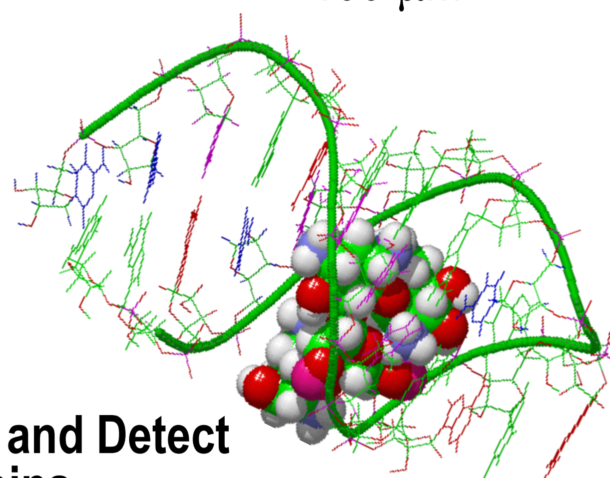


Kinesin walks on Microtubule
~100 μm





Biosensors
Detection from DNA to Proteins
10nm-100 μm



DNA to Bind and Detect Proteins
10nm-100 μm

Sensor

- A sensor is an instrument that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or motion)

- It collects and measures data regarding some property of a phenomenon, object, or material

- Sensors are an important part to any measurement and automation application

- The sensor is responsible for converting some type of physical phenomenon into a quantity measurable by a data acquisition (DAQ) system

Why Nanosensors

- Particles that are smaller than the characteristic lengths associated with the specific phenomena often display new chemistry and new physics that lead to new properties that depend on size

- When the size of the structure is decreased, surface to volume ratio increases considerably and the surface phenomena predominate over the chemistry and physics in the bulk

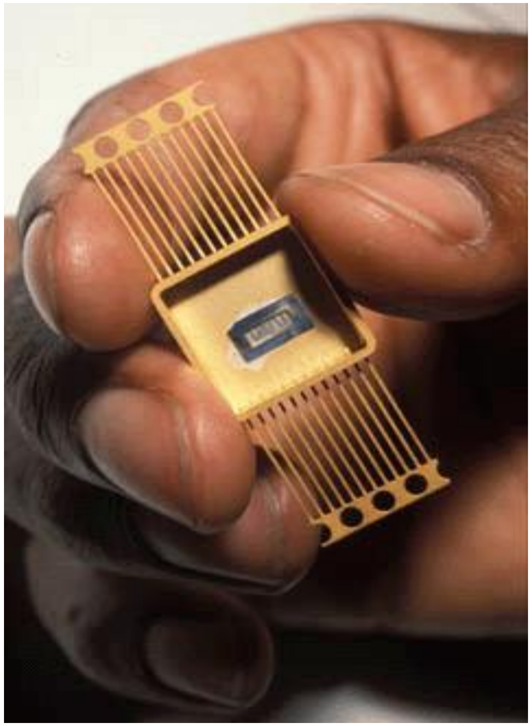
- The reduction in the size of the sensing part and/or the transducer in a sensor is important in order to better miniaturise the devices

- Science of nano materials deals with new phenomena, and new sensor devices are being built that take advantage of these phenomena

- Sensitivity can increase due to better conduction properties, the limits of detection can be lower, very small quantities of samples can be analysed, direct detection is possible without using labels, and some reagents can be eliminated.

Definition of Nanosensors

- Nanosensor: an extremely small device capable of detecting and responding to physical stimuli with dimensions on the order of one billionth of a meter
- Physical Stimuli: biological and chemical substances, displacement, motion, force, mass, acoustic, thermal, and electromagnetic

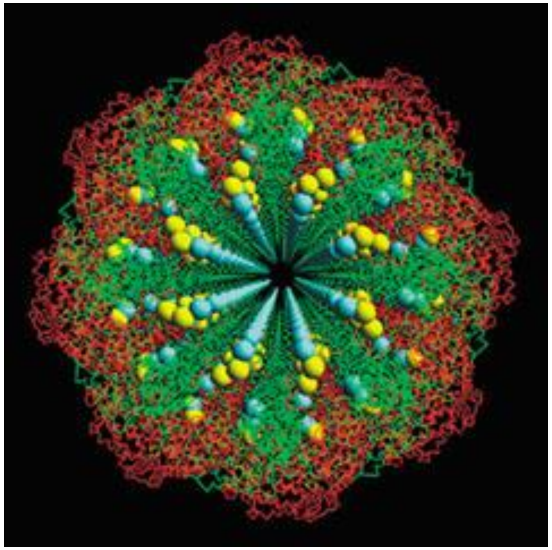


http://www.rpi.edu/locker/25/001225/public_html/nanowebprojects/laurasmith/nanosensors.ppt

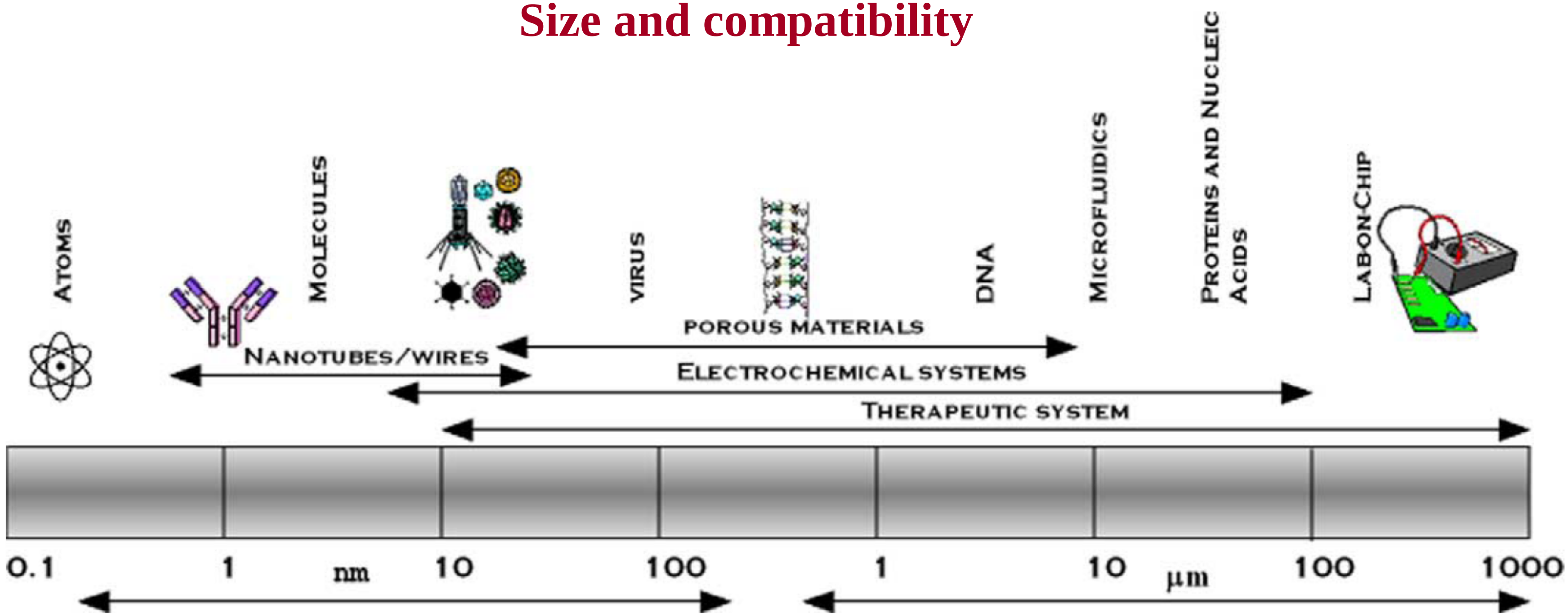
Definition of Nanosensors (cont.)

Current nanosensors device:

- Nanostructured materials - e.g. porous silicon
- Nanoparticles
- Nanoprobes
- Nanowire nanosensors
- Nanosystems
  - Cantilevers, NEMS, mostly theoretical



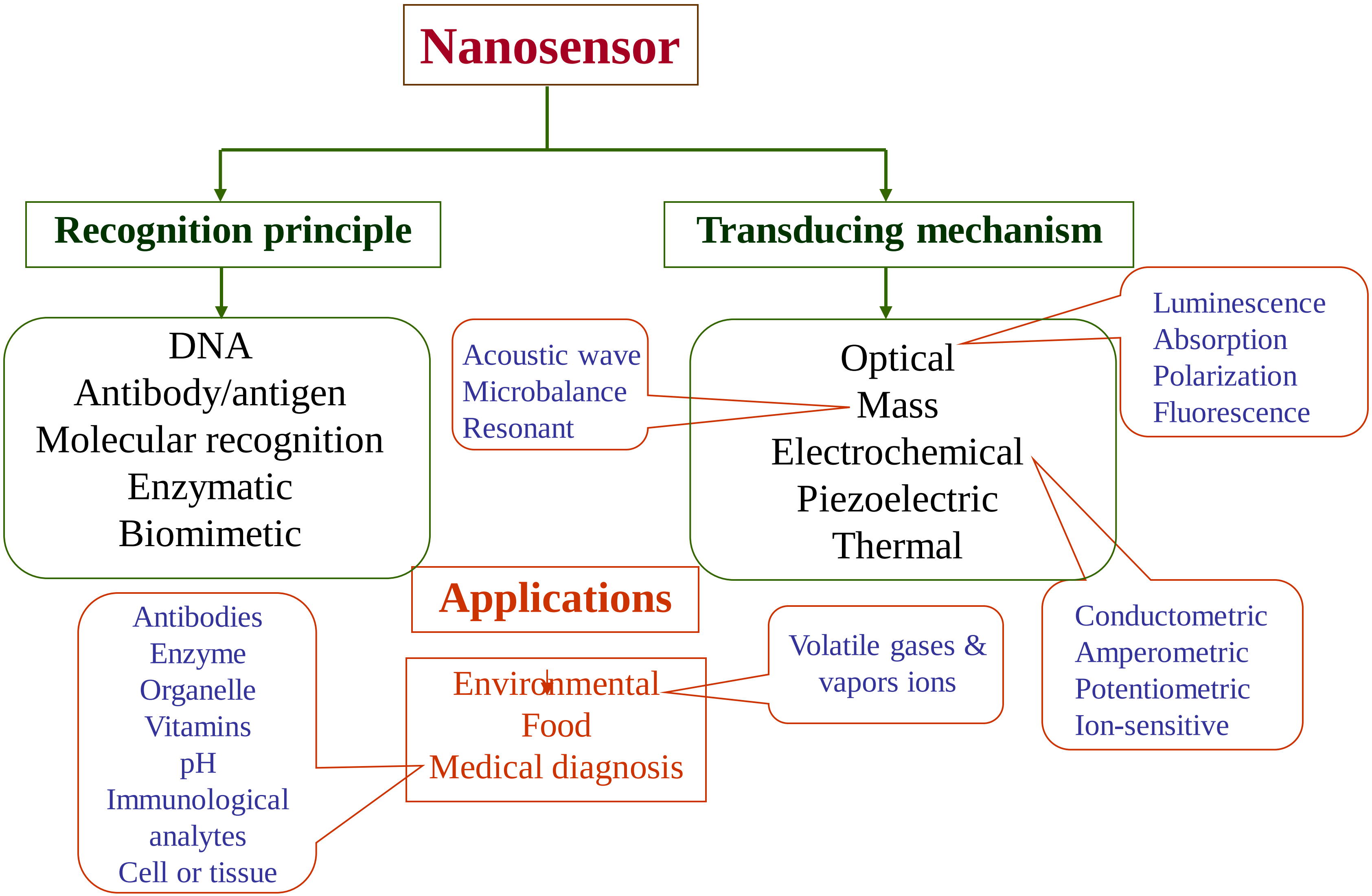
Size and compatibility



Nano sensors deliver real-time information about the antibodies to antigens, cell receptors to their glands, and DNA and RNA to nucleic acid with a complimentary sequence

Sensitivity of the conventional biosensors is in the range between 10^3 and 10^4 colony forming units (CFU)/ml. The dimensional compatibility of nanostructured materials renders nanotechnology as an obvious choice derived from its ability to detect ~ 1 CFU/ml sensitivity

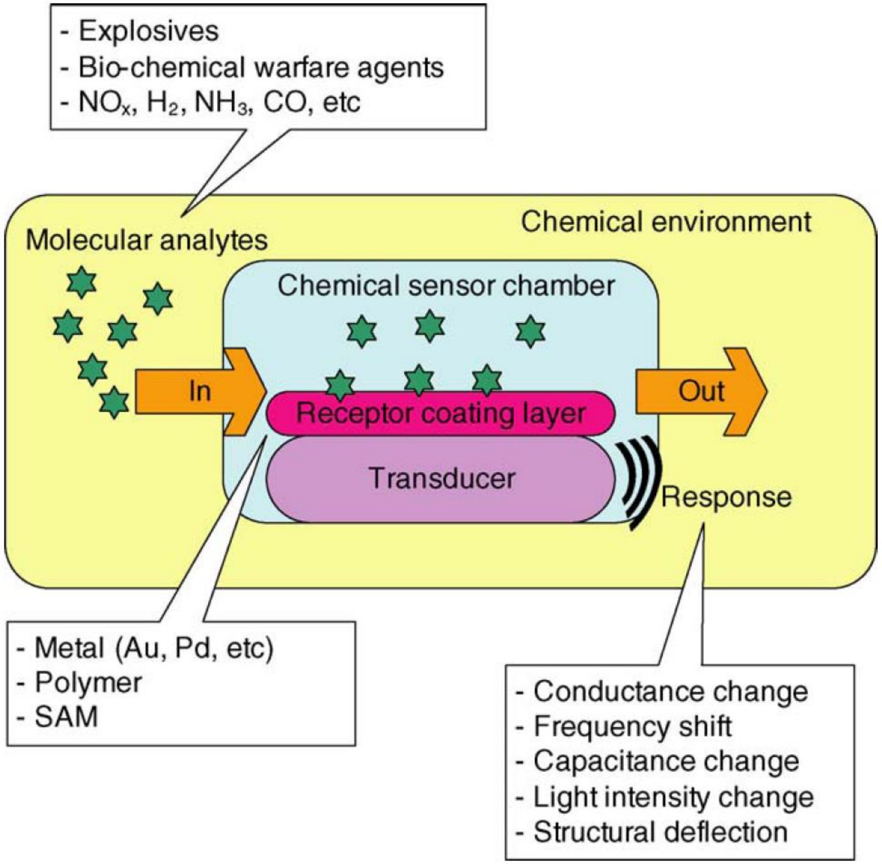
Reduced detection time than conventional methods



Scheme 1. Representation of recognition process and application of Nanosensor

Electronic Nose

General structure of a chemical sensor



Three figures of merit related to gas sensing technology:

- Reversibility
- Sensitivity
- Selectivity

Exceptional properties of carbon nanotubes

- ✓ CNT have a high length-to-radius ratio, which allows for greater control over the unidirectional properties of the materials produced

- ✓ they can behave as metallic, semiconducting or insulating material depending on their diameter, their chirality, and any functionalisation or doping

- ✓ they have a high degree of mechanical strength. In fact they have a greater mechanical strength and flexibility than carbon fibres

- ✓ their properties can be altered by encapsulating metals inside them to make electrical or magnetic nanocables or even gases, thus making them suitable for storing hydrogen or separating gases

Metal oxide nano-crystals for sensing

- Metal oxides possess a broad range of electronic, chemical, and physical properties that are often highly sensitive to changes in their chemical environment.

- The sensing properties of semiconductor metal oxide (nano-belts, nano-wires or nano-ribbons) assures improved selectivity and stability due to there crystallinity

- Their peculiar characteristics and size effects make them interesting both for fundamental studies and for potential nano-device applications, leading to a third generation of metal oxide gas sensors

Working principle of metal oxide gas sensors

1. Conductimetric metal oxide gas sensors rely on changes of electrical conductivity due to the interaction with the surrounding atmosphere
2. When a metal oxide is semiconducting, the charge transfer process induced by surface reactions determines its resistance

Sensing mechanism in metal oxide gas sensors is related to ionosorption of species over their surfaces

Ionosorbed species when operating in ambient air are oxygen and water

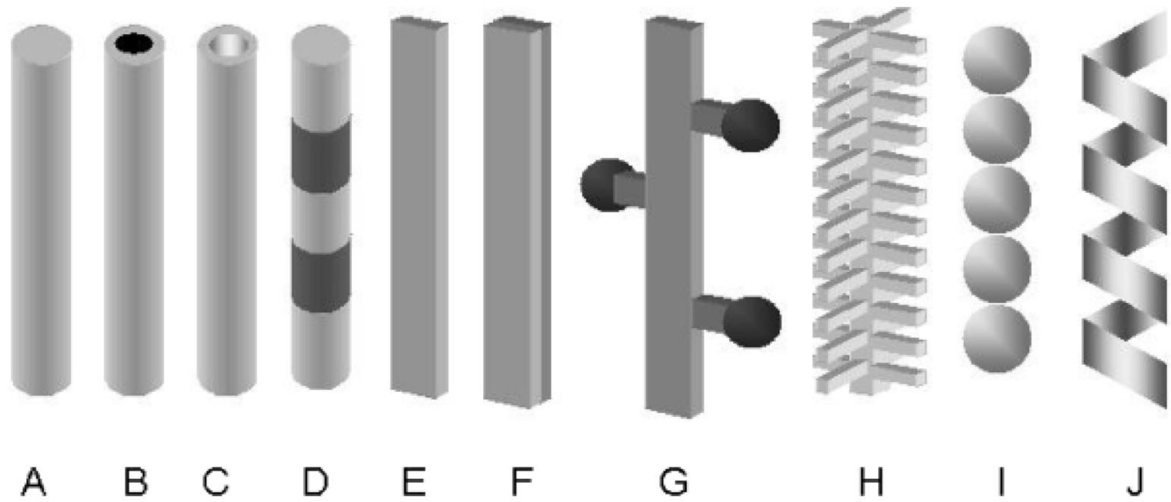
For some reducing gases, gas detection is related to the reactions between the species to be detected and ionosorbed surface oxygen

$$\mathrm{CO_{gas}} \rightarrow \mathrm{CO_{ads}}$$

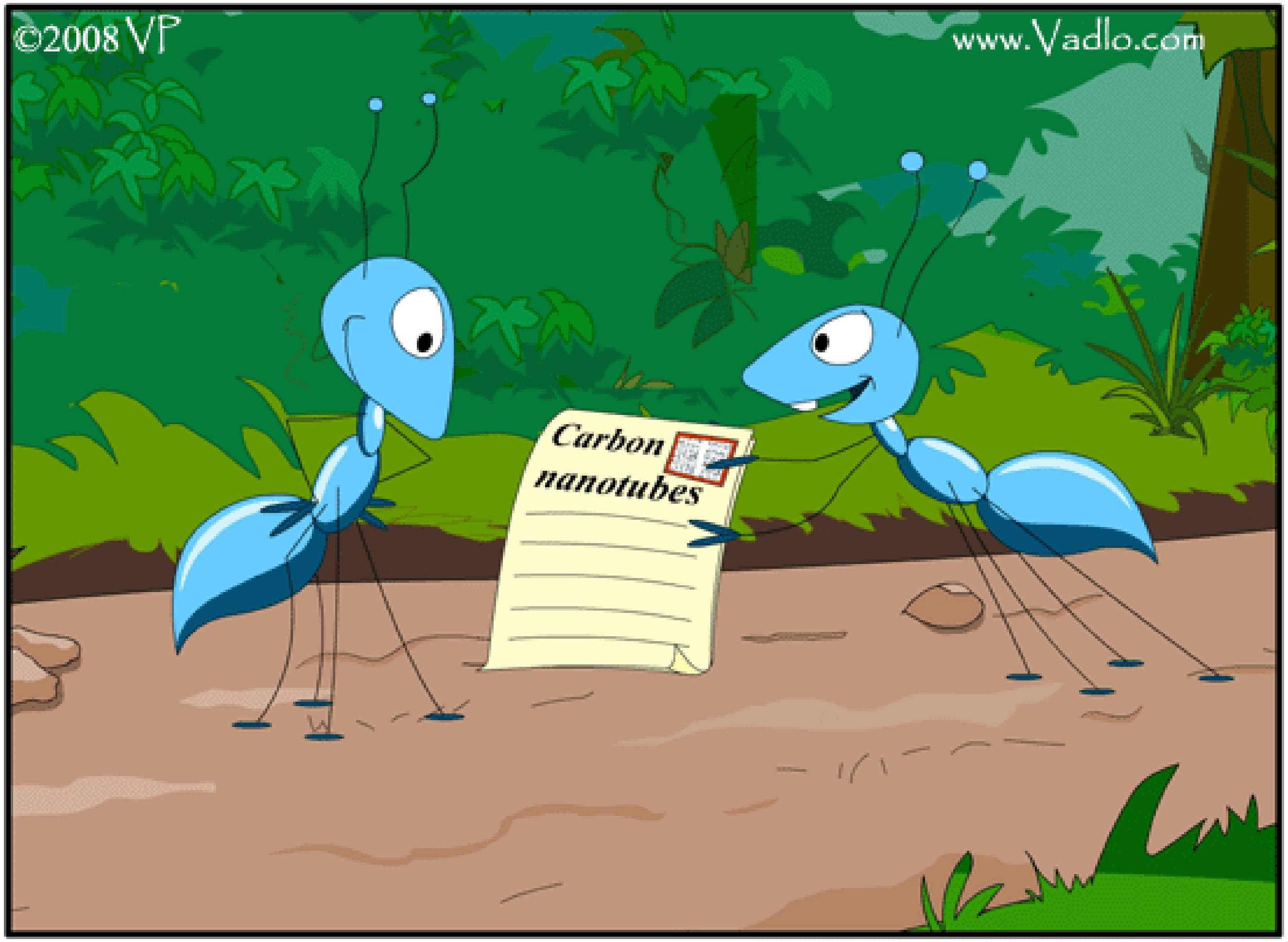
$$\mathrm{CO_{ads}} + \mathrm{O_{ads}}^{-} \rightarrow \mathrm{CO_{2,gas}} + e^{-}$$

These consume ionosorbed oxygen and in turn change the electrical conductance of metal oxide

A schematic summary of the kinds of quasi-one-dimensional metaloxide nanostructures



(*A*) nanowires and nanorods; (*B*) core-shell structures with metallic inner core, semiconductor, or metal-oxide; (*C*) nanotubules/nanopipes and hollow nanorods; (*D*) heterostructures; (*E*) nanobelts/nanoribbons; (*F*) nanotapes, (*G*) dendrites, (*H*) hierarchical nanostructures; (*I*) nanosphere assembly; (*J*) nanosprings.



Finally, we can drink Coke with a straw.