Jean-Claude Boudenot
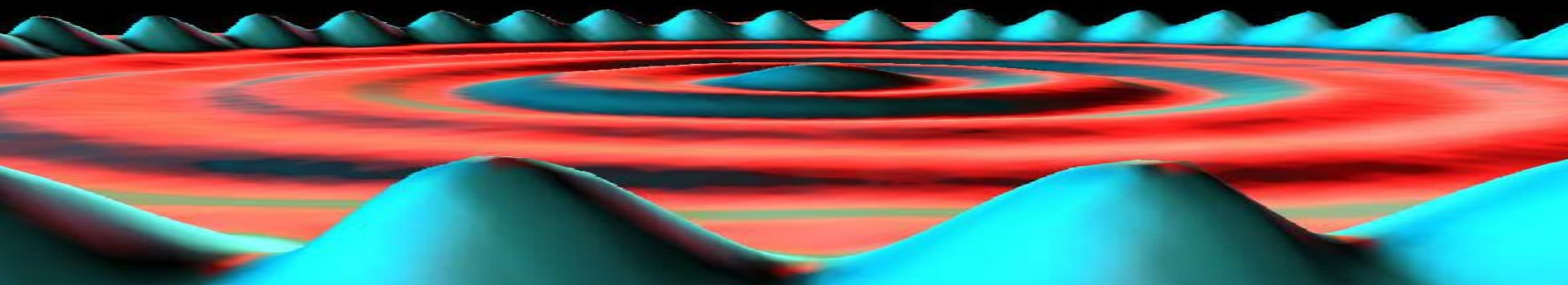**Thales Research & Technology**

XXISt century : The century of Nanoconvergence

From data storage to power cables

Nanotechnology is not new !

Lycurgus' cup, Roman Empire IV[E] Century, British Museum
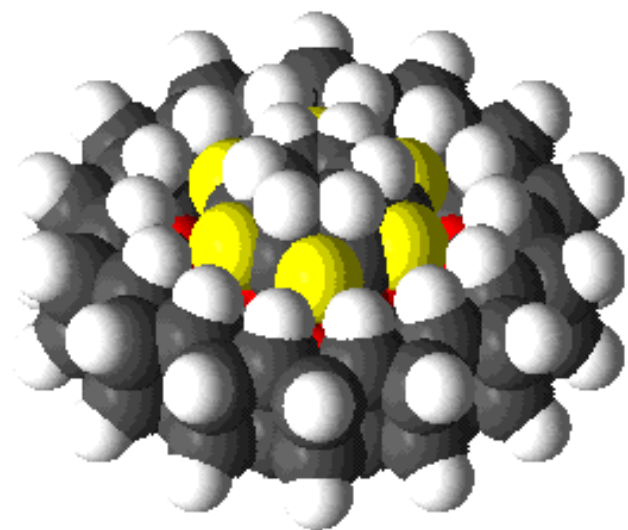

Transmitted light = red ; reflected light = green
(40 nm particles in the glass)

What is nanotechnology ?

Convergence between technology, physics, chemistry and biology

Exploit the specific properties of the world at atomic scale (mesoscopic and quantum effects)

If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering

Neal Lane, Former Assistant to the US President for Science and Technology

Melting point depends on the size !
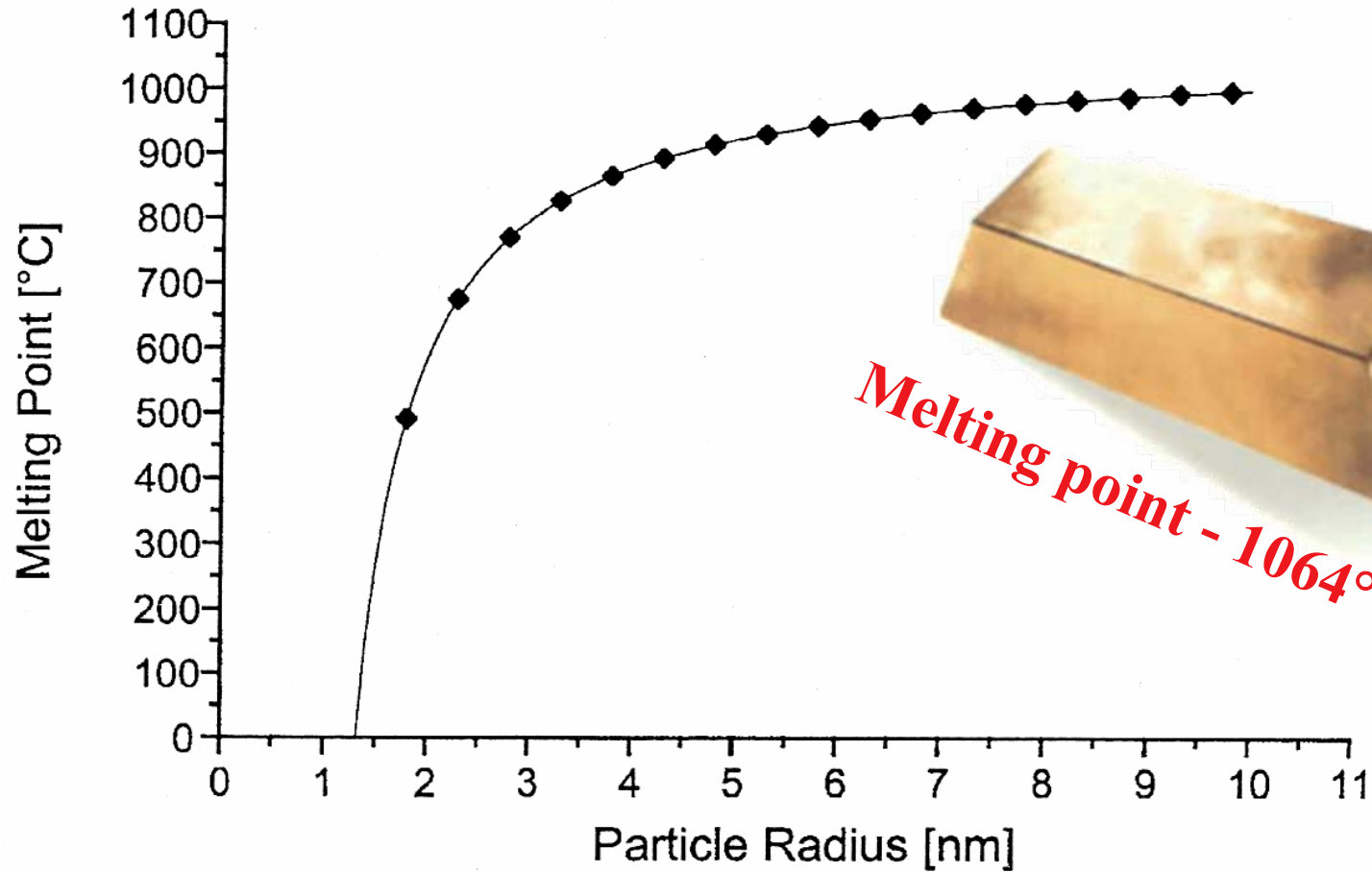
*Source: K.J. Klabunde, 2001*

OUTLINE

- Computing and Data Storage

- Materials and Manufacturing

- Health and Medicine

- Energy and Environment

- Transportation

- Security

- Carbon nanotubes, the way to transport electricity

OUTLINE

- **Computing and Data Storage**

- Materials and Manufacturing

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- Carbon nanotubes, the way to transport electricity

Computing & Data storage

- Processors performance X 10^6 (Gflops -> Pflops)

- Small mass storage devices $\rightarrow$ multi-tera bit levels

- Smart nanosensors: collecting, processing and communicating massive amounts of data with minimal size, weight, and power consumption

- Higher transmission frequencies : more efficient utilization of optical spectrum to provide at least 10 times the current bandwidth

- Quantum computing

Power Density Extrapolation
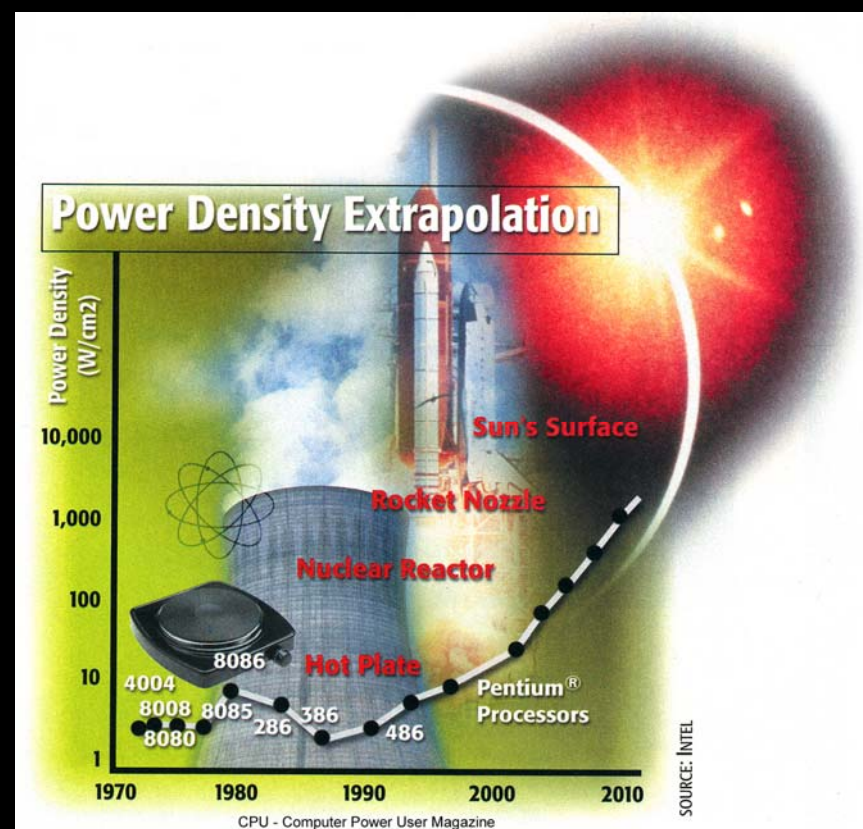
Data storage capacity

Current data storage density ~ 10^9 bits/cm^2

1 bit ~ 100 atoms (at the best)

Theoretical data storage capacity = X 1000 (10^{12} bits/cm^2)

3D => Data storage capacity could be ~ 10^{16} bits/cm^3
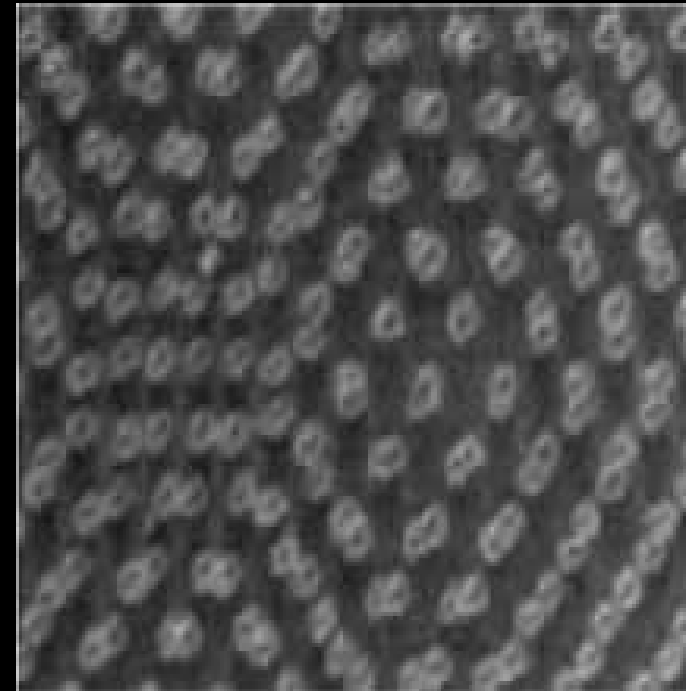
(10^{12} bits/cm^2 x 10^4/cm)

IBM Millipede

Cantilever array on CMOS chip

Storage medium on MEMS scanner
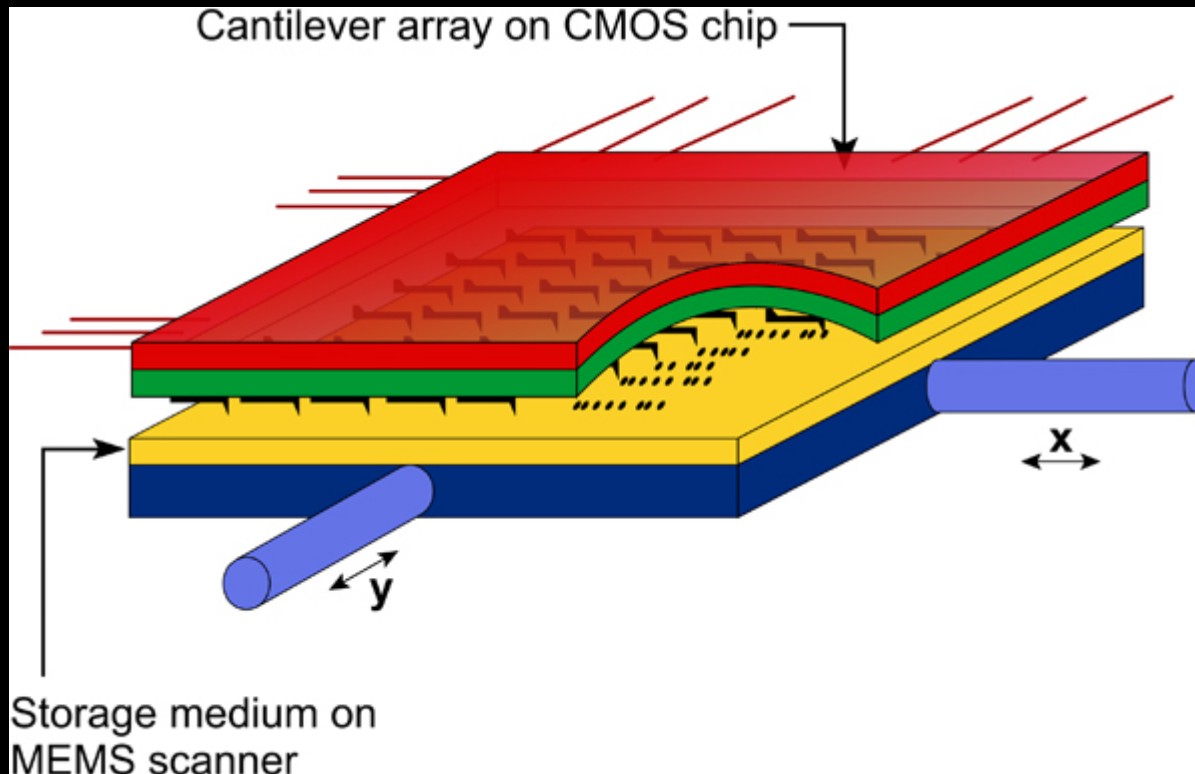
Combine the advantage of the hard disk (storage capacity, target ~ 1 Tbit /in²) and the advantage of DRAM (speed access)

Principle: nanometric holes on the surface of an thermo active polymer
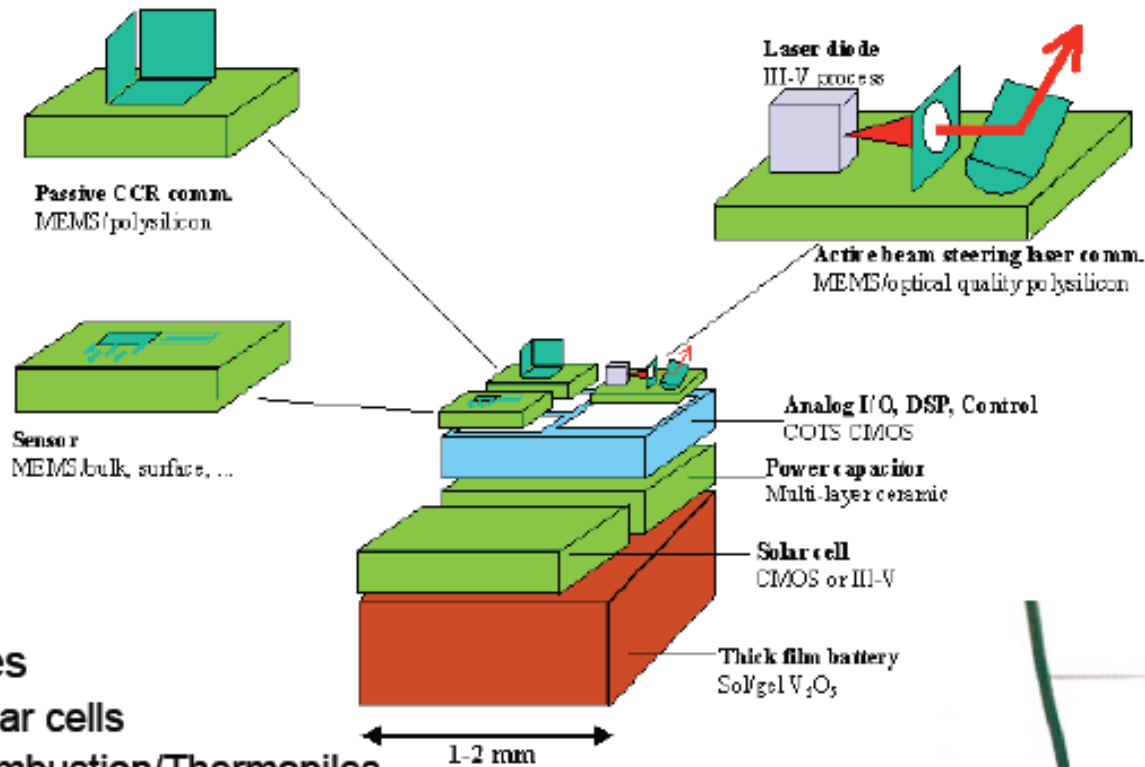
IBM Millipede

3.10^{10} bits / cm^2

10 nm

IBM Advanced Storage Roadmap

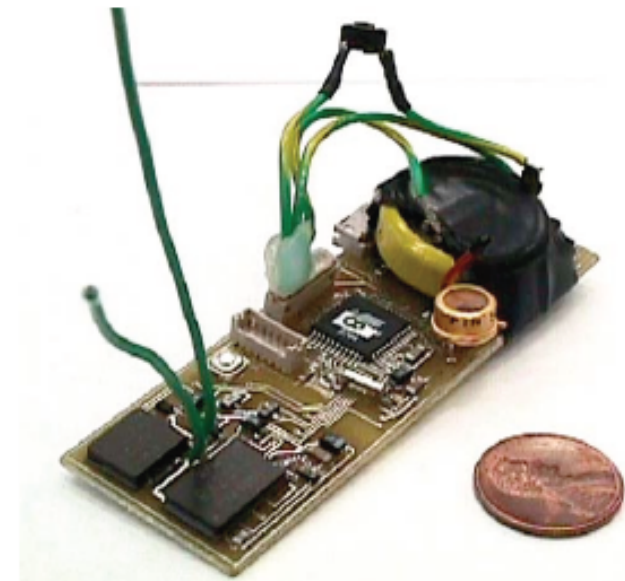ED GROCHOWSKI at ALMADEN
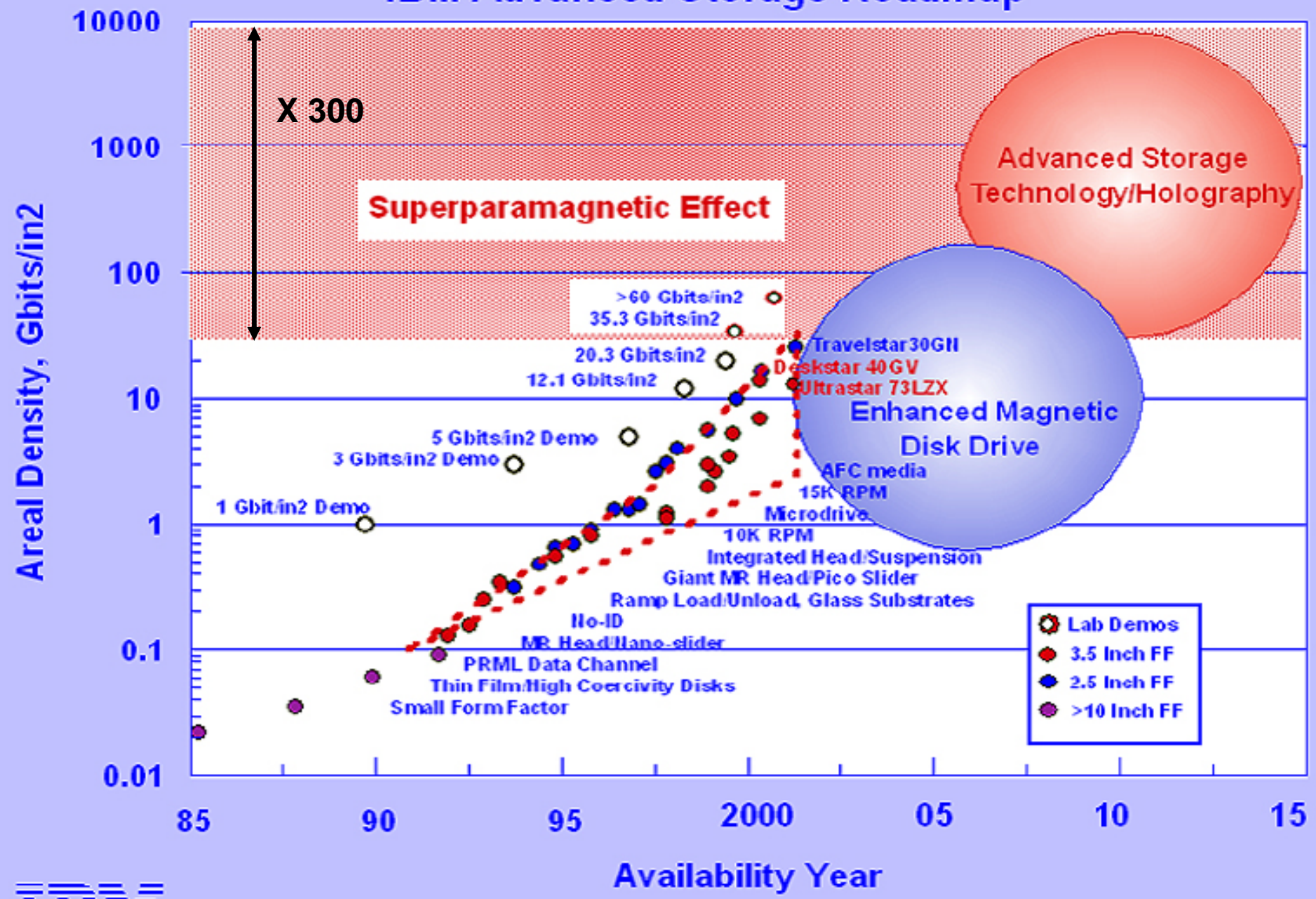
Smart dust components / smart sensors

Smart nanosensors

- Autonomous in energy
  - Sensing
  - Processing
- Communicating

Passive CCR comm.
MEMS/polysilicon

Laser diode
III-V process

Active beam steering laser comm.
MEMS/optical quality polysilicon

Sensor
MEMS/bulk, surface, ...

Analog I/O, DSP, Control
COTS CMOS

Power capacitor
Multi-layer ceramic

Solar cell
CMOS or III-V

Thick film battery
Sol/gel V_2O_5

1-2 mm

- **Sources**
  - Solar cells
  - Combustion/Thermopiles
- **Storage**
  - Batteries ~1 J/mm^3
  - Capacitors ~1 mJ/mm^3
- **Usage**
  - Digital control: nJ/instruction
  - Analog circuitry: nJ/sample
  - Communication: nJ/bit

Smart sensors
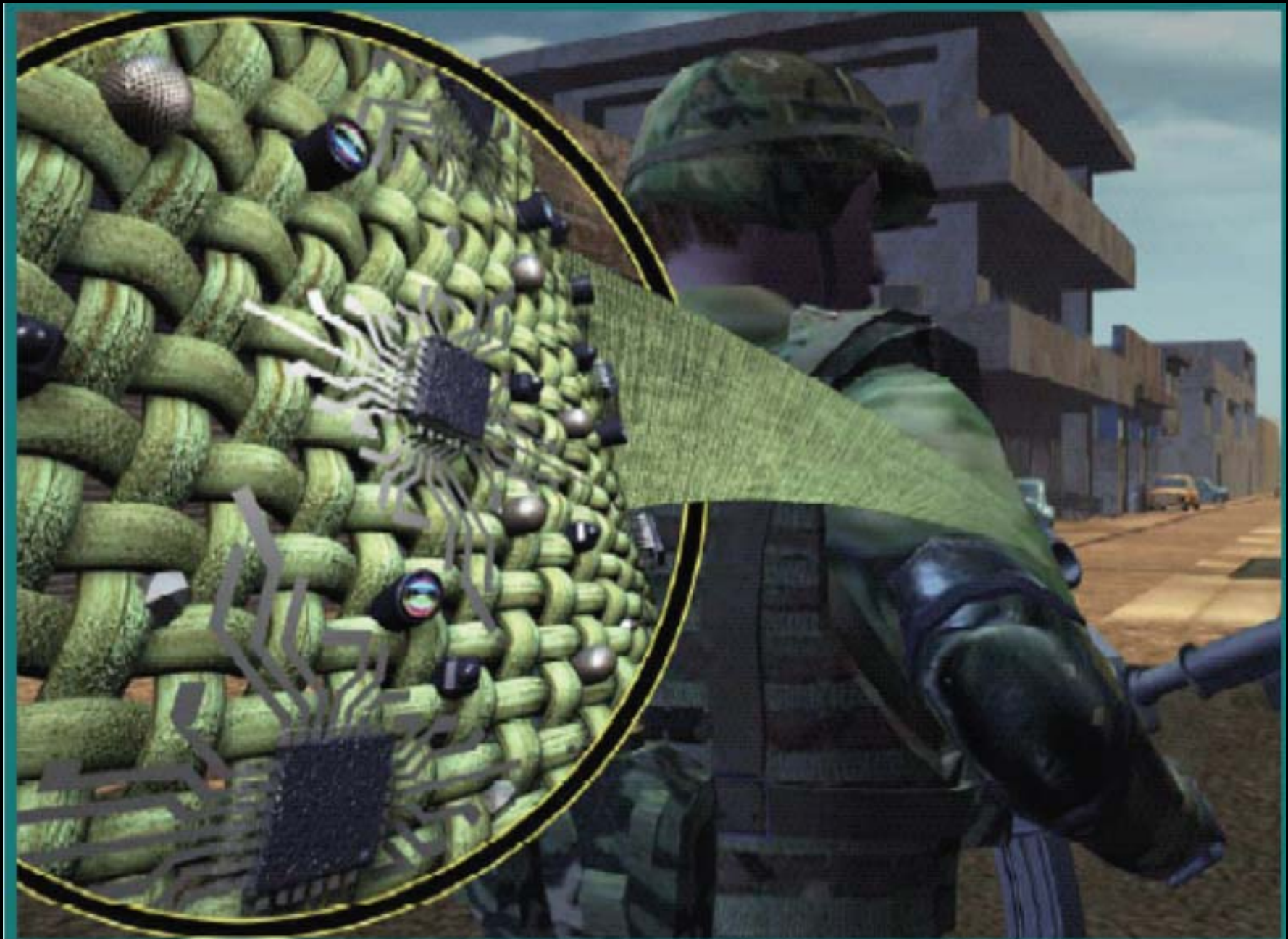
Smart sensors on micro flyers
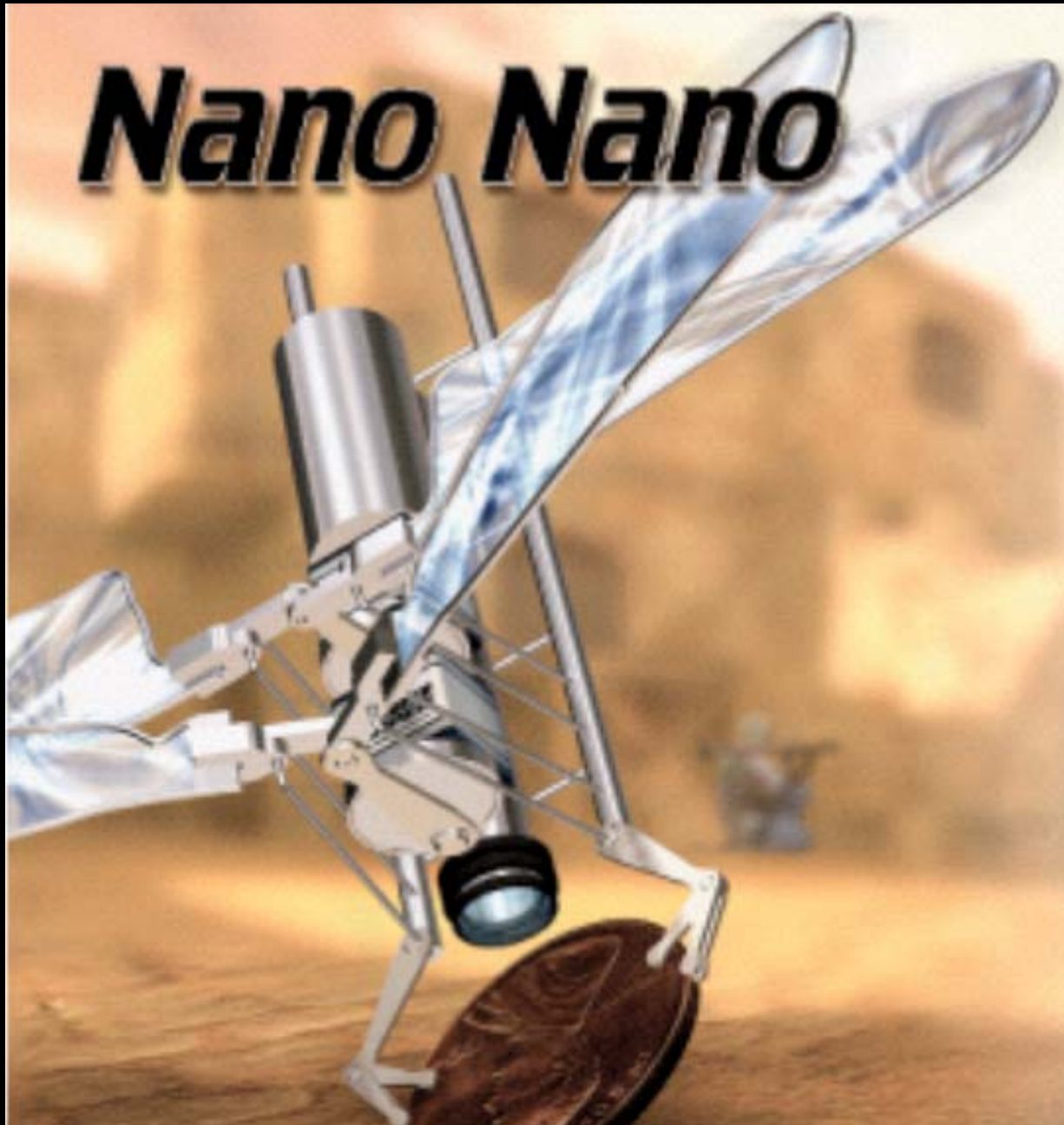
UAV
insect size

Quantum computing

Schrödinger's cat

Take a cat, cyanide, a radioactive particle, put the whole in a box and let wait one hour!

Letter from Schrödinger to Einstein, 1935
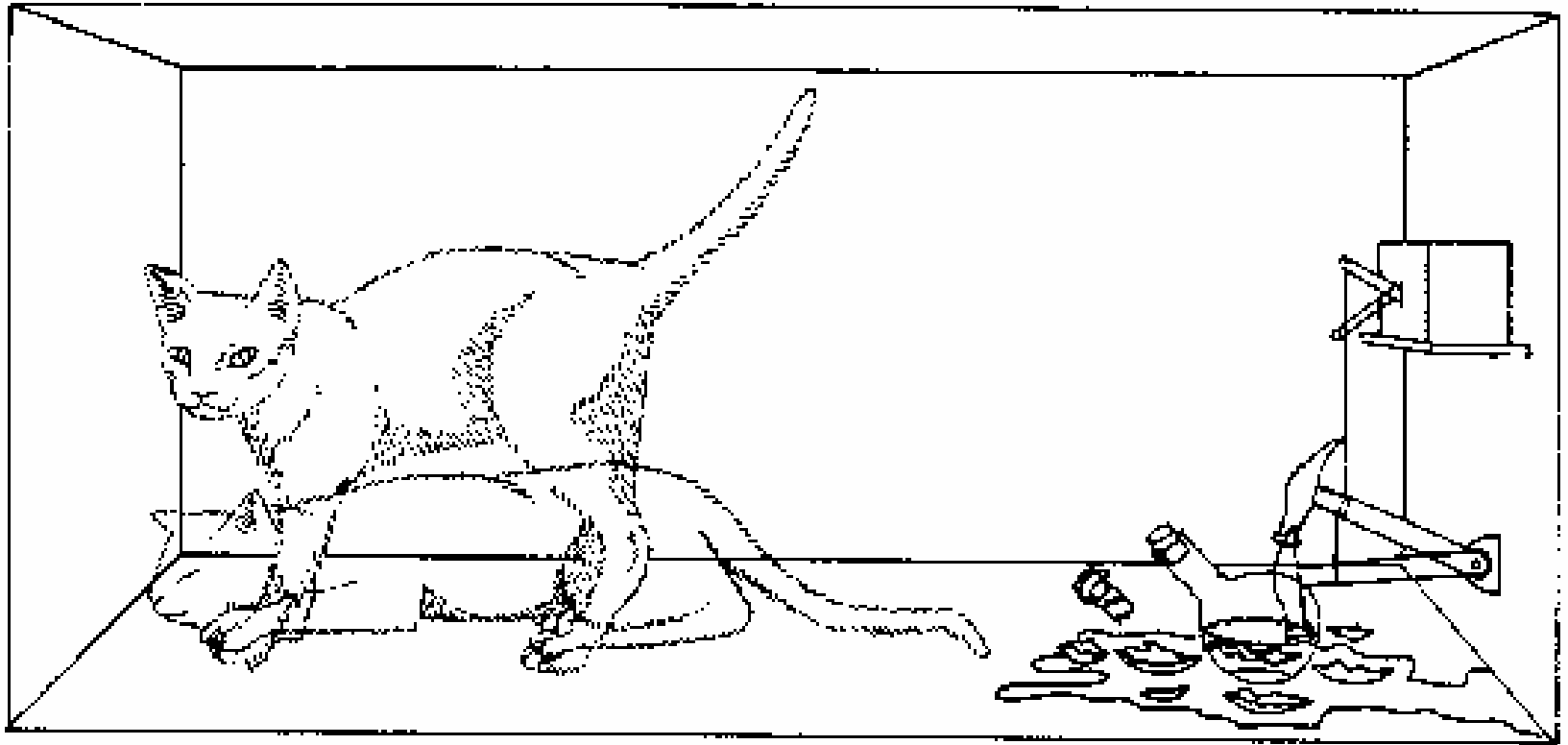
$$|\psi> = 1/\sqrt{2} \, |\text{Dead cat}> + 1/\sqrt{2} \, |\text{Alive cat}>$$

Quantum computing

A traditional bit is **1** or **0**

A Quantum bit (Qubit) is a superposition of state **1** and **0**

$$|\psi> = \alpha|0> + \beta|1>$$

$(0 \leq \alpha \leq 1 \ \text{ and } \ 0 \leq \beta \leq 1)$

Quantum computing
Is it SF ?
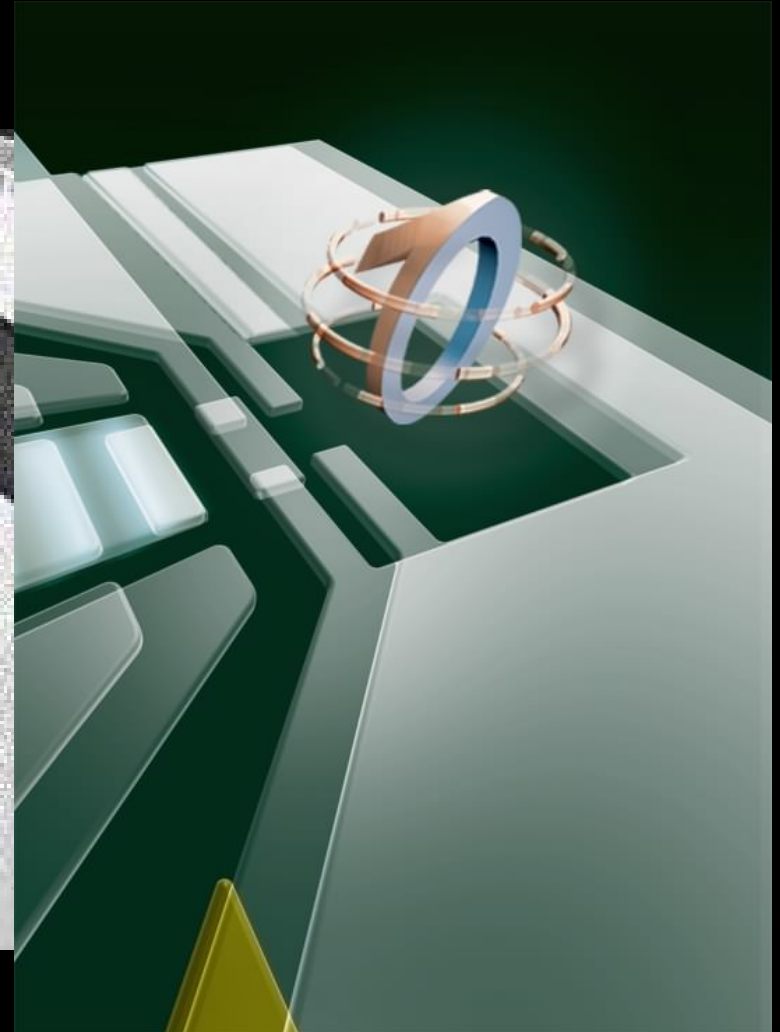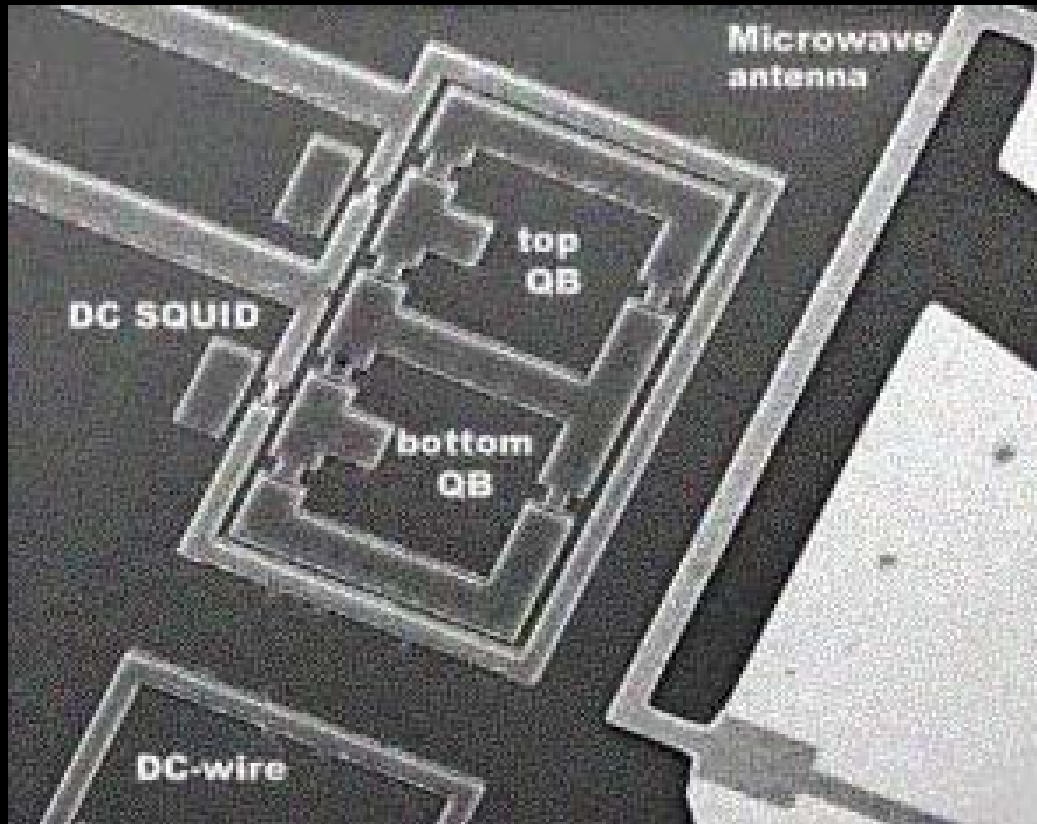
Quantum computing
Shor's algorithm (1995)

Principle of RSA cryptography: factorization of a number

The solution is easy to verify (multiplication) but difficult to find (factorization in prime number)

Example:

Classical computing: three months to factorize a number of 130 digits and 10^{10} years (the age of the Universe) for a number of 400 digits

Quantum computing: still three months to factorize a number of 130 digits but only 3 years for a number of 400 digits!

Quantum computing
First tentative

Qubit Ion trap
(NIST)

Quantronium super conducting qubit
(CEA)

Quantum computing is not for
tomorrow !

Quantum cryptography

Example: Idquantique (start up) : www.idquantique.com

Quantum cryptography already exists :
60 km with OF ; 150 km with free space transmission

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- Carbon nanotubes, the way to transport electricity

Materials and manufacturing
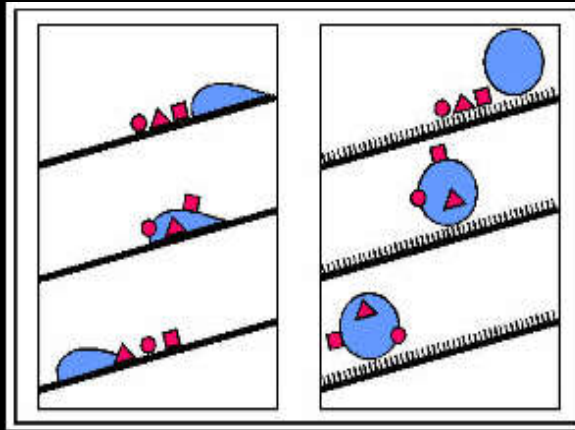
Self-cleaning surface (lotus effect)

W. Barthlott, Univ. of Hamburg

Epicuticular wax

REM recording of a holographically produced self-cleaning surface.
© Fraunhofer ISE
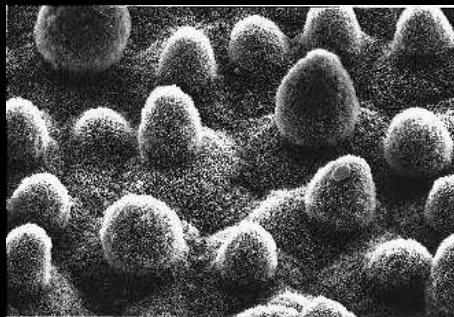
(Source: Metin Sitti, CMU)

Self-cleaning surface
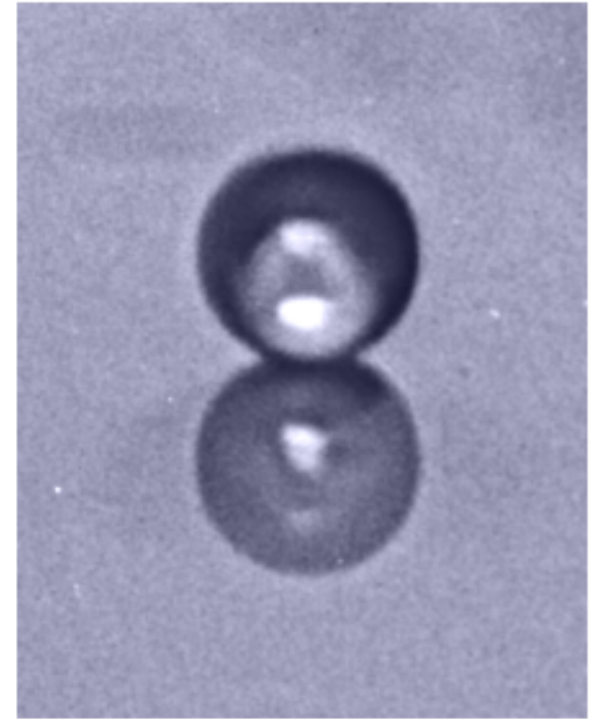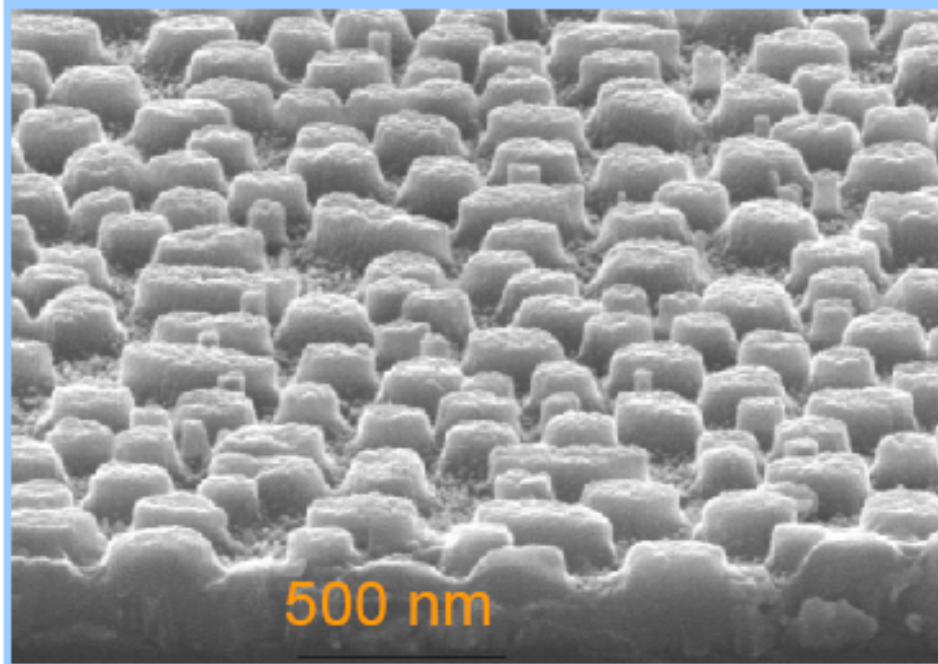
Nano relief => the water does not wet

Self-cleaning glass

Pilkington's self-cleaning glass

1
DIRT
TiO$_2$ NANO COATING
GLASS

2

U V

3
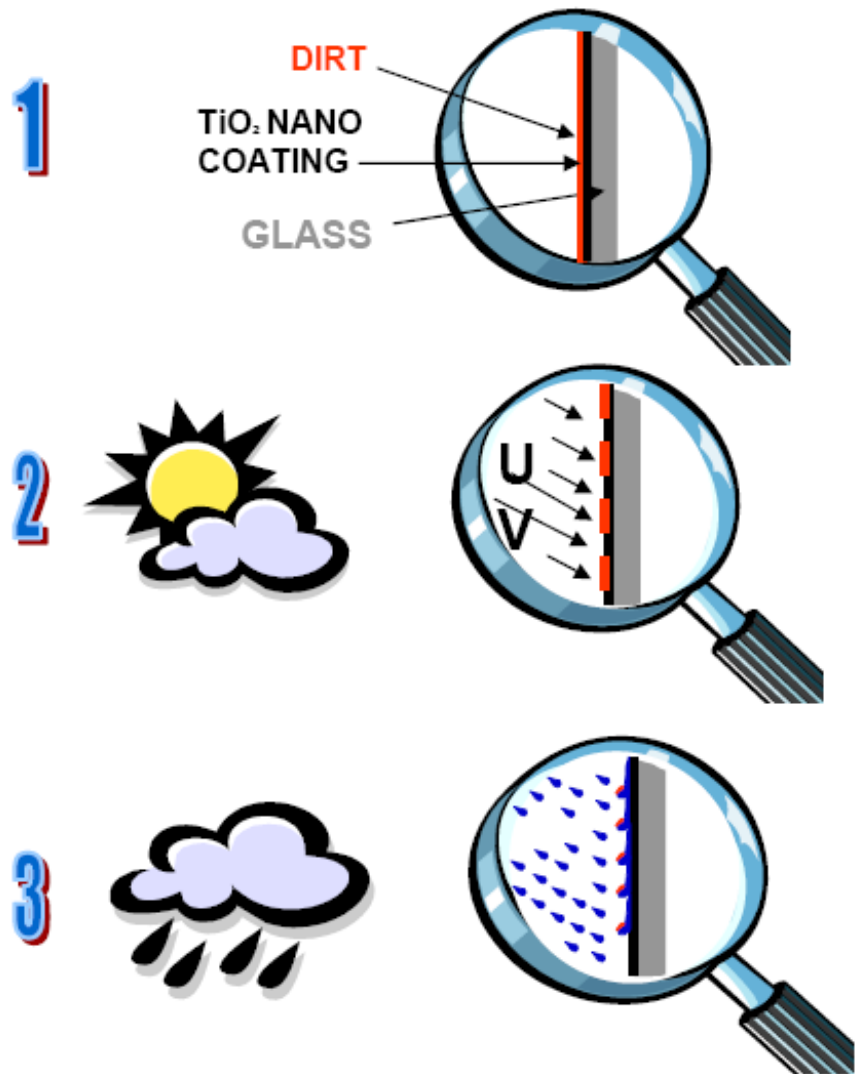
SPACEDAILY
YOUR PORTAL TO SPACE

Counterweight

Geosynchronous
orbit

Cable

Carbon nanotubes

Climber
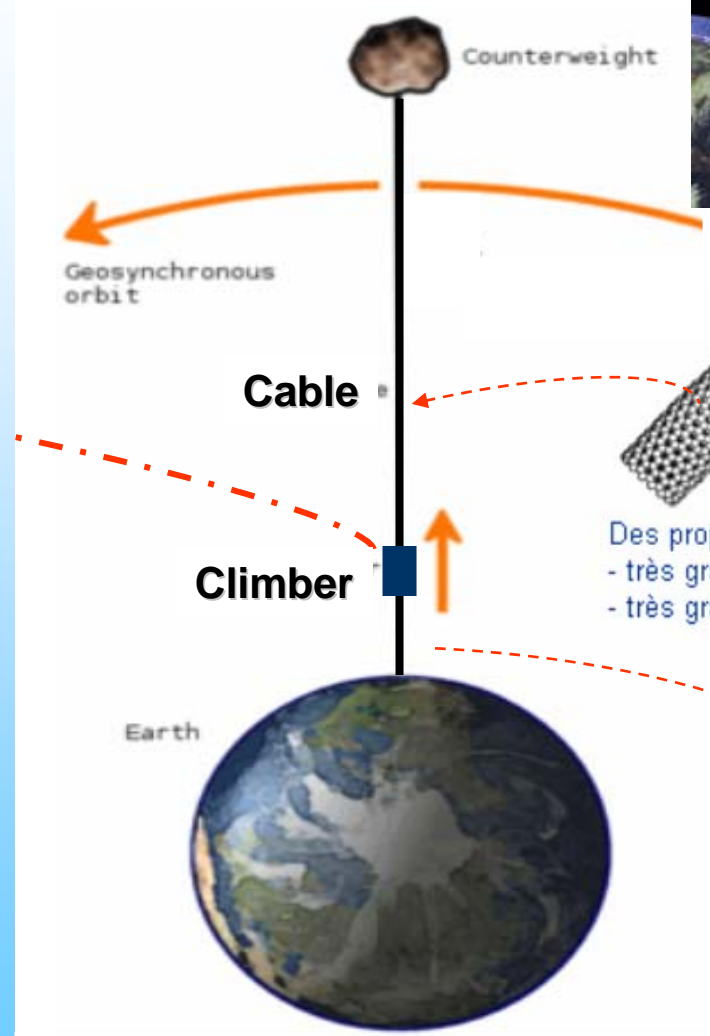
Des propriétés mécaniques hors du commun :
- très grande élasticité (module d'élasticité > 1000 GPa),
- très grande flexibilité (crack stress : 45 GPa)

Earth

A space elevator would consist of a cable
attached to the surface and reaching
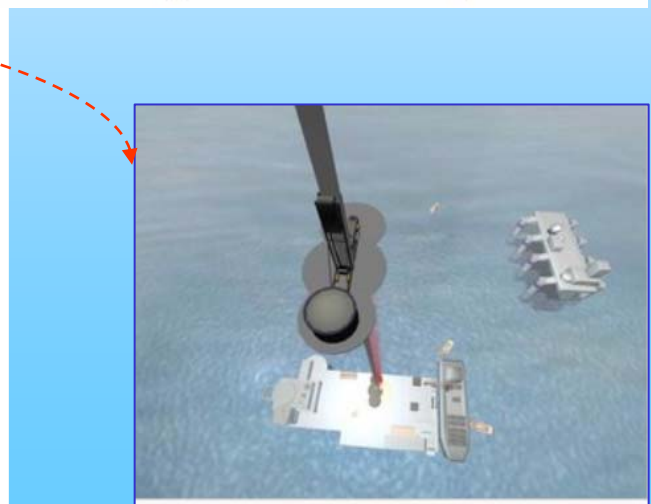
ne concept for the space elevator has it tethered to a
obile seagoing platform.

Space elevator

Edwards Bradley's project :
The satellite is placed in orbit thanks to the CNT cable

The satellite is pushed thanks to the ground laser which strike the solar panels installed under the platform

Estimated cost ~ 6 billion $ for the first project

Nano ceramic

Capacitors

Mirrors

Medical

Optics
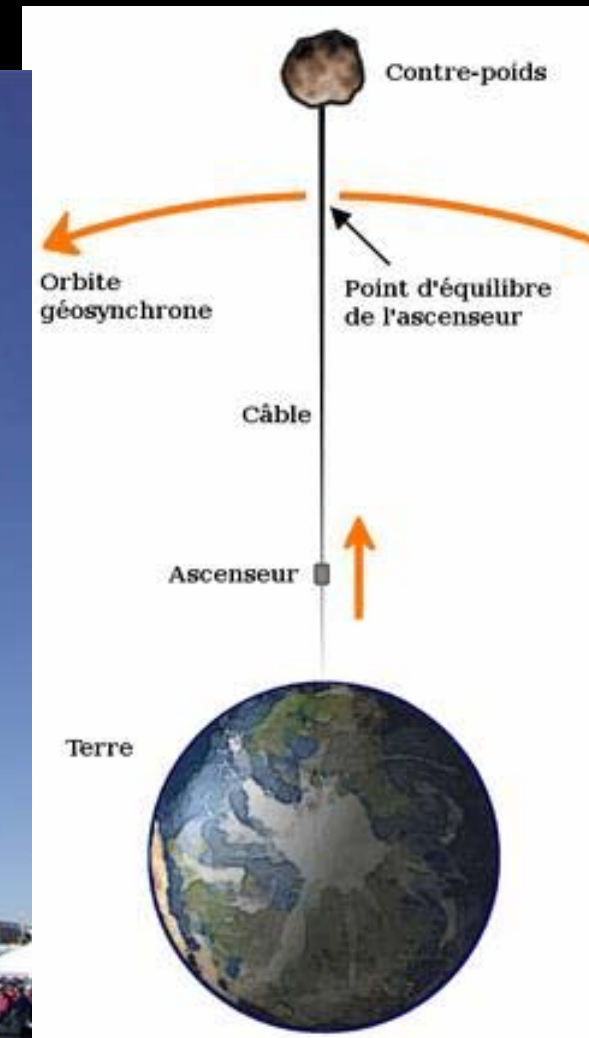
Nano Ceramic laser
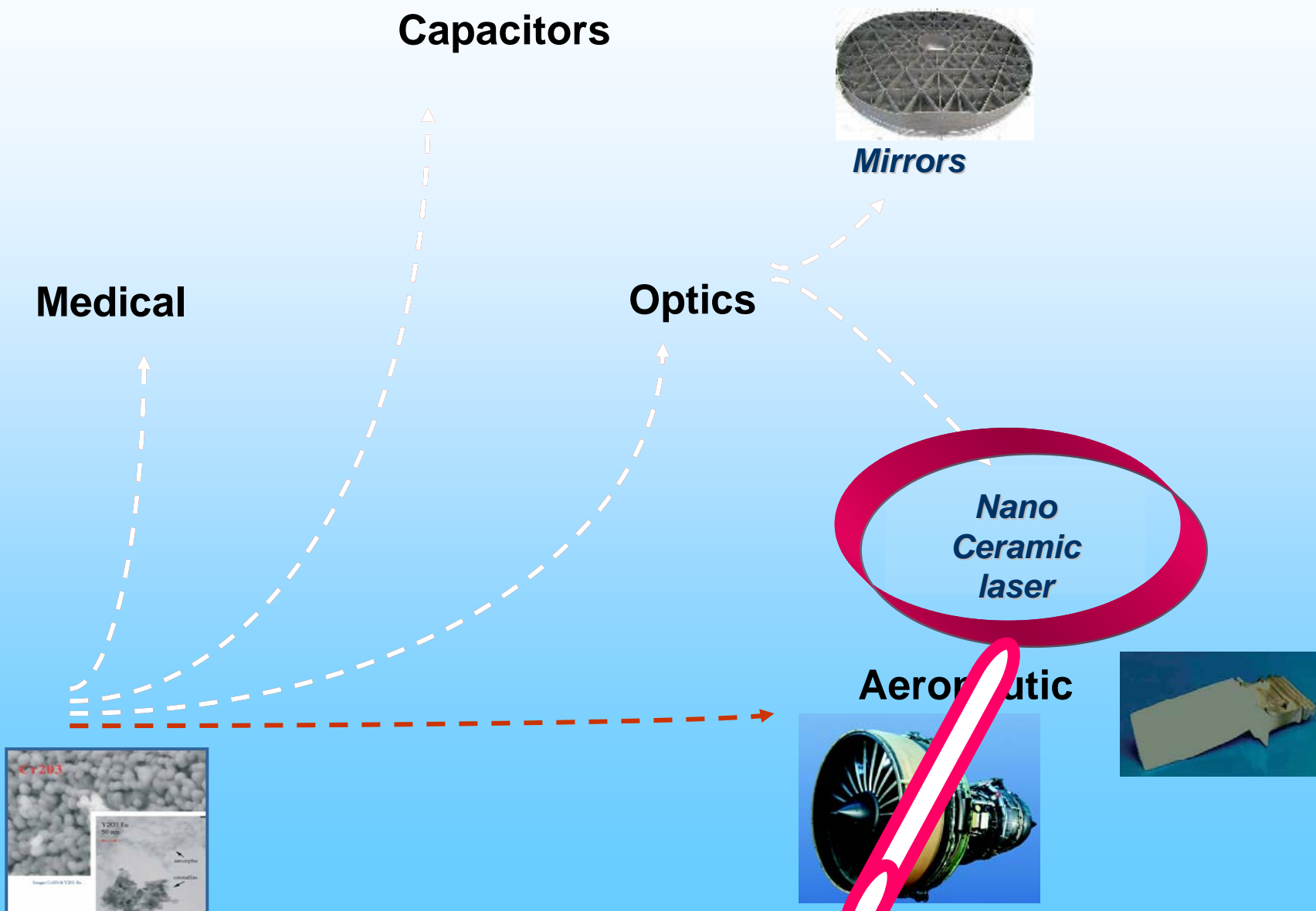
Aeronautic

Nano ceramic

When the wavelength is of about the size of the grain is smaller than the wavelength, the light is not diffused in material

light
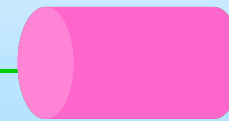
Nano Ceramic

YAG

$Y_3Al_5O_{12}$: Nd

Nano ceramic

Capacitor

Medical

Optics

Mirrors

Nano Ceramic laser

Aeronautic

European project
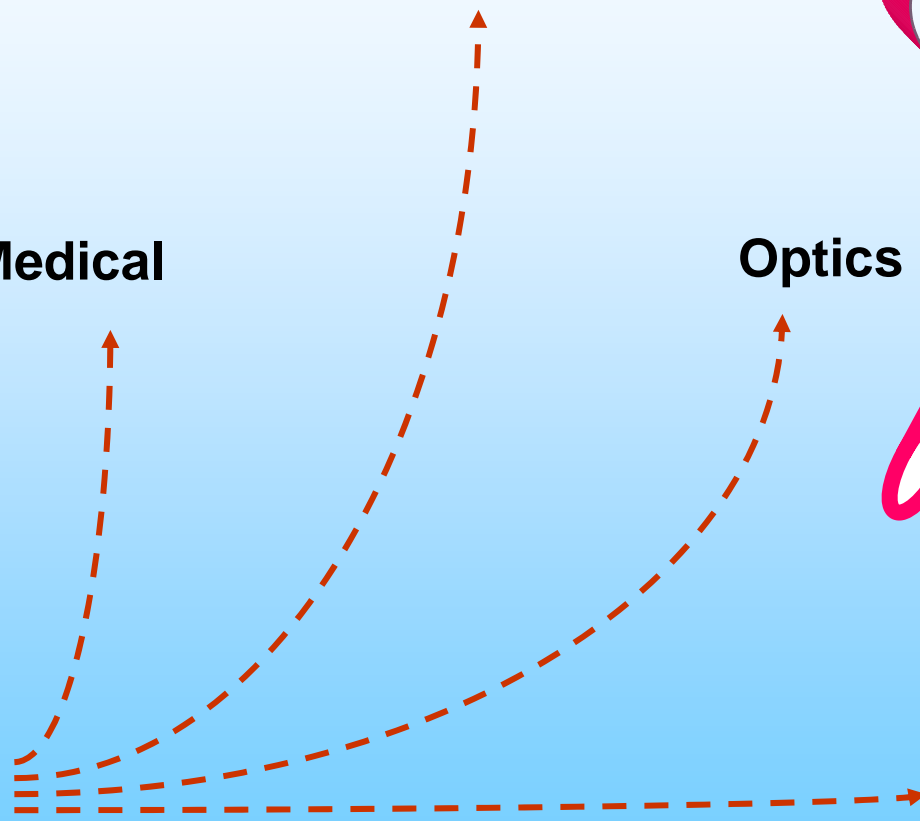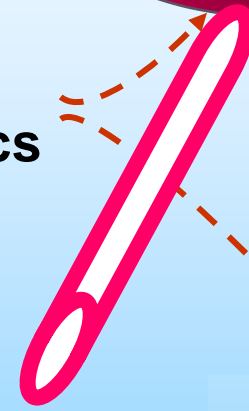
Mirrors for space application

Glass :
60 kg / m^2

Yesterday

CeSiC :
25 kg / m^2

ALCATEL ALENIA SPACE

12 kg / m^2

Today

Future

Nano ceramic

Capacitor

Mirrors

Medical

Optics

Nano Ceramic laser

Aeronautic
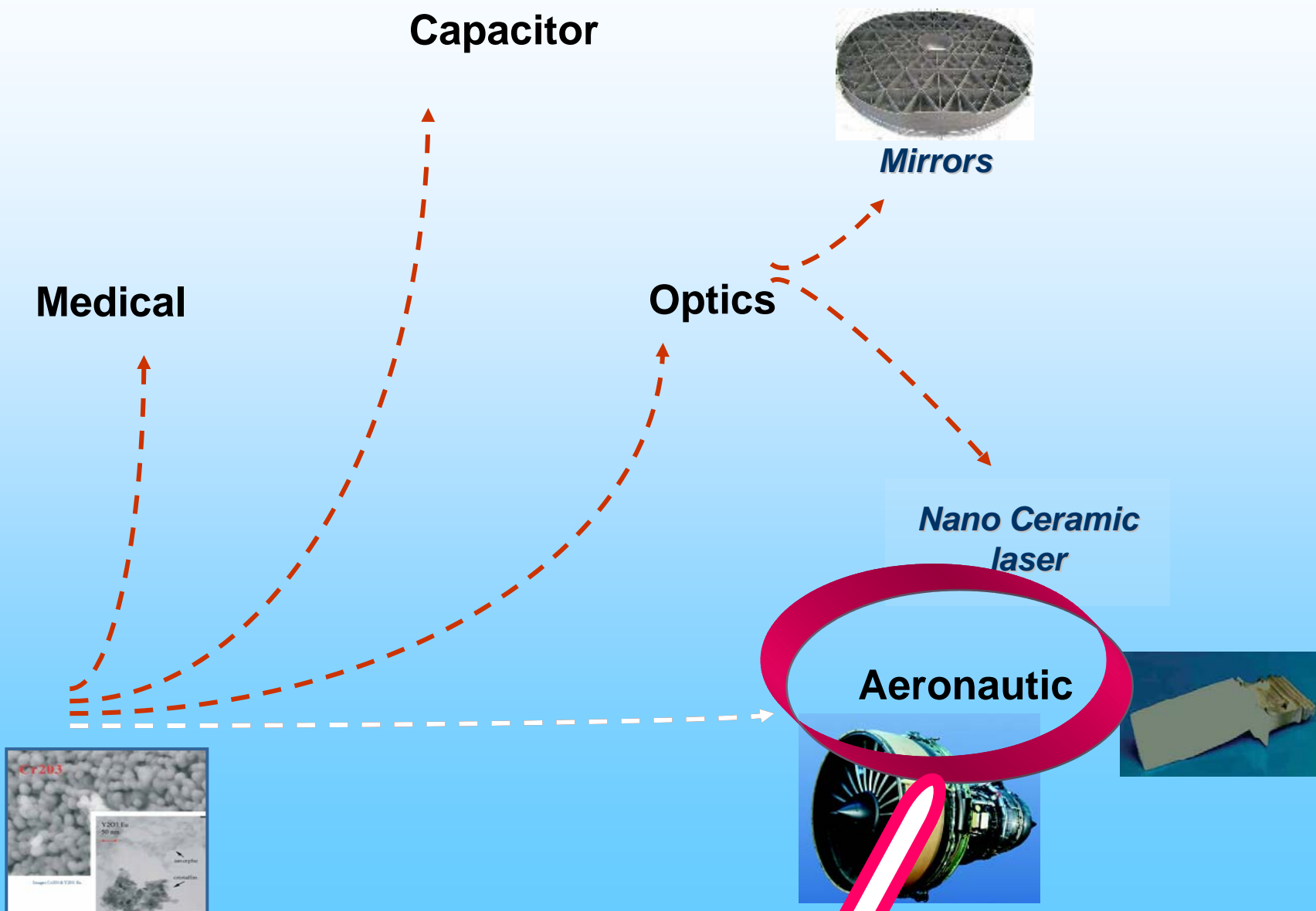
Jet

GP7200

Various heat-resistant materials and alloys
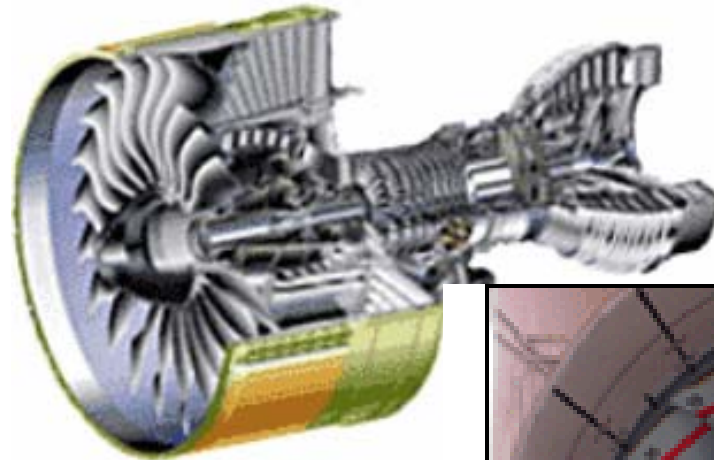
∼ **Titanium**
∼ **Ti6A4V**
∼ **Ti6A4V with SiC**

Entrance turbine **Compressor** **Turbine**
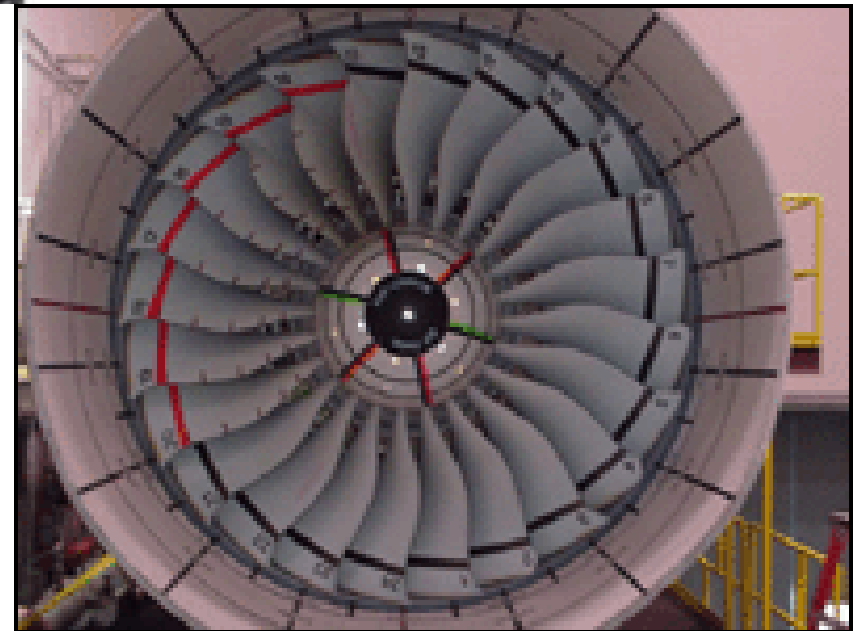
GP 7200 jet for A380
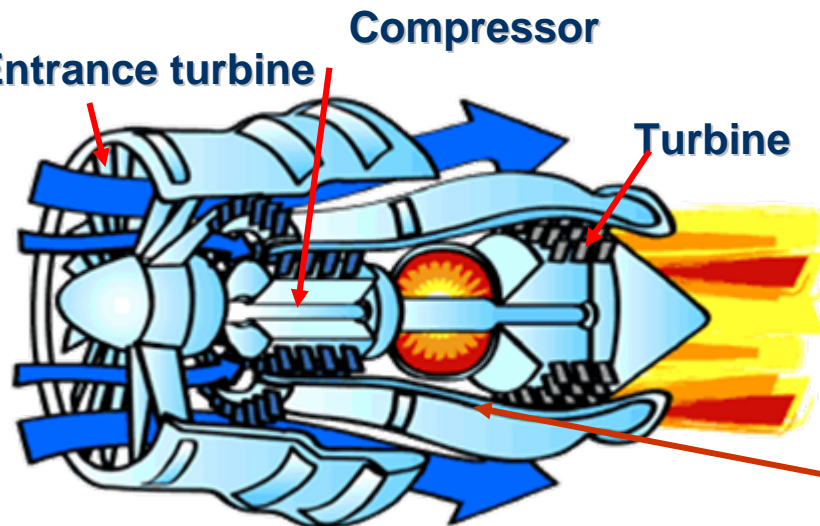
Composite combustion chamber containing **nanoparticules ceramics**

OUTLINE

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- Carbon nanotubes, the way to transport electricity

Health and Medicine

This nanoscopic "submarine" could, in the near future, penetrate in the blood vessels to destroy microbes, to correct genetic errors, to remove cancerous cells and to repair tissue
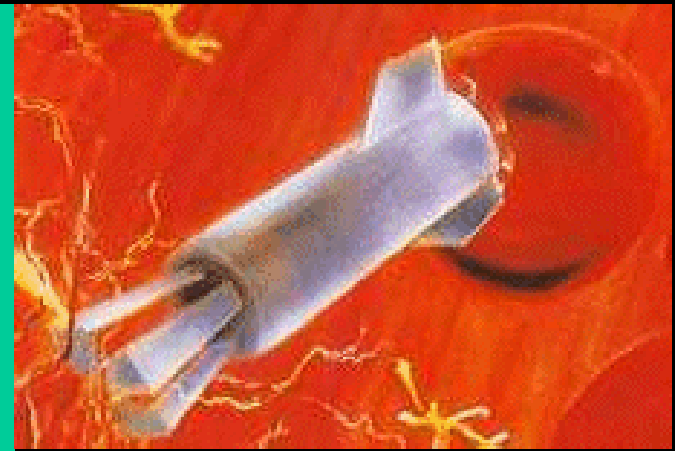
An artificial carrier
e.g. a carbon nanotube

Drugs (genes for cell transfection)

A coating
able to dissolve intra or extra-cellularly, depending if the drug release is inside or outside the cell

Cell ligands,
able to bind a surface receptor of the target cell to transfect
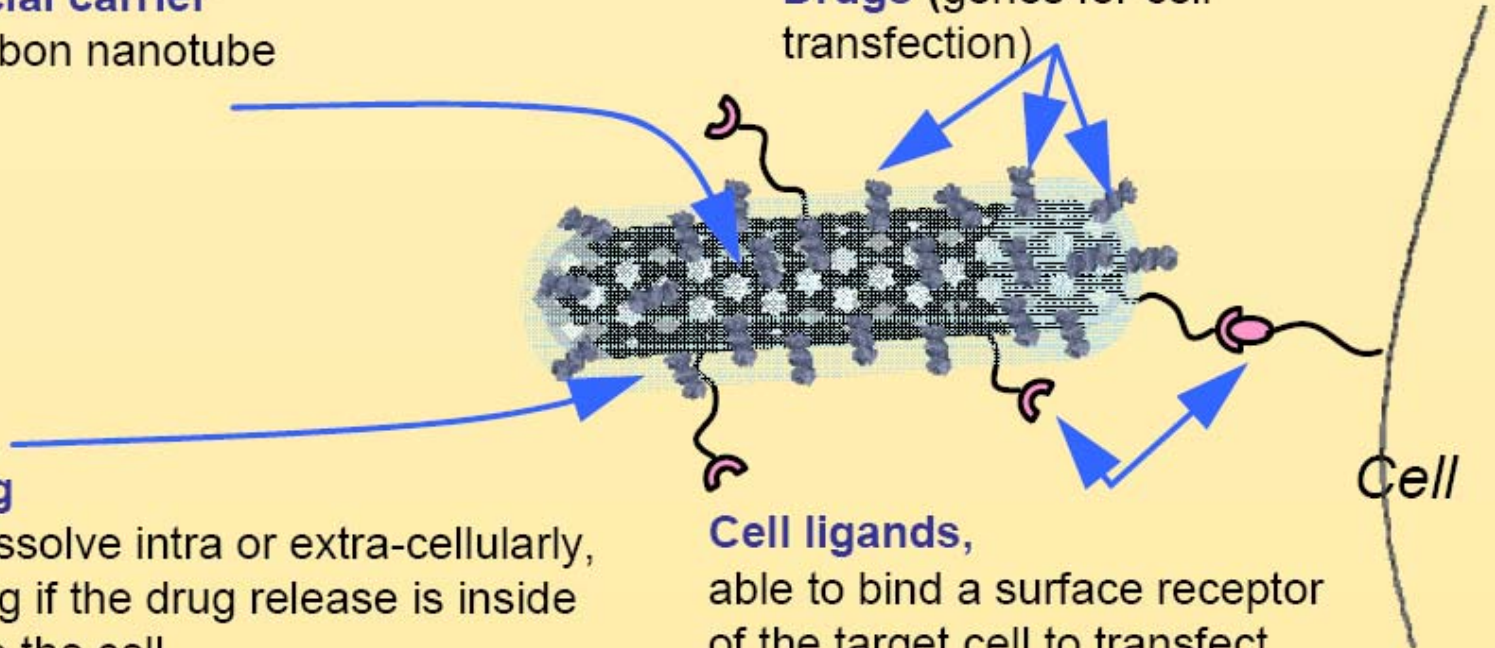
Cell

Health and Medicine
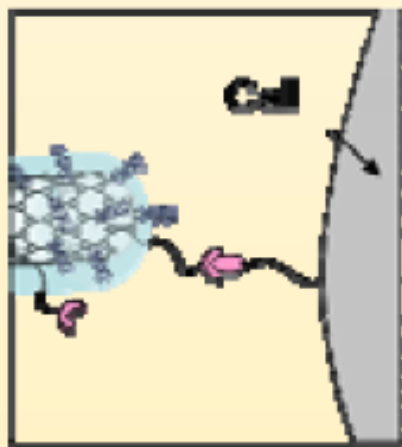
The cellular vector binds the target cell
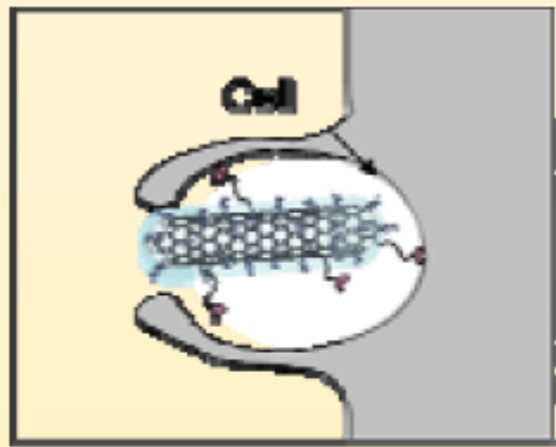
The cell phagocytes the vector
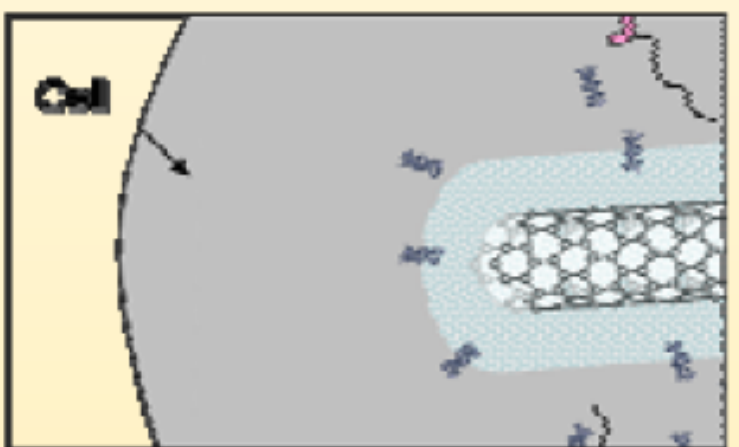
The vector has been up-taken by the cell: the coating dissolves and the genes are released
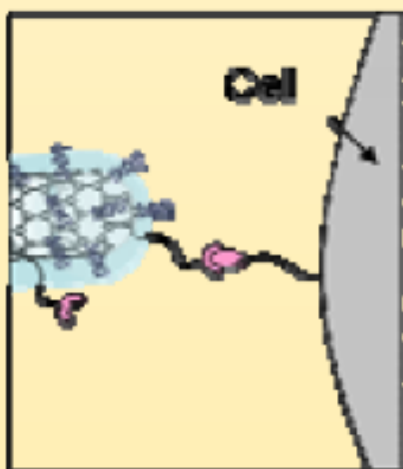
Cellular vector – cell binding
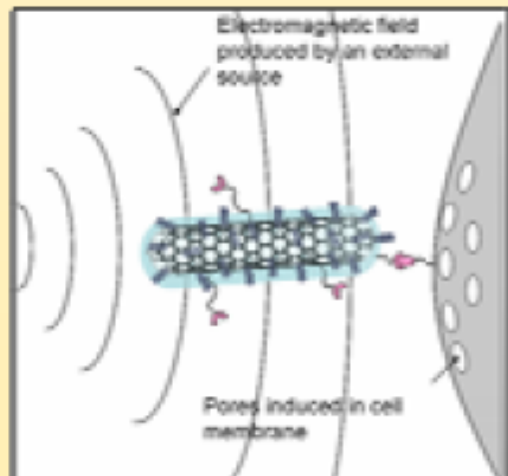
Cell electroporation via the cellular vector
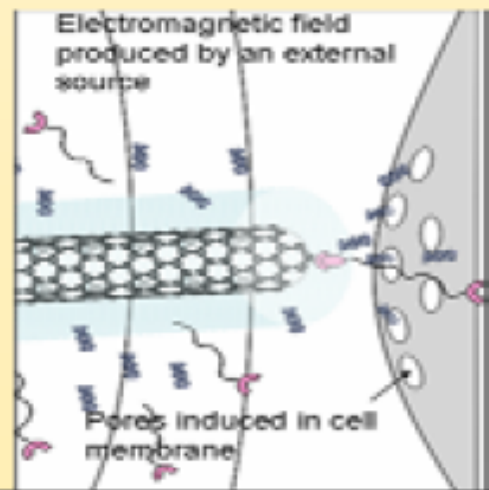
The coating dissolves, genes are released and diffuse across the pores

Health and Medicine

Detection of cancerous cells

Diagnosis of mellitus diabetes
Detection of acetone in the breath of the patient
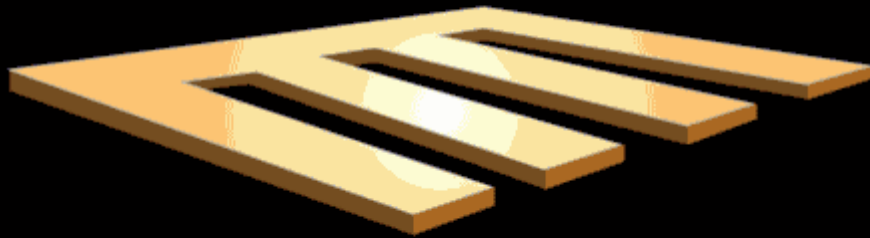
Diagnosis of cancer
The cantilevers can facilitate the diagnosis of cancer when they bind to the cancerous molecules

Cancer cell

Proteins

Antibodies

Binding events change cantilever conductance
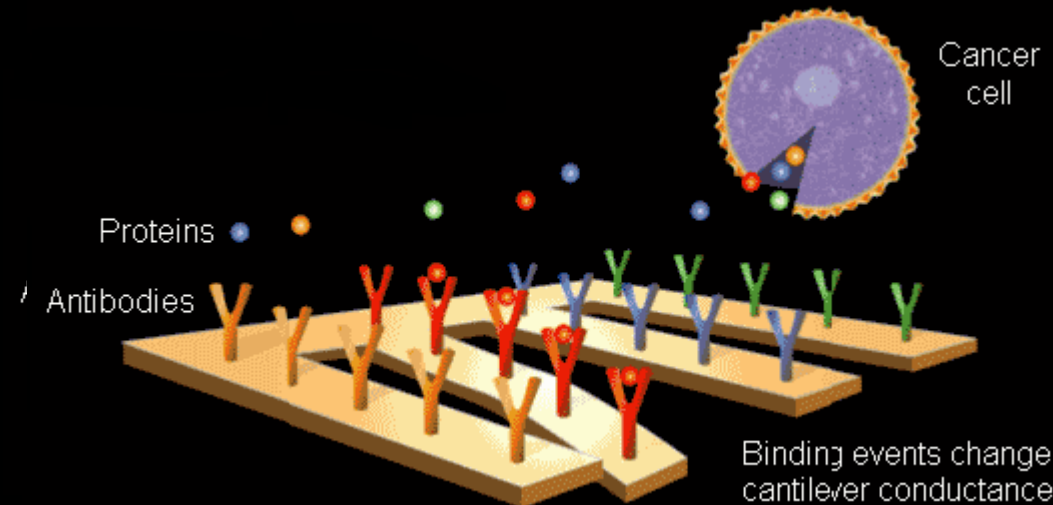
Health and Medicine

Electric detection of virus in solution by nanowire field-effect transistors

Different molecules/viruses flow through the channel

Fluidic flow

Selective binding of protein/virus to appropriate nanowire

Channel

Information relayed through electrodes to computer

Nanowire sensor

Source

Drain

Current

Particles flow through the microfluidic channel

Nanowire sensor

Electrodes
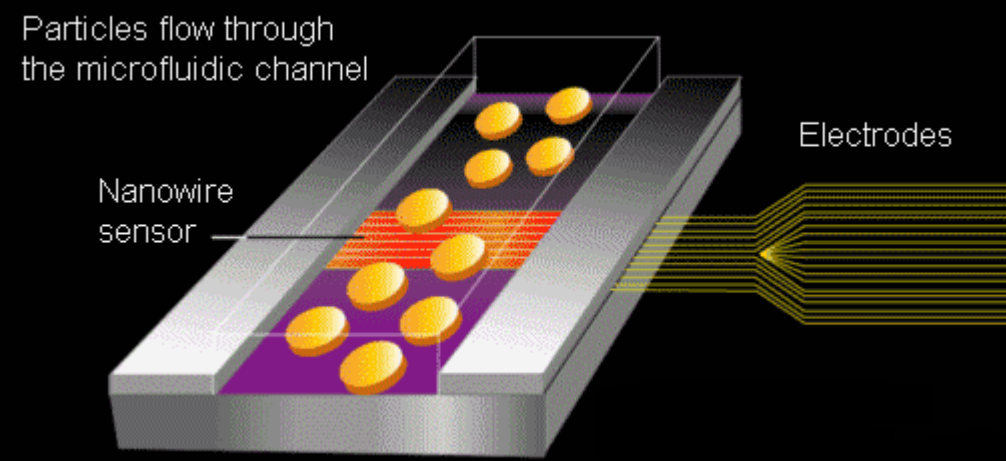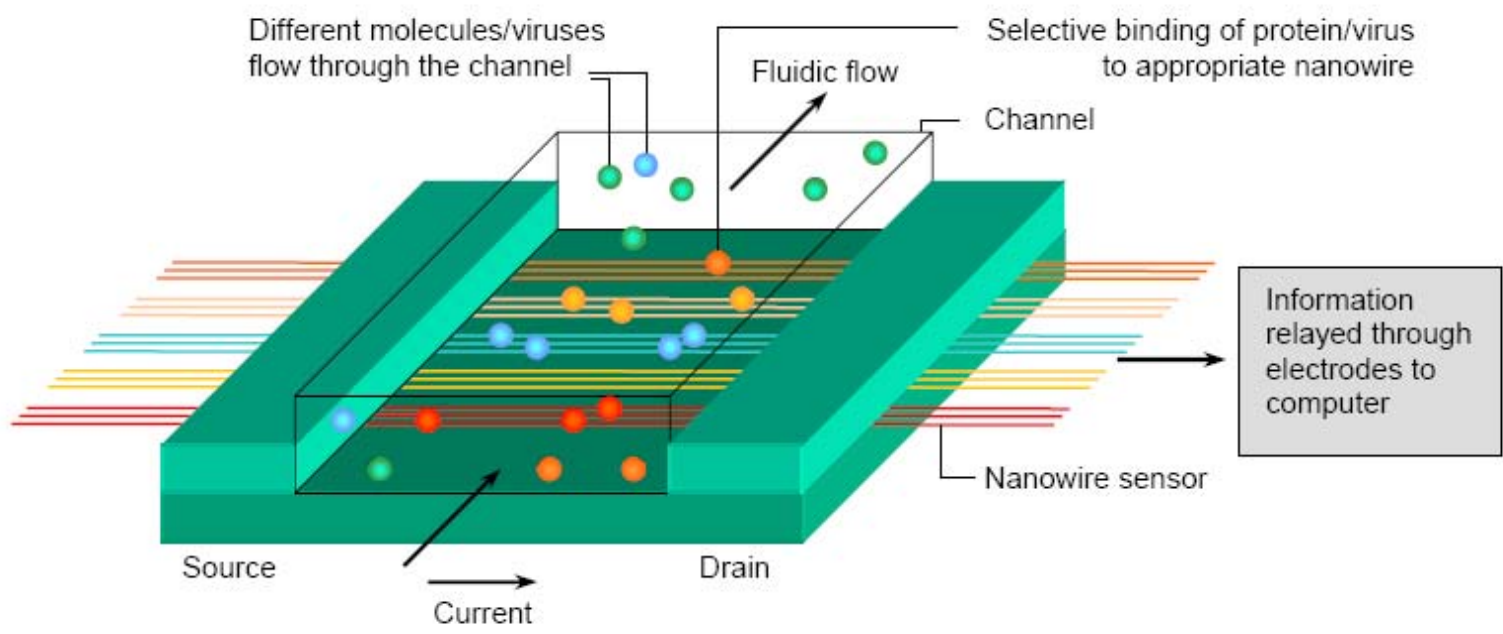
Health and Medicine

Administration of drug

by micro syringe

(e.g. insulin)
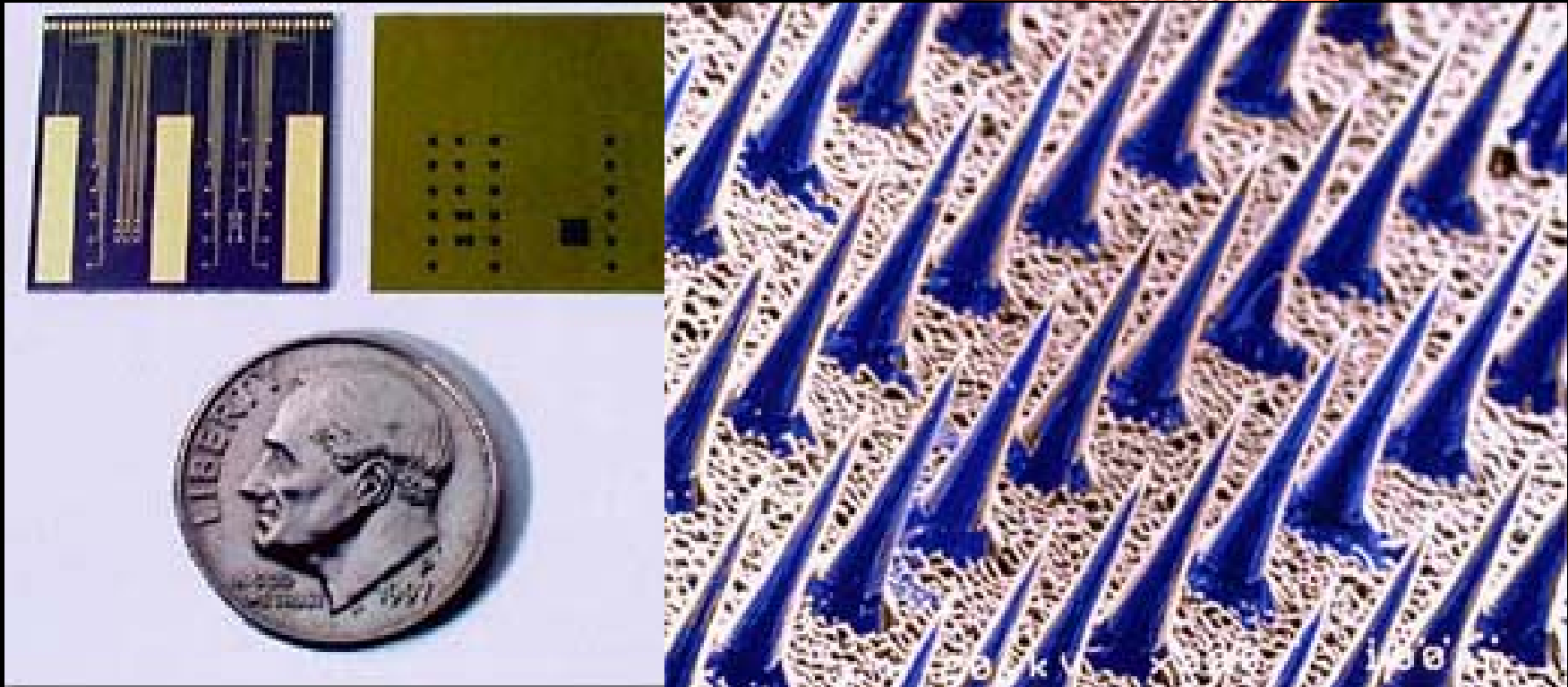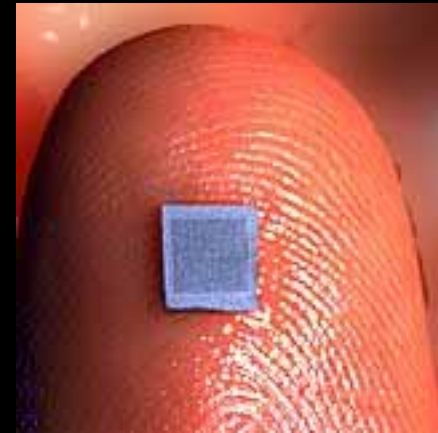
Health and Medicine

Implant materials, bones repair
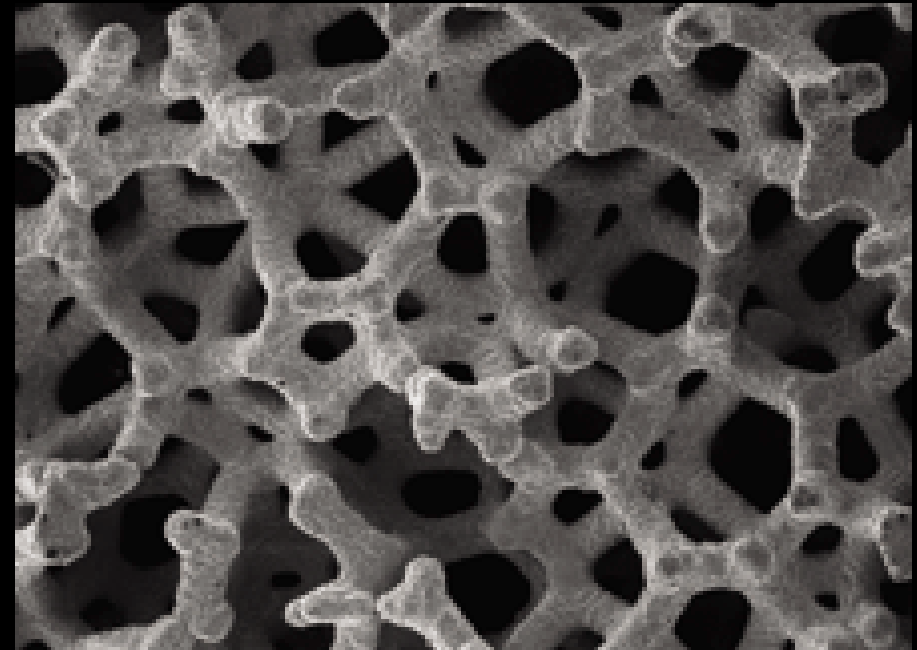
Health and Medicine

Bio resorb materials
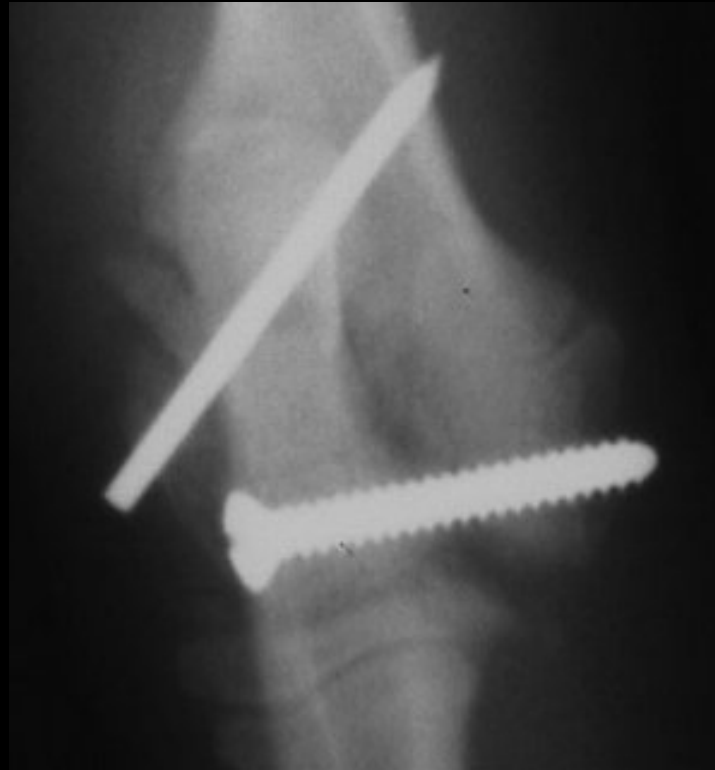
Health and Medicine

Vision aid, retinal implant
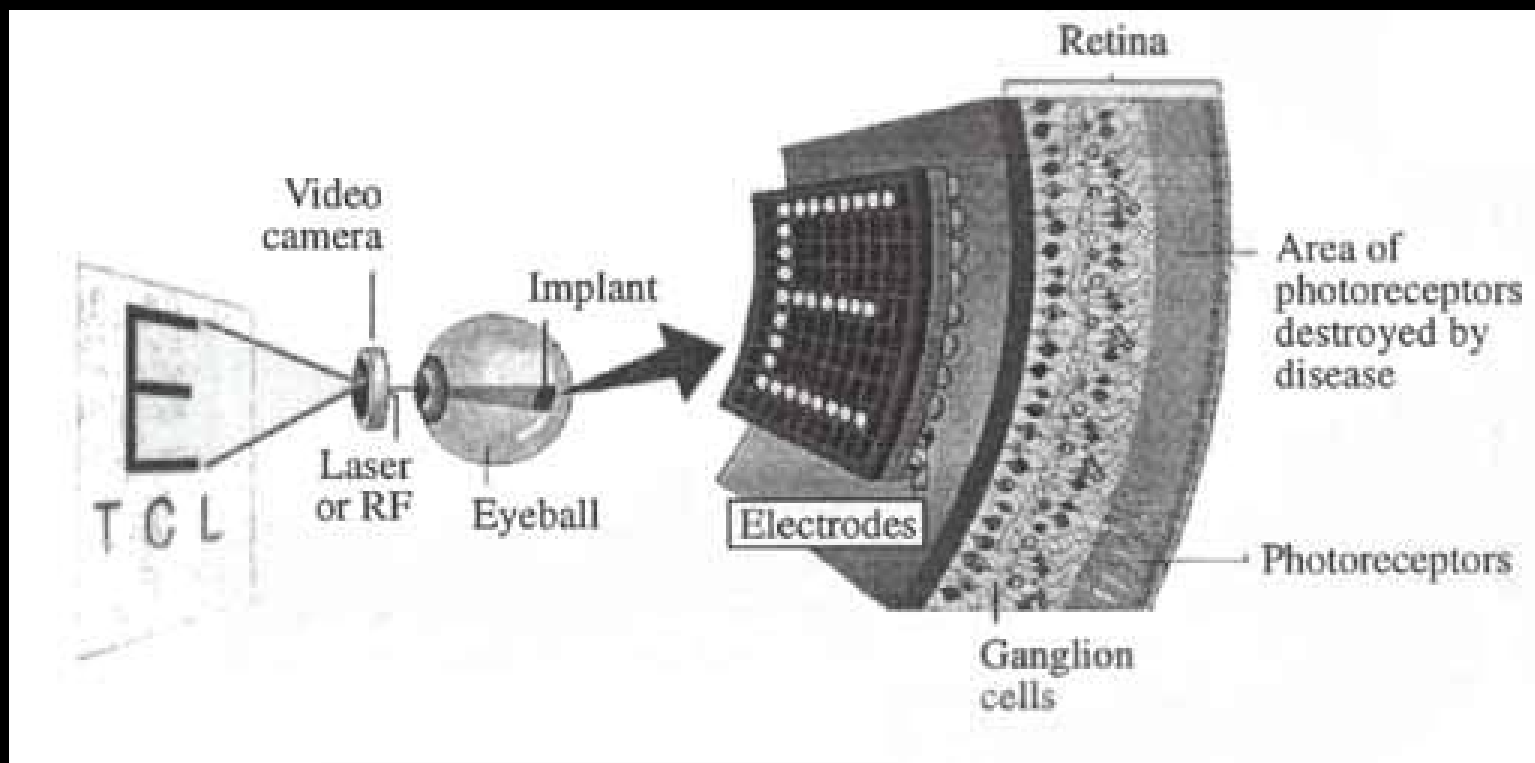
Health and Medicine

Vision aid, retinal implant

The interface with the neurons is made by microfluidic channels; stimulations are carried out by chemical ways
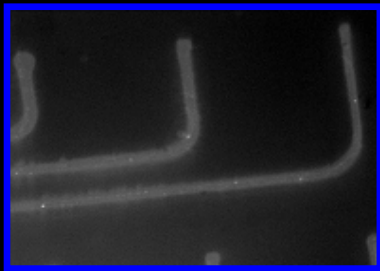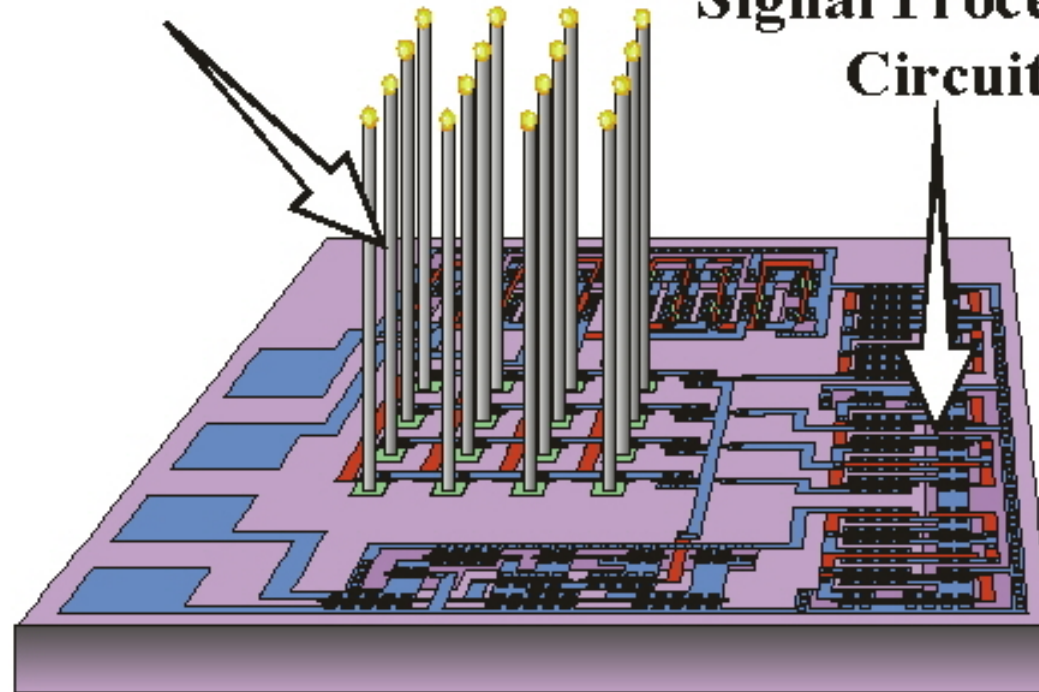
Makoto Ishida
Department of Electrical & Electronic Engineering,
Toyohashi University of Technology

Health and Medicine

Lab on Chip (3D view)
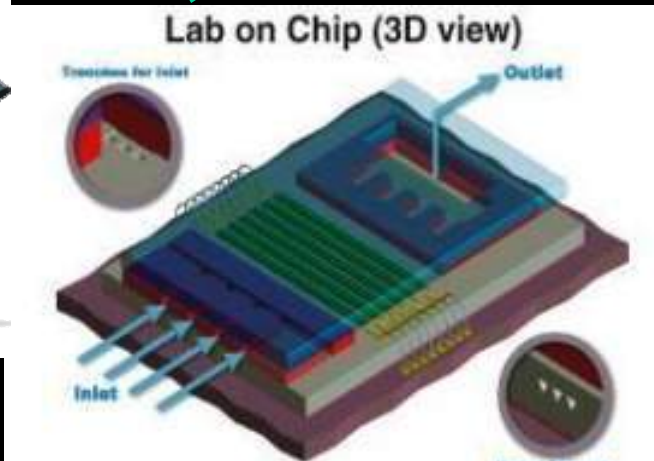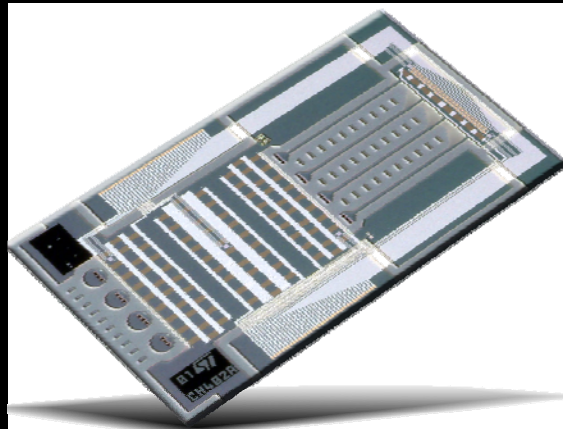
Pharmaceutical lab

Lab on chip

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- Carbon nanotubes, the way to transport electricity

Energy and Environment

Two aspects: production and utilization

- **Energy Production**
  - Clean and low cost

- **Energy Utilization**
  - High efficiency lighting
  - Solid state lighting can reduce total electricity consumption by 10% and cut carbon emission by the equivalent of 28 million tons/year*

* Equivalent to 3 times the total power consumption of France

Lighting

Ambient intelligence – Philips HomeLab

Lighting

Siemens CT MM1

Lighting

From transparency to opacity

St Gobain

V≠0   V

E

PDLC   ITO
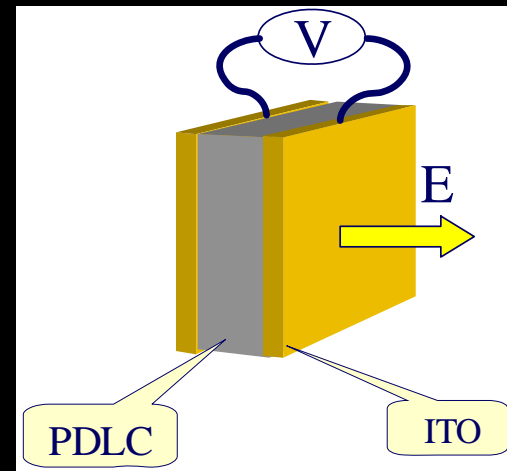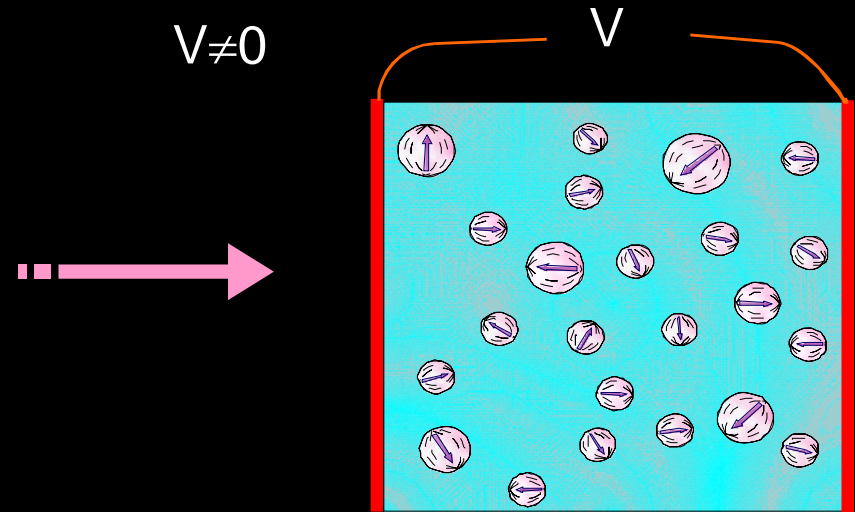
Energy and Environment
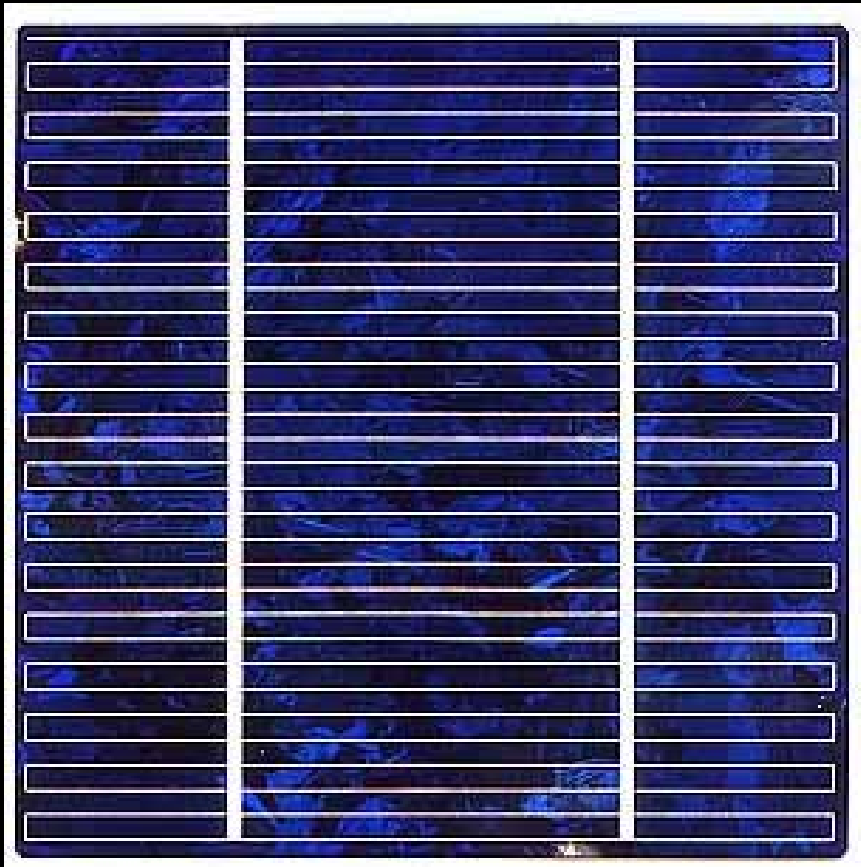
5 à 28 % Efficiency

80 % Efficiency

Energy and Environment
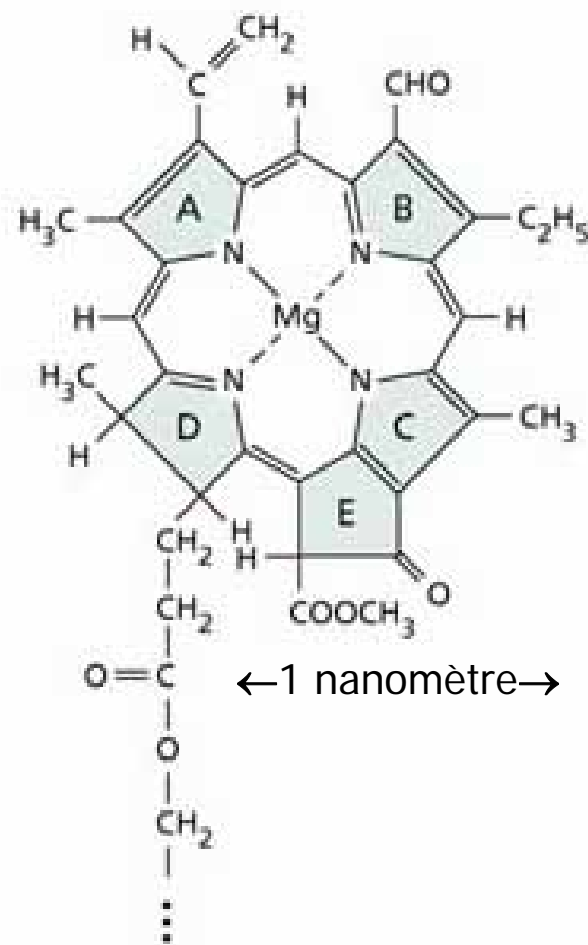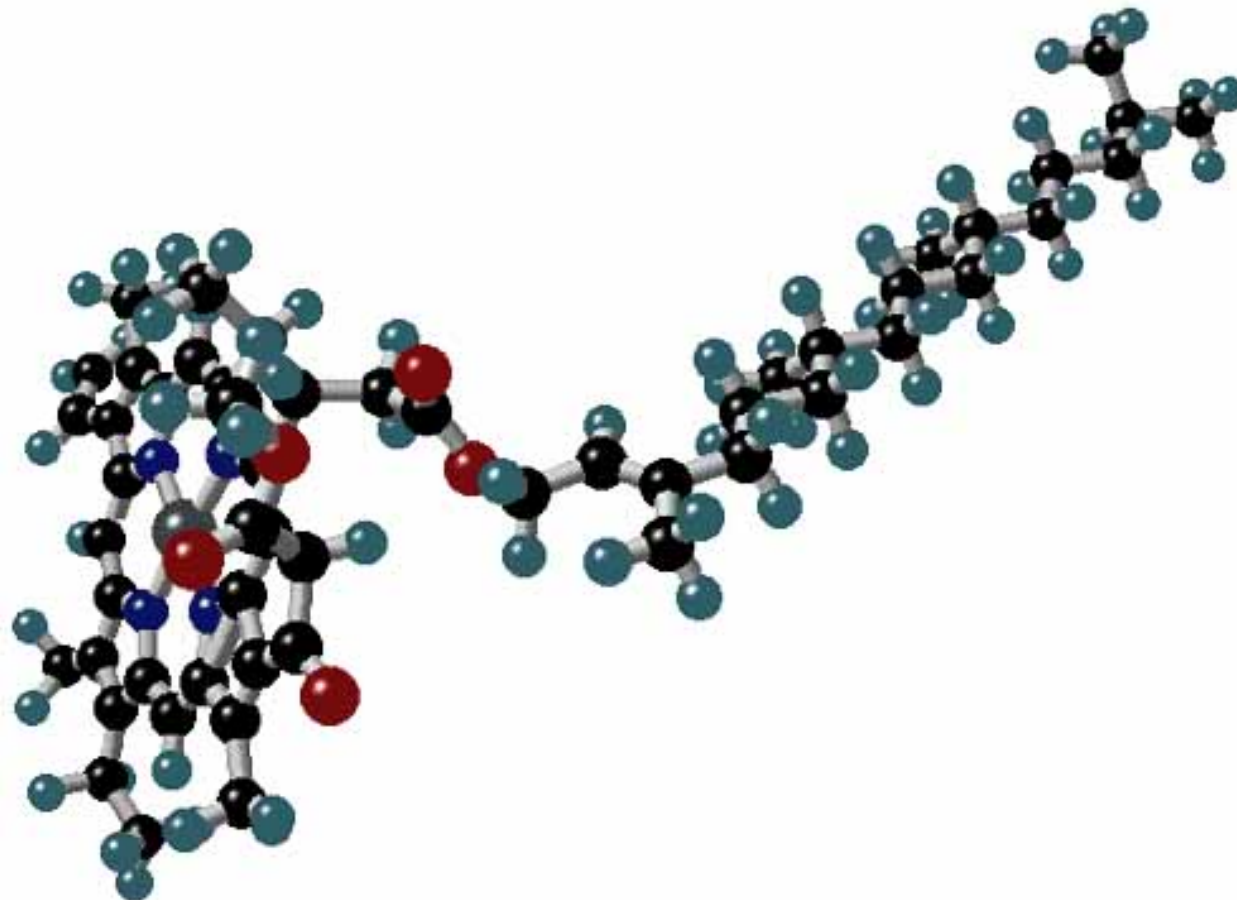
Reproducing the chlorophyllian synthesis

←1 nanomètre→

Energy and Environment

Reproducing the chlorophyllian synthesis

Brudvig Lab, Yale
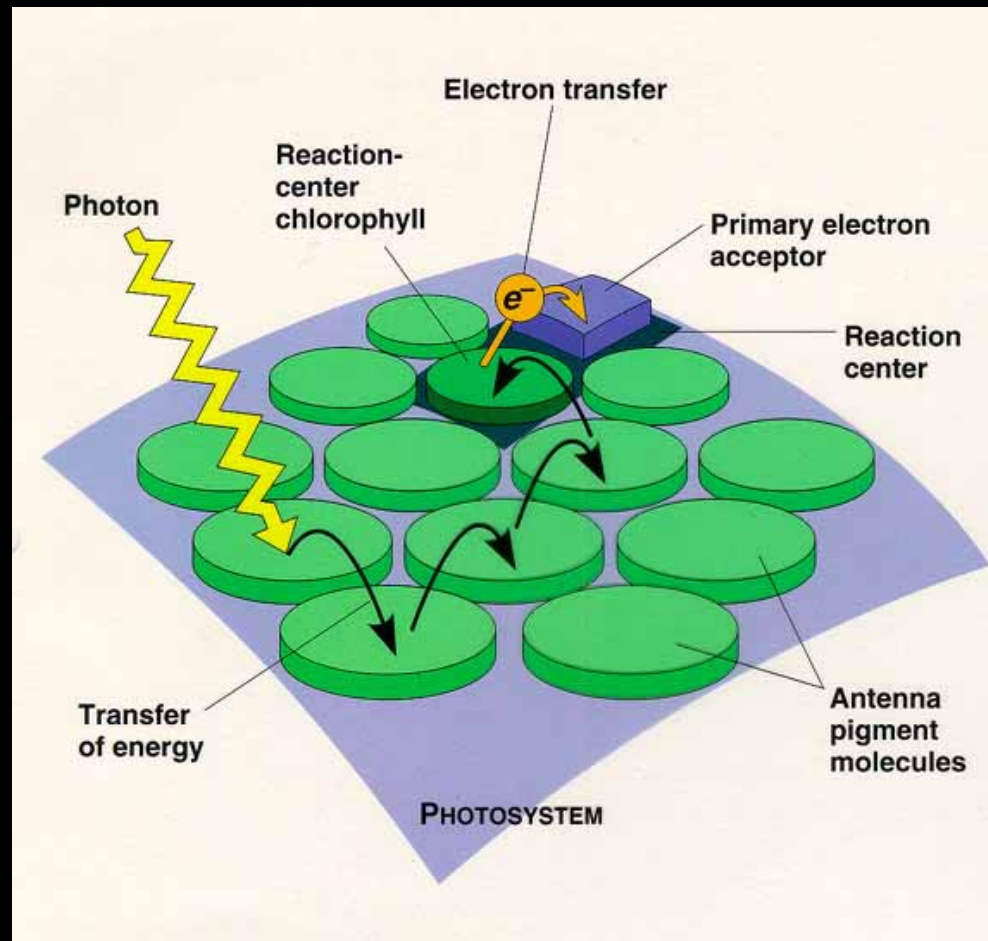
Energy and Environment

Solar cells
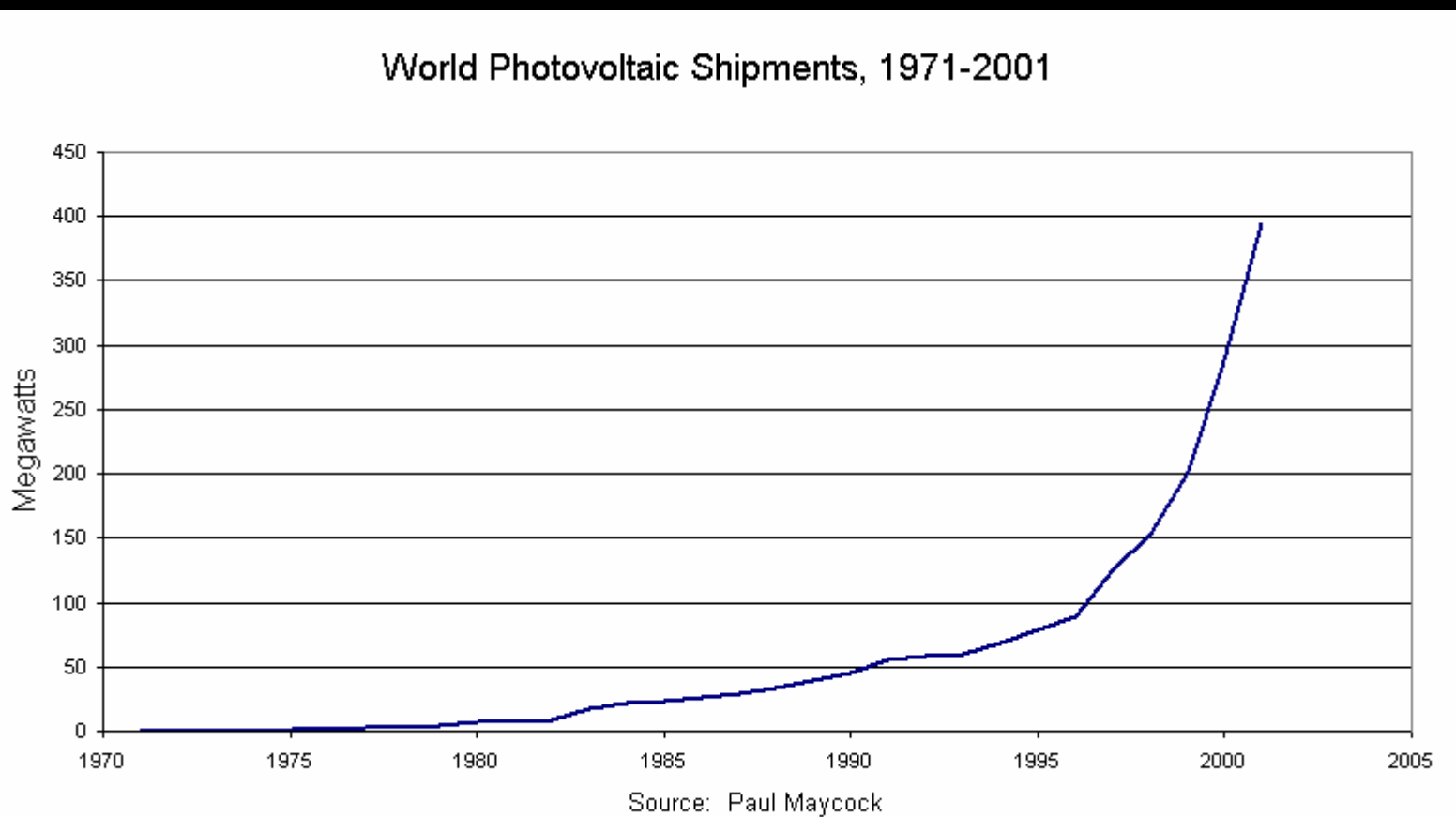
2000 : 400 MW

2003 : 800 MW

2006 : 1800 MW

2001 : 3 G$

2006 : 10 G$

2011 : 20-30 G$

World Photovoltaic Shipments, 1971-2001

Source: Paul Maycock

OUTLINE

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- **Transportation**

- Security

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Transportation

Morphing wing
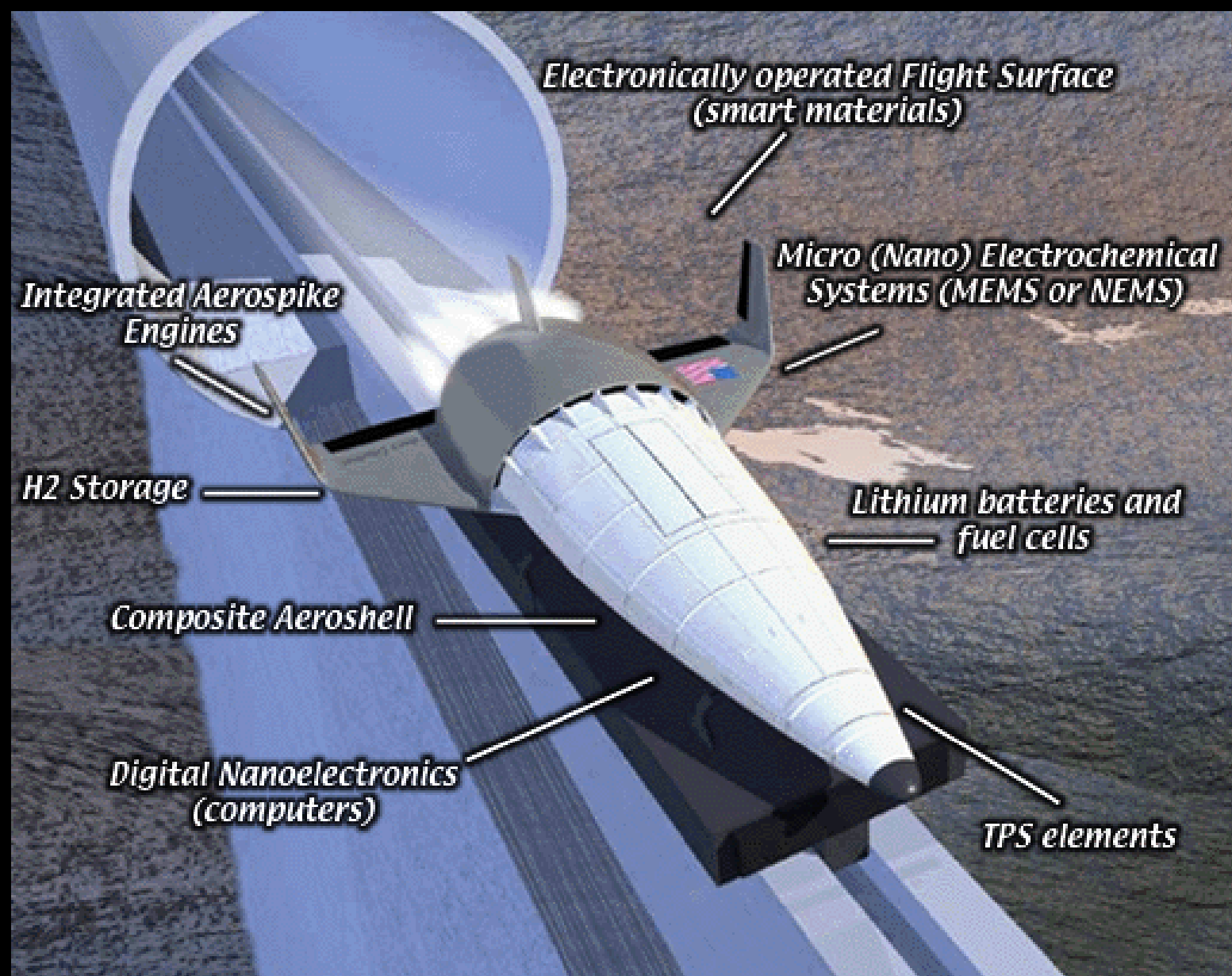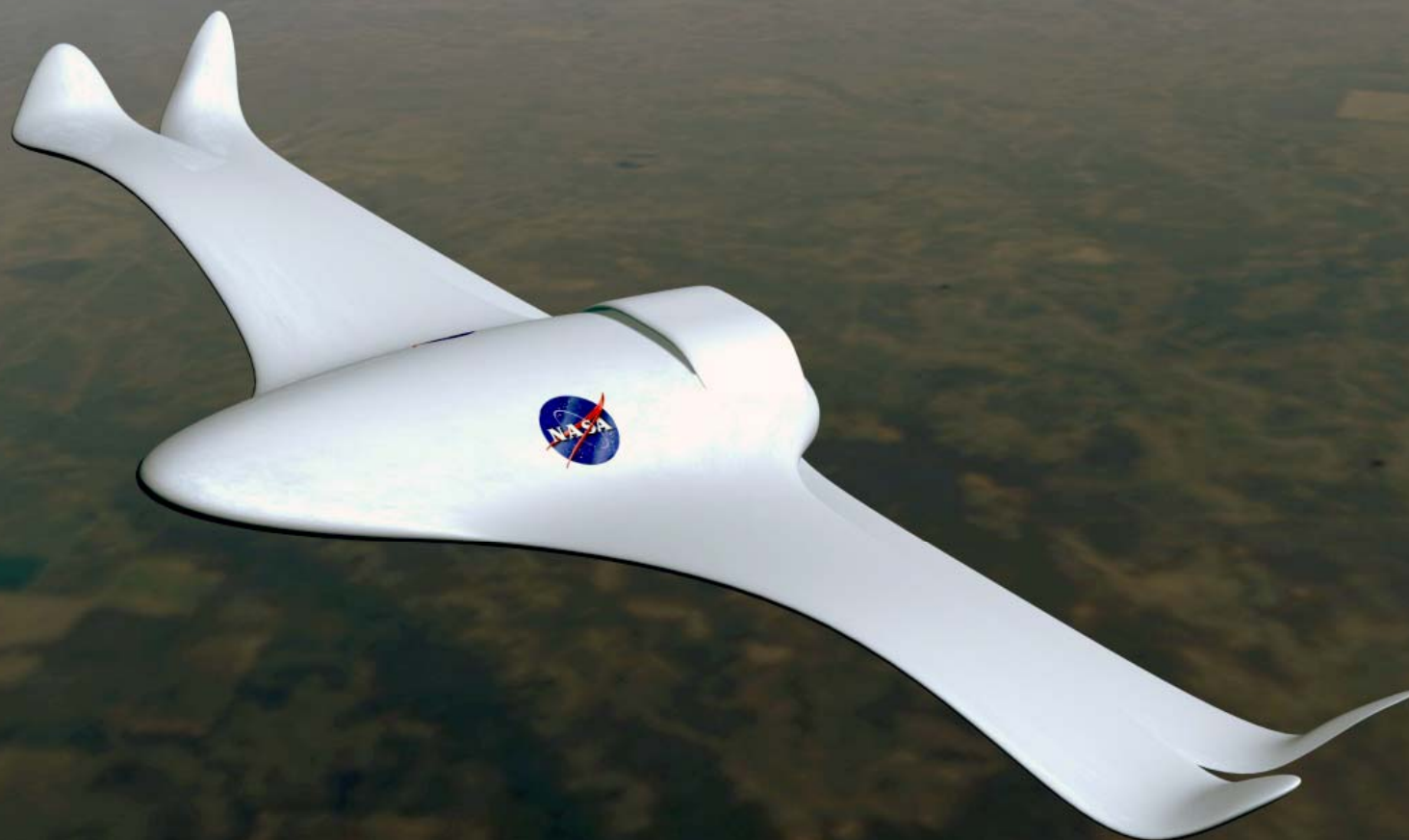
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: ED01-0348-1   Date: 2001   Photo by: NASA
An artist's rendering of the 21st Century Aerospace Vehicle, sometimes nicknamed the Morphing Airplane, shows
advanced concepts NASA envisions for an aircraft of the future.

Morphing wing

Traditional Hinged Control Surface

Morphing Surface Wing
Notice less required deflection for
equivalent hinged maneuvers

Designing the 21st Century Aerospace Vehicle

**Terry Weisshaar, manager of DARPA'
morphing aircraft structure program
at the Pentagon**

Artist's concept of an adaptive, or "morphing," aerospace vehicle

Sliding skin could morph from fast attack plane
configuration to a slower long distance plane.
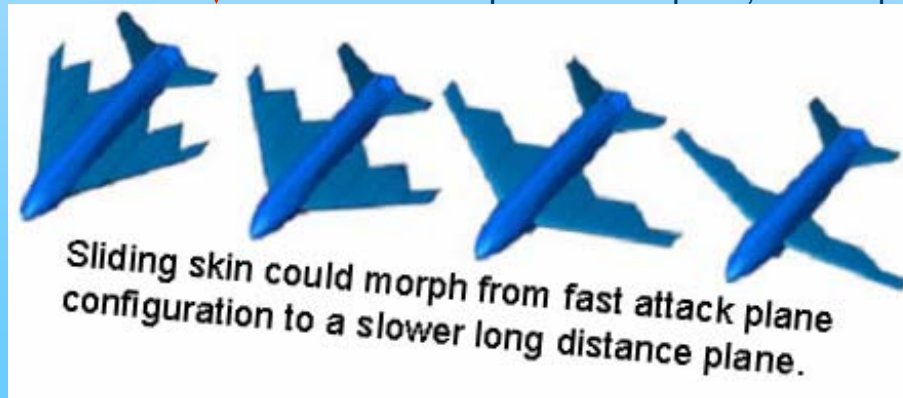
Space exploration
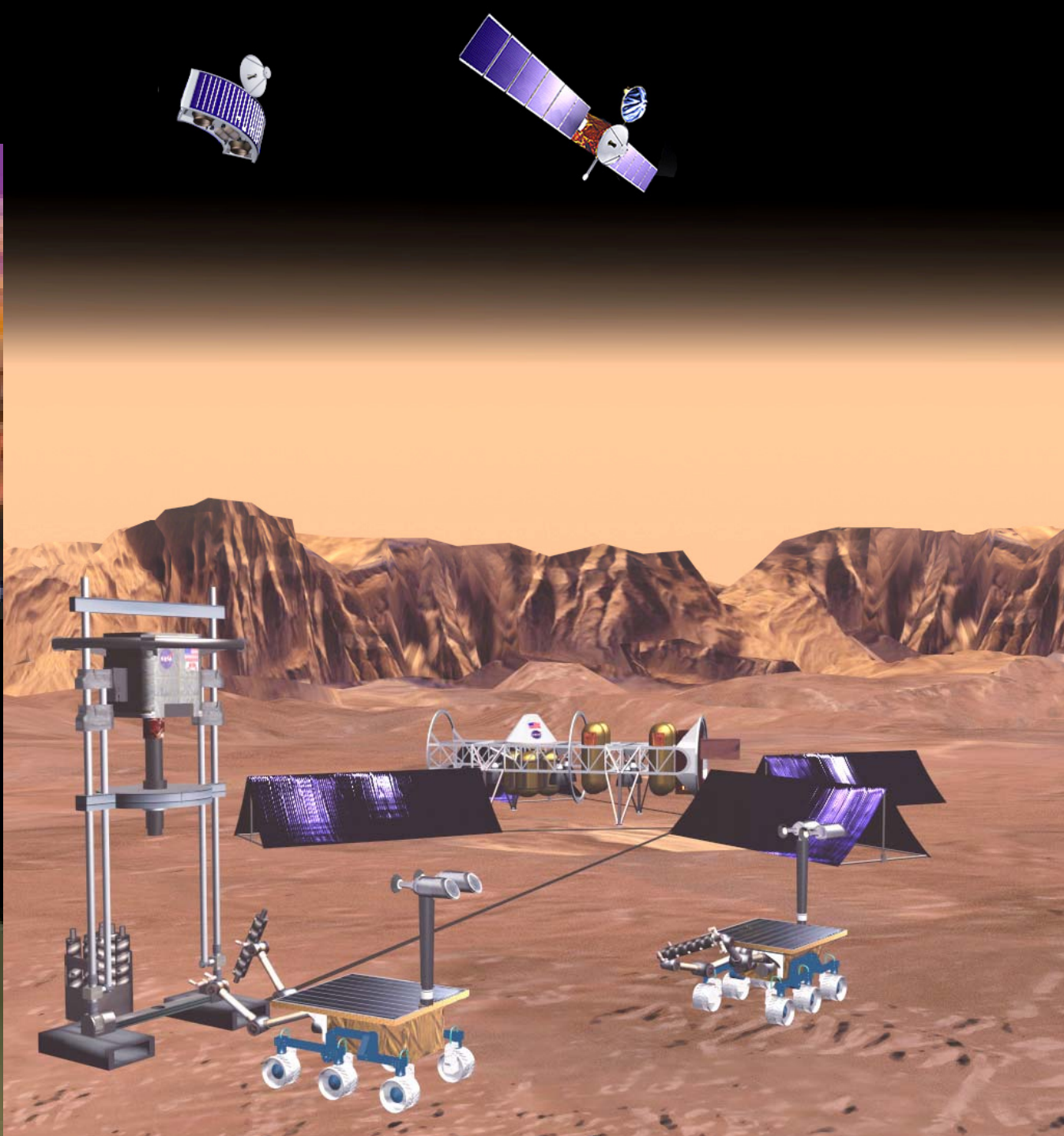
Transportation / energy

Hydrogen storage
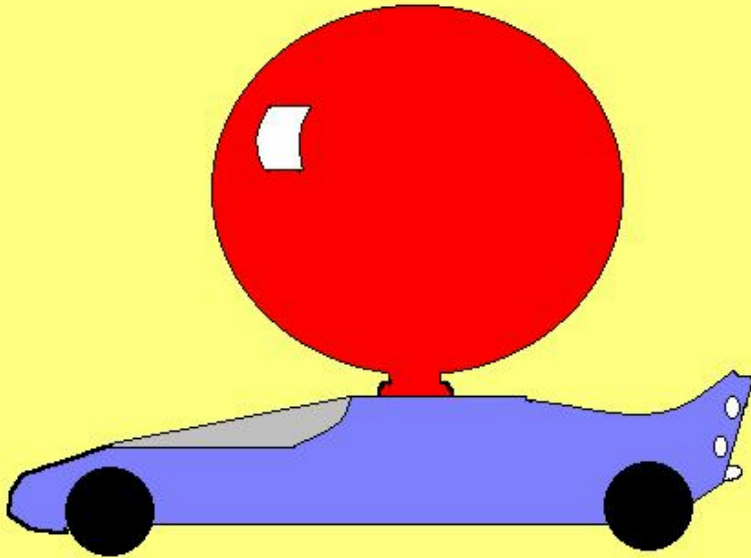
A hydrogen tank having an energy storage equivalent to a gasoline tank should be 3000 times larger!

Transportation

Hydrogen storage

The carbon nanotubes are able to store from 4,2% to 65% of their weight of hydrogen

The density of stored hydrogen can be close to that of liquid hydrogen
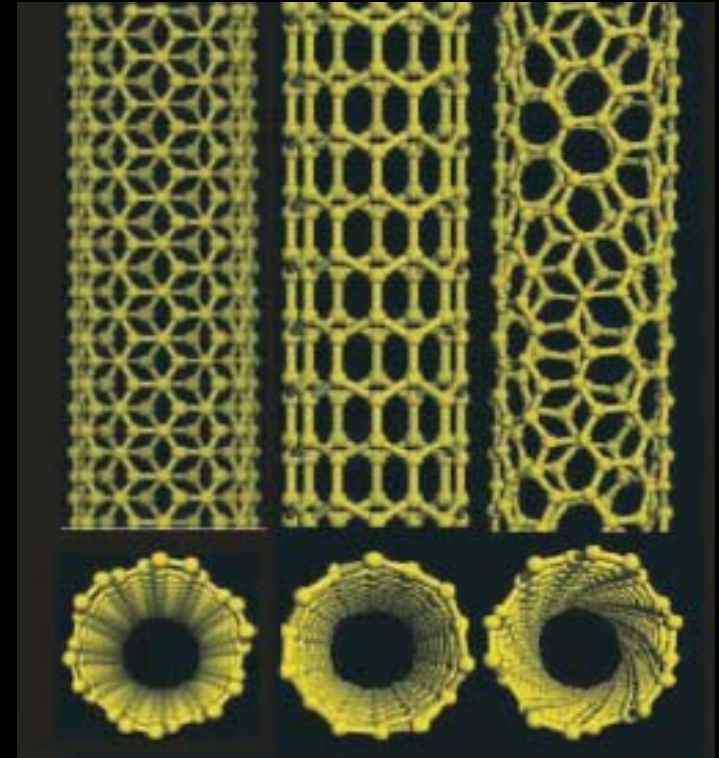
OUTLINE

- Computing and Data Storage

- Materials and Manufacturing

- Health and Medicine

- Energy and Environment

- Transportation

- **Security**

- Carbon nanotubes, the way to transport electricity

1m   1mm   100μm   10μm   1μm   100nm   10nm   1nm   1Å

1 atome   3 Å

Quantum Cascade Laser

12-30 μm

50 nm

0.7 - 3 mm

~1 nm

1 cheveu = 50μm
         = 0.00005m

25 Å

AlSb   **InAs**   **AlSb**

E_{12}
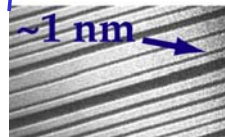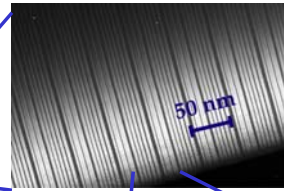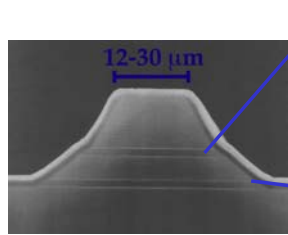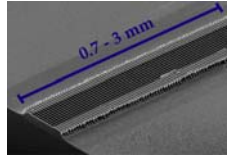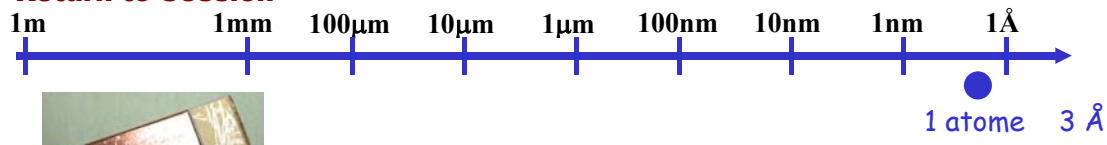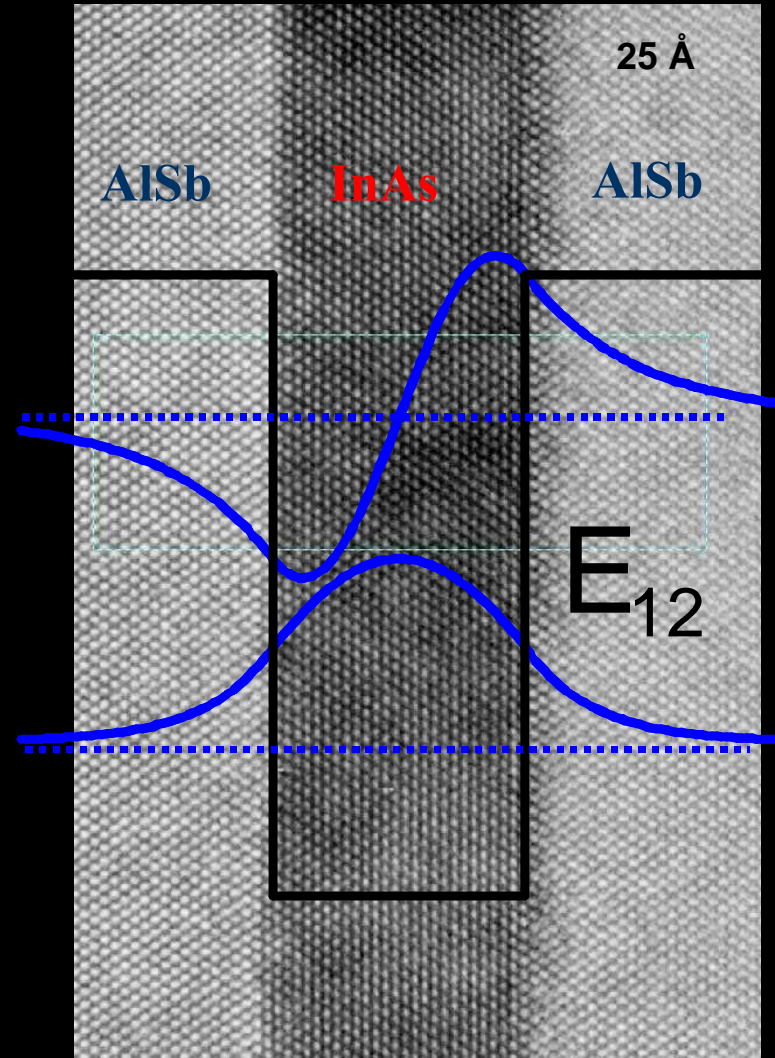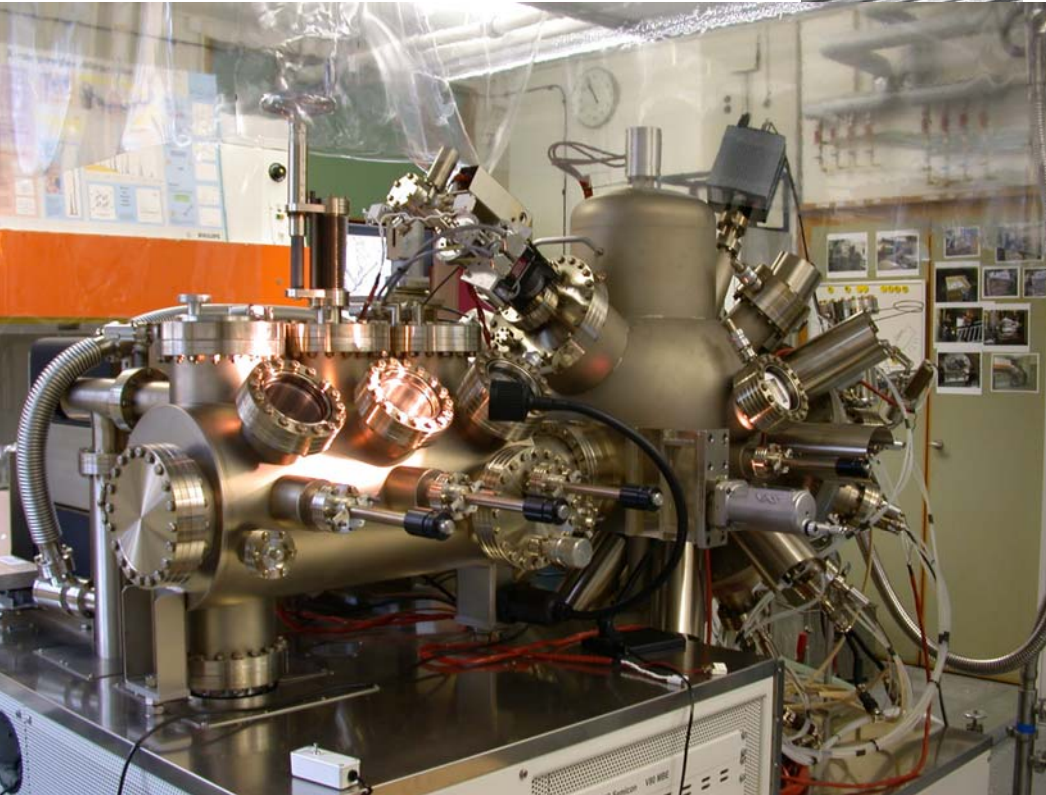
QC Laser spectrometer operating principle
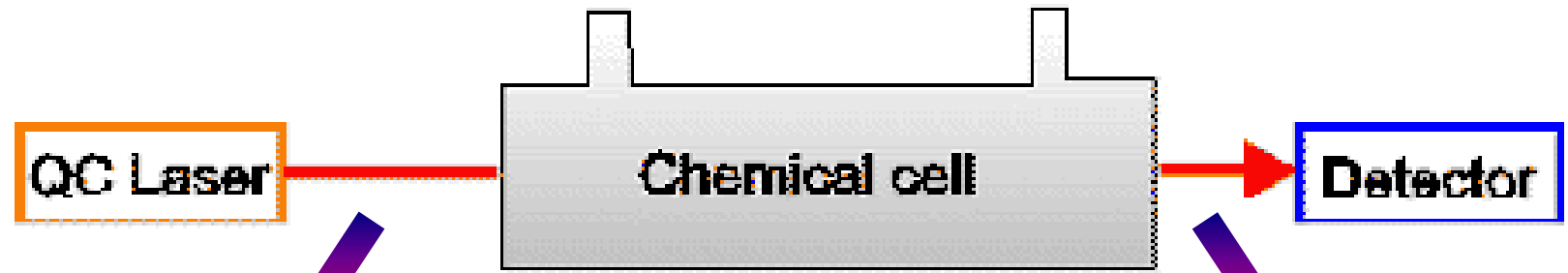
Light Pulse (I_0) Before Sample
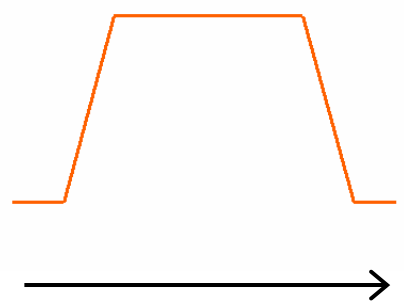
Sample Transmission
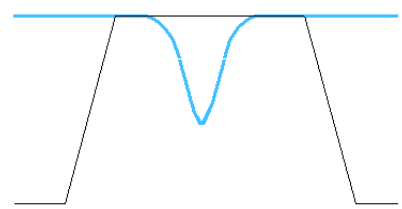
Light Pulse (I_a) After Sample
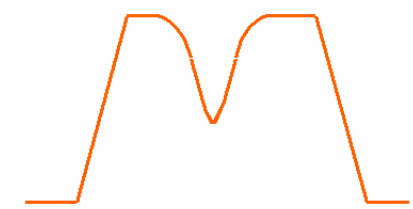
Time (t)

Wavelength (λ)

Time (t)

Current pulse applied to diode contact

Wavelength tuning for pulse current duration by Instantaneous heating effect

Linear tuning to ± 1% for 200ns

Security : CNT Transistor for gas detection

Dai et al.

Department of chemistry, Stanford University

Top view

électrodes

20 /30 SWNTs

Bottom view

source   SWNT   drain

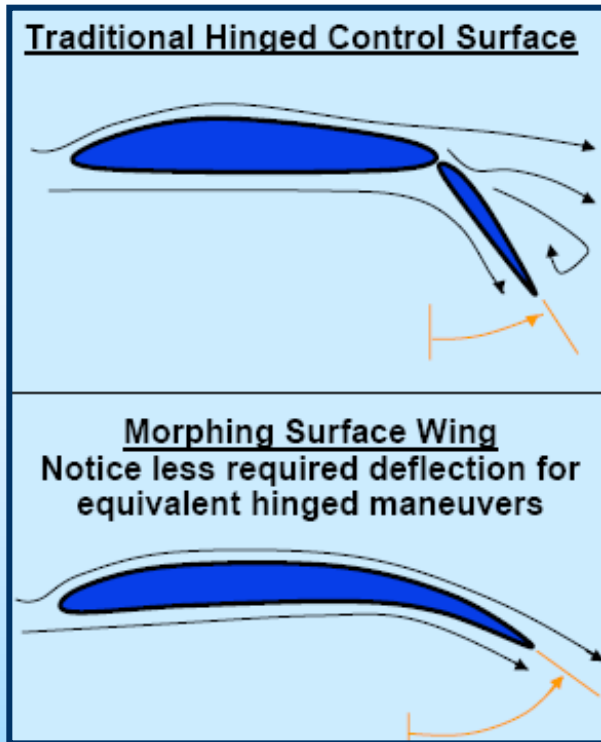SiO_2 (500 nm)

Pd/Au

Si
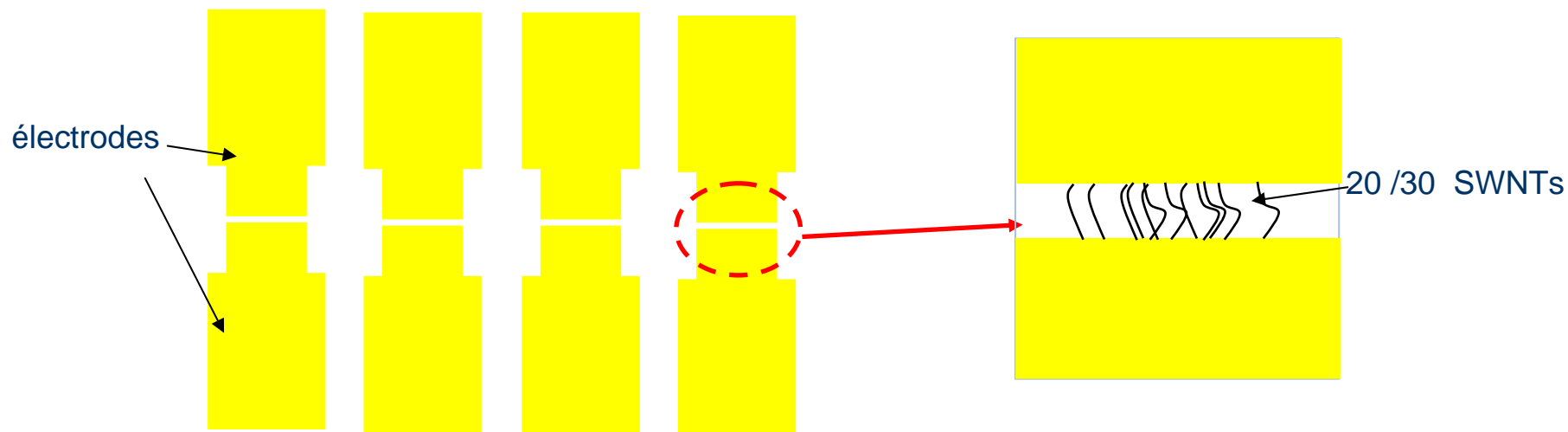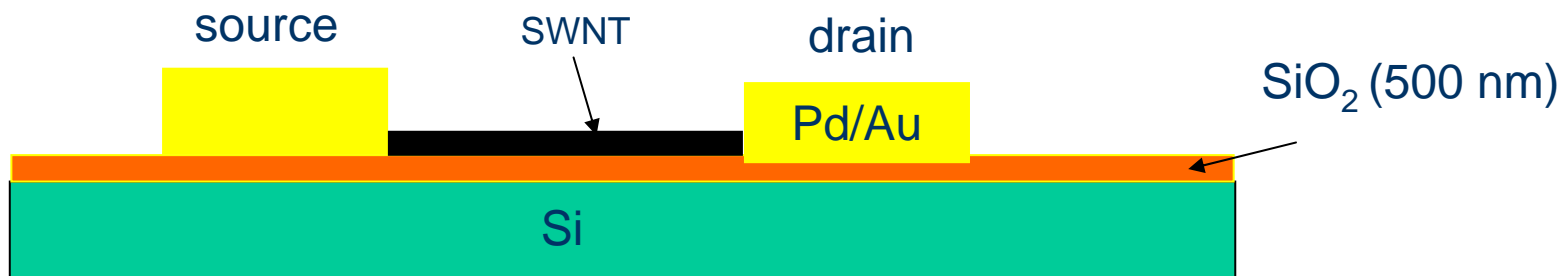
Security : CNT Transistor for gas detection

OUTLINE

- Computing and Data Storage

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- Health and Medicine

- Energy and Environment

- Transportation

- Security

- **Carbon nanotubes, the way to transport electricity**

Carbon nanotube
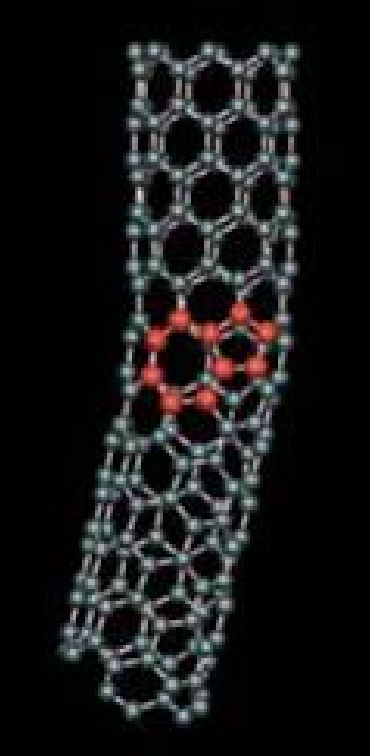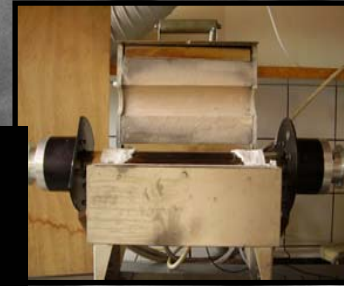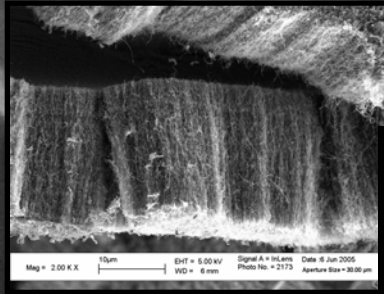
Single & Multi wall nanotubes
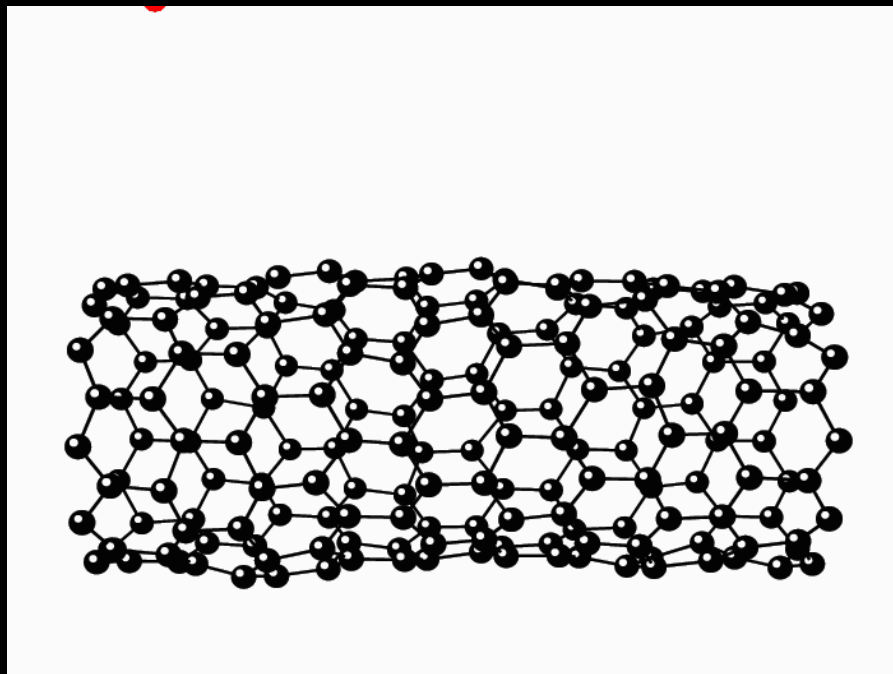
Single wall
carbon nanotube :
2/3 SC + 1/3 metallic

$\varnothing \sim 1$ nm
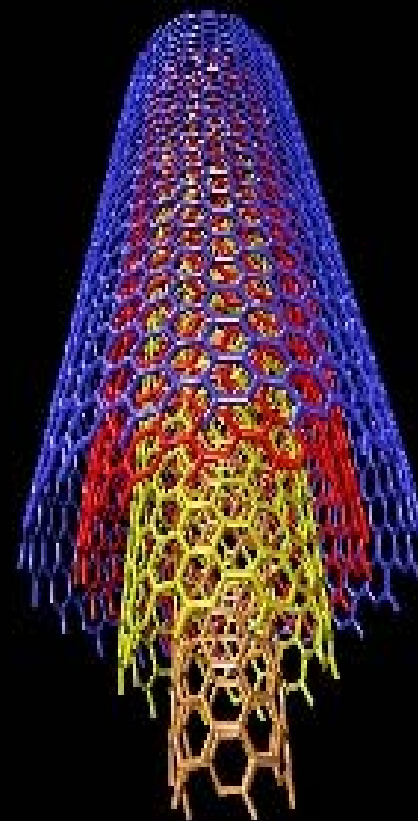
Multiwall
carbon nanotube :
metallic

$\varnothing \sim 20$ nm

Why Single Wall Carbon Nanotubes?

MOLECULAR PERFECTION & EXTREME PERFORMANCE

- The Strongest Fiber Possible.
- Selectable Electrical Properties
  - Metallic Tubes Better Than Copper
  - Semiconductors Better Than InSb or GaAs
- Thermal Conductivity of Diamond.
- The Unique Chemistry of Carbon.
- The Scale and Perfection of DNA.
- The Ultimately Versatile Engineering Material.

diamond

C_{60} "buckminsterfullerene"

graphite

Single-Wall Nanotube (SWNT)
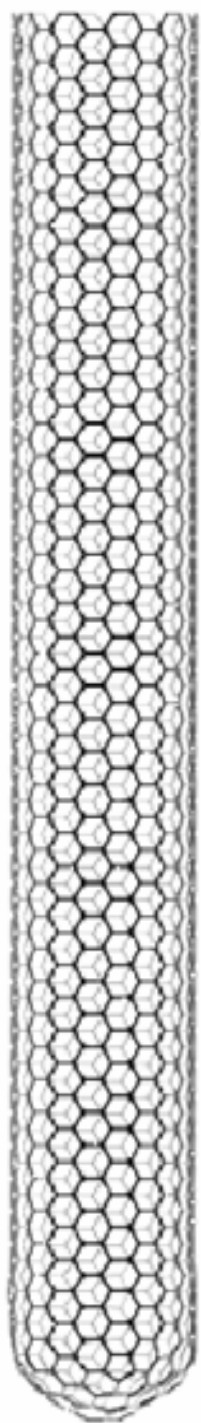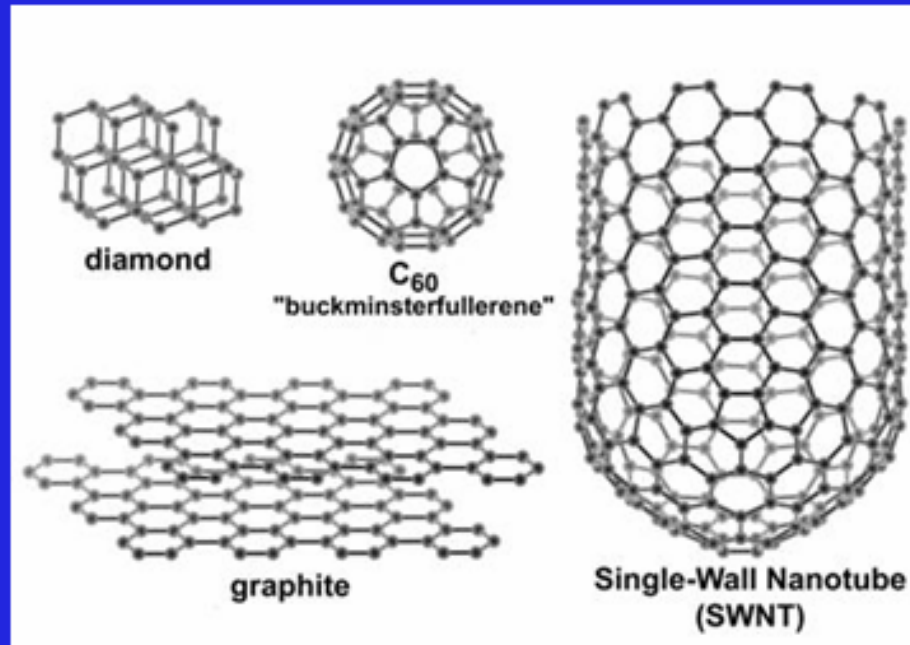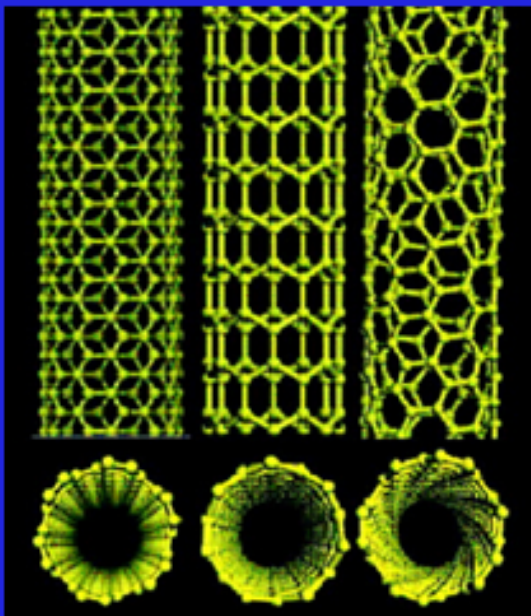
Electronic properties

- Electric conductivity = twice that of copper

- Able to support great density of current (10^9 A/cm^2)

- Excellent electronic emissivity (point effect)

- Can be functionalized (chemistry of carbon)

- SWNT can be metallic or semiconductor (depending on the chirality)
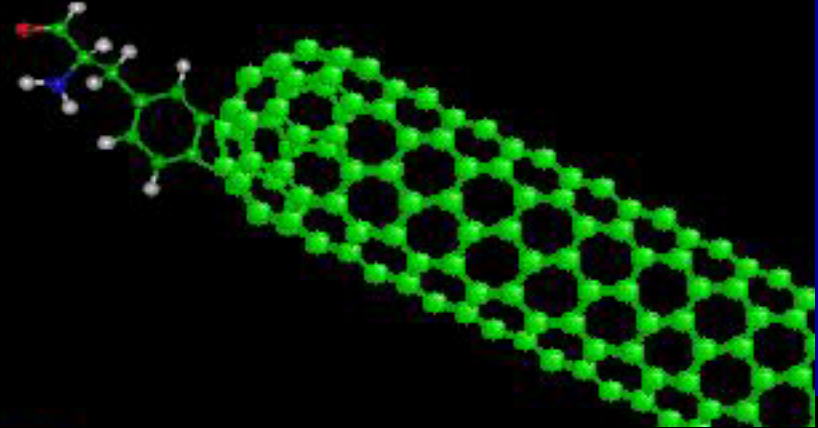
CNT : the way to transport electricity ?

Adapted from Richard Smalley

I think electric transmission is the destiny of this material and I want to make it happen

Richard Smalley,

co-discoverer of fullerene, Nobel Prize for Chemistry, 1996
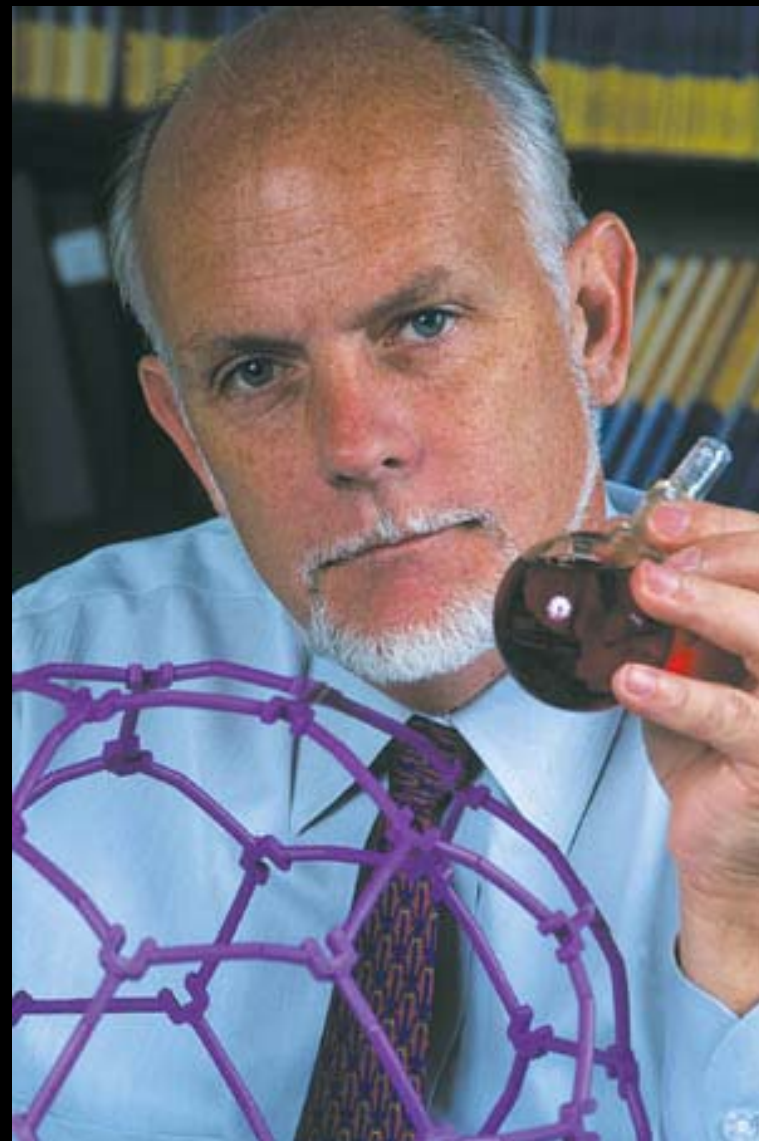
The ENERGY REVOLUTION
(The Terawatt Challenge)

2003

14 Terawatts

210 M BOE/day

0.5%

Oil, Coal, Gas, Fission, Biomass, Hydroelectric, Solar, wind, geothermal

Source: International Energy Agency

2050

30 -- 60 Terawatts
450 – 900 MBOE/day

Oil, Coal, Gas, Fusion / Fission, Biomass, Hydroelectric, Solar, wind, geothermal
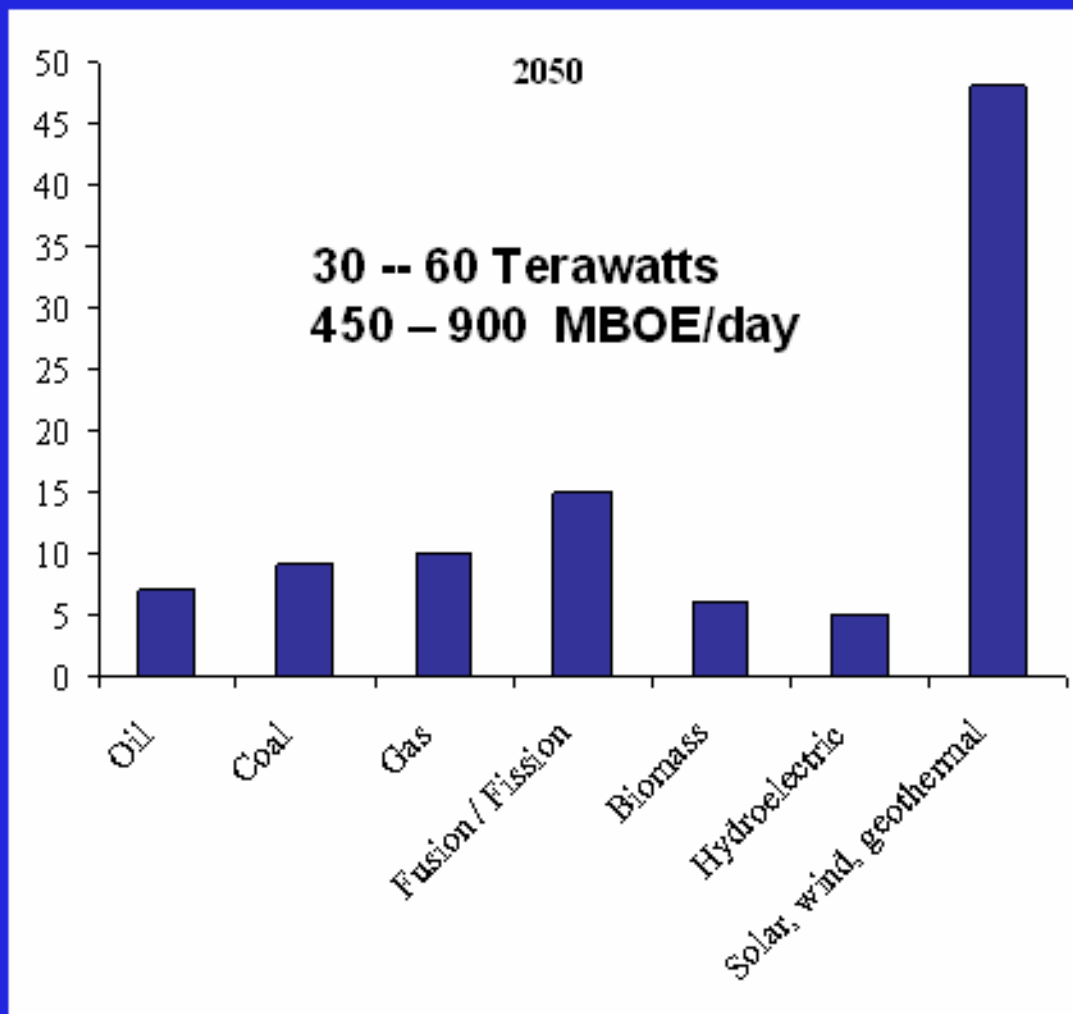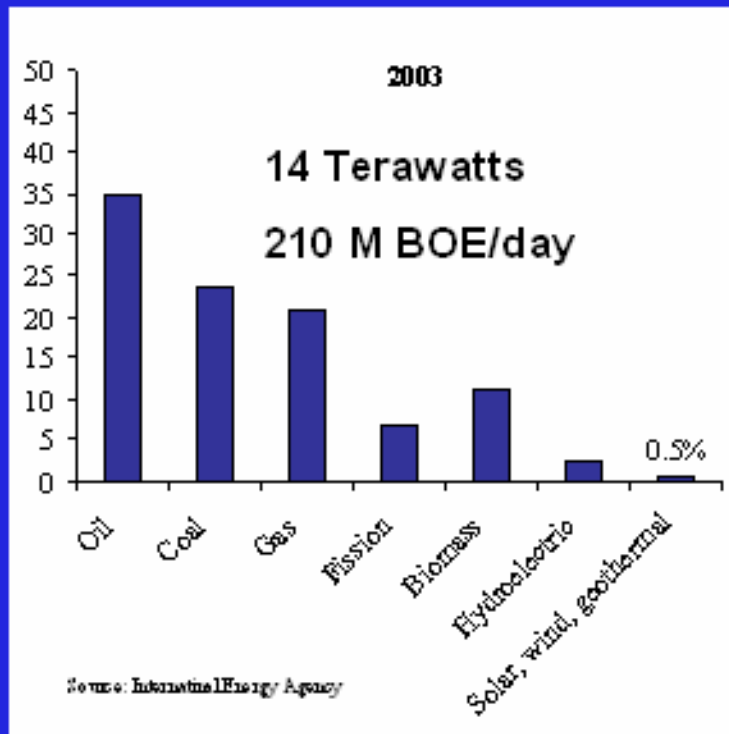
Energy:
The Basis of Prosperity
20st Century = OIL
21st Century = ??

10 Terawatt minimum for 10^{10} people

165,000 TW of sunlight hit the earth

Earth shown for size comparison
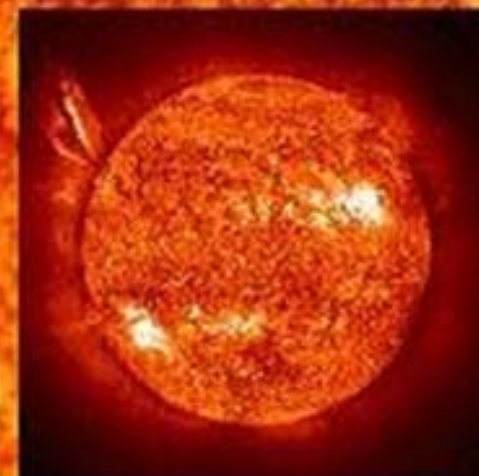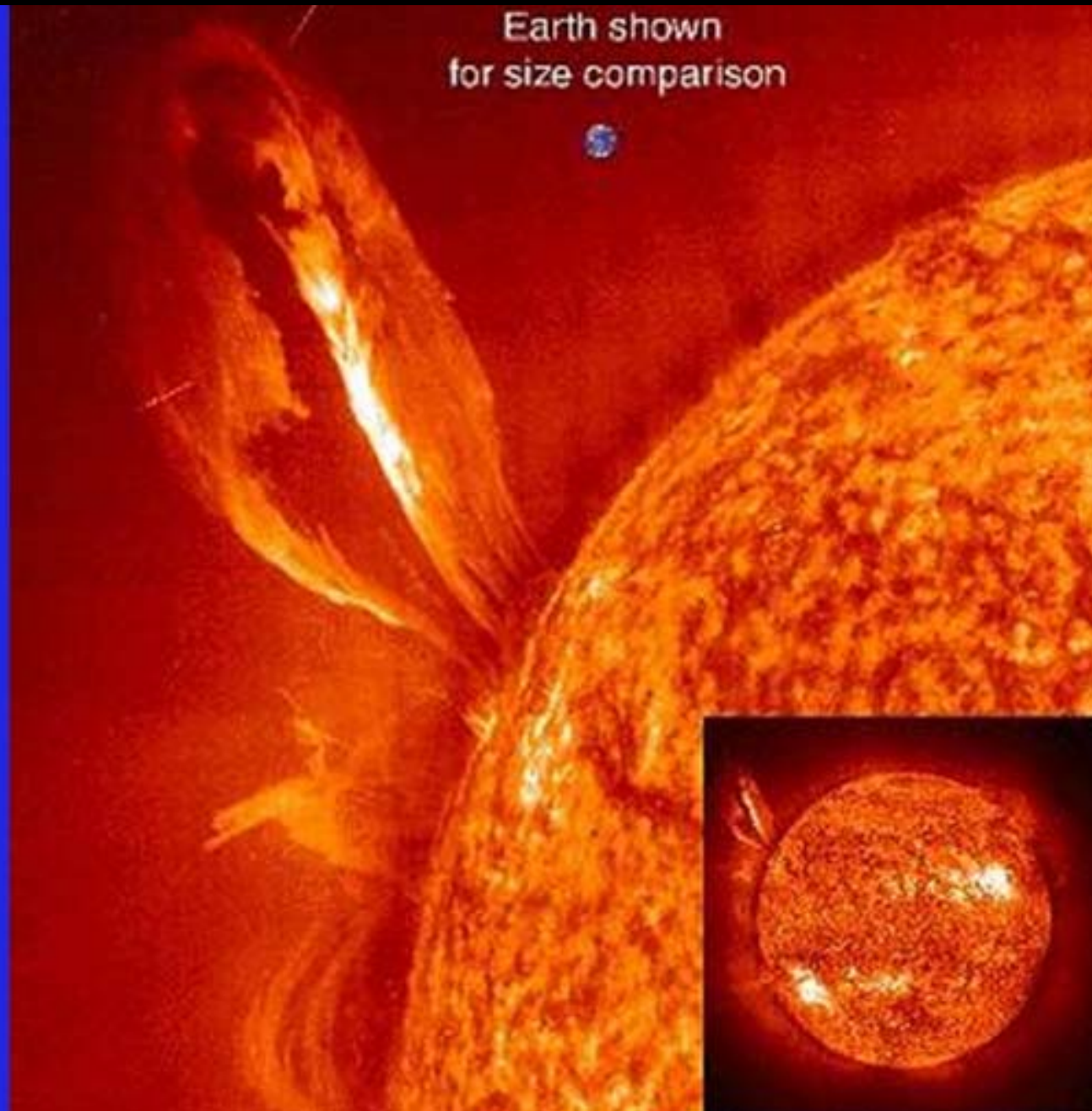
One World Energy Scheme for 30-60TW in 2050:
The Distributed Store-Gen Grid

- Energy transported as **electrical energy** over wire, rather than by transport of mass (coal, oil, gas)
- Vast electrical power grid on continental scale interconnecting ~ 100 million asynchronous "local" storage and generation sites, entire system continually innovated by free enterprise
- "Local" = house, block, community, business, town, …
- **Local storage** = batteries, flywheels, hydrogen, etc.
- **Local generation** = reverse of local storage + local solar and geo
- Local "buy low, sell high" to electrical power grid
- Local optimization of days of storage capacity, quality of local power
- **Electrical grid does not need to be very reliable, but it will be robust**
- Mass Primary Power input to grid via HV DC transmission lines from existing plants plus remote (up to 2000 mile) sources on TW scale, including vast solar farms in deserts, wind, NIMBY nuclear, clean coal, stranded gas, wave, hydro, space-based solar…"**EVERYBODY PLAYS**"
- **Hydrogen, methanol, ethanol are transportation fuels**
- Transition technology – Plug-in Hybrids

Energy Nanotech Grand Challenges
from Meeting at Rice University May 2003
Report available!

1. Photovoltaics -- drop cost by 100 fold.

2. Photocatalytic reduction of CO_2 to methanol.

3. Direct photoconversion of light + water to produce H_2.

4. Fuel cells -- drop the cost by 10-100x + low temp start.

5. Batteries and supercapacitors -- improve by 10-100x for automotive and distributed generation applications.

6. H_2 storage -- light weight materials for pressure tanks and LH2 vessels, and/or a new light weight, easily reversible hydrogen chemisorption system

7. Power cables (superconductors, or quantum conductors) with which to rewire the electrical transmission grid, and enable continental, and even worldwide electrical energy transport; and also to replace aluminum and copper wires essentially everywhere -- particularly in the windings of electric motors and generators (especially good if we can eliminate eddy current losses).

SWNT Quantum Wire

Expected Features
- 1-10x Copper Conductivity
- 6x Less Mass
- Stronger Than Steel
- Zero Thermal Expansion

Key Grid Benefits
- Reduced Power Loss
- Low-to-No Sag
- Reduced Mass
- Higher Power Density

SWNT Technology Benefits
- Type & Class Specific
- Higher Purity
- Lower Cost
- Polymer Dispersible
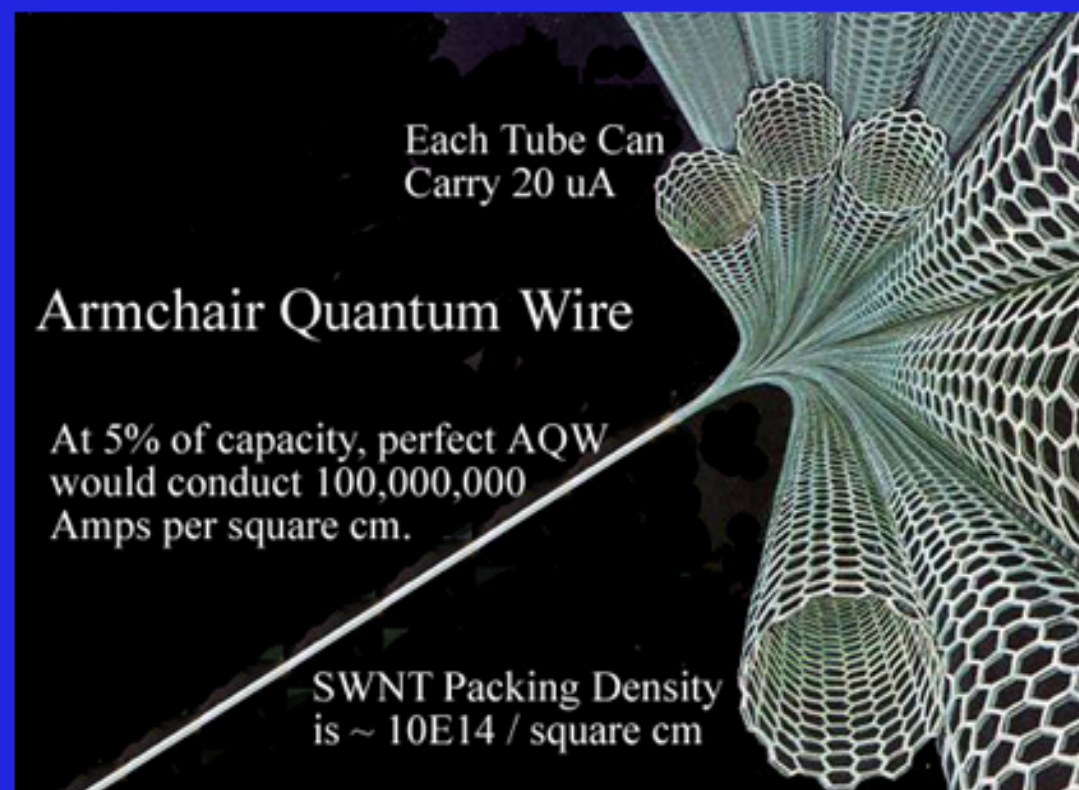
Each Tube Can Carry 20 uA

Armchair Quantum Wire

At 5% of capacity, perfect AQW would conduct 100,000,000 Amps per square cm.

SWNT Packing Density is ~ 10E14 / square cm

Production Scale-Up Path

- Rice made 1 mg / day in 1997

- Lab-scale reactor at 1 gm / hour (2002)

- CNI Pilot plant producing 20 lb /day

- CNI now testing 100 lb / day reactor

Estimated future global production of nanotubes

Reference: Cientifica 2004
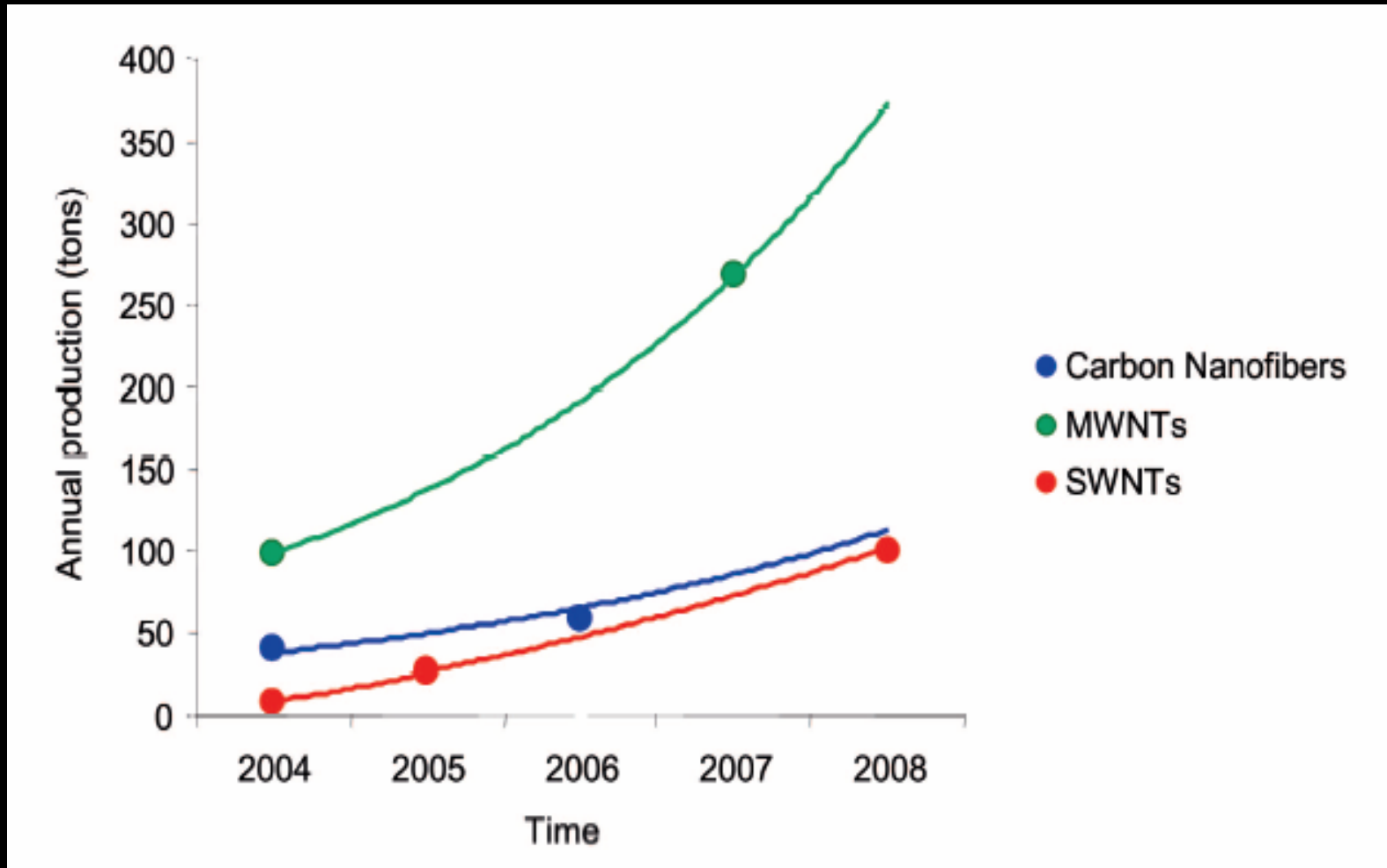
Prototype Wire - SWNT Fibers

- Producing Neat SWNT Fibers
- Dry-Spun from Oleum
- 6 to 14 Wt. % SWNT Dope
- Extruded as 50 μm Dia. Fibers
- 10^9 Tubes in Cross Section
- 100 Meters Long

Acc.V Spot Magn   Det WD ├───────────┤ 200 μm
30.0 kV 3.0 120x   SE   7.5   Hivac
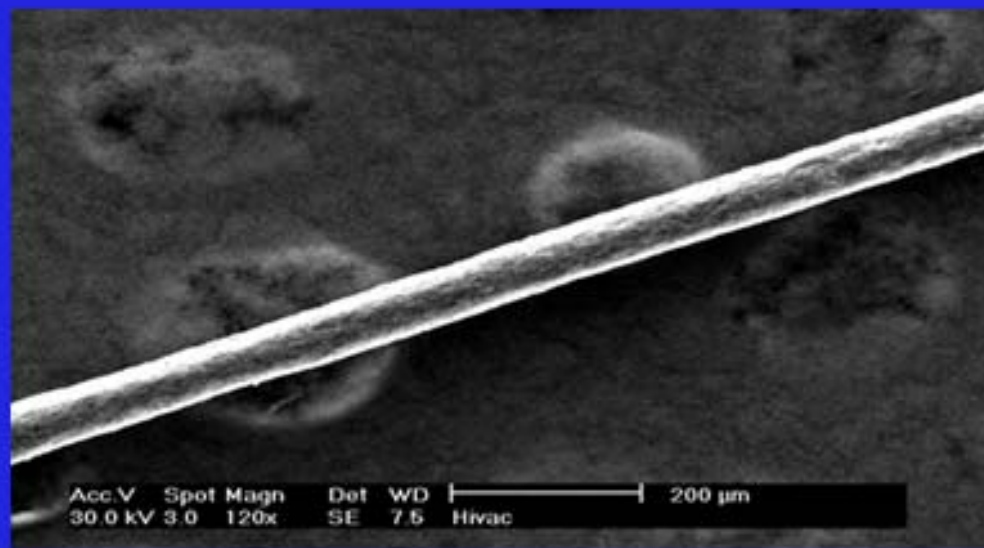
Science <u>305</u>, 1447-1450, 3 September 2004!!!

Quantum Wire on The Grid

Key Grid Benefits

- Eliminate Thermal Failures
- Reduce Wasted Power
- Reduce Urban R.O.W. Costs
- Enable Remote Generation

003/45/7844

5
ug. 2003

Amperage vs. Temperature Rise
795 kcmil ACSR, ACCR, AQW & 1367 kcmil AQW

SWNT 1367 @ 2.5 x Cu

SWNT 795 @ 1 x Cu

ACCR, 795 kcmil

ACSR, 795 kcmil

- ◆ ACCR 795
- ■ SWNT 795 (1xCu)
- ▲ SWNT 1367 (2.5xCu)
- × ACSR 795 (Std.)

Temperature Rise (C)

300, 250, 200, 150, 100, 50, 0

Cable Amperage

0, 10,000, 20,000, 30,000, 40,000

Chart Area
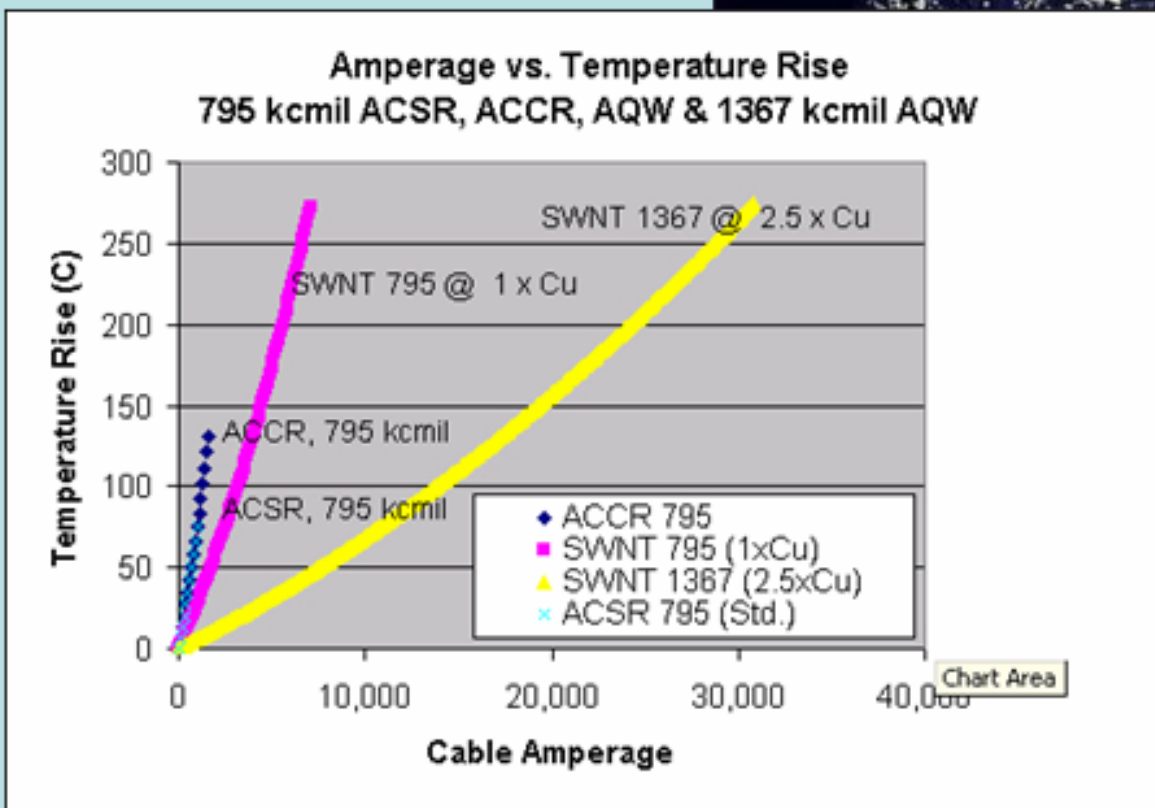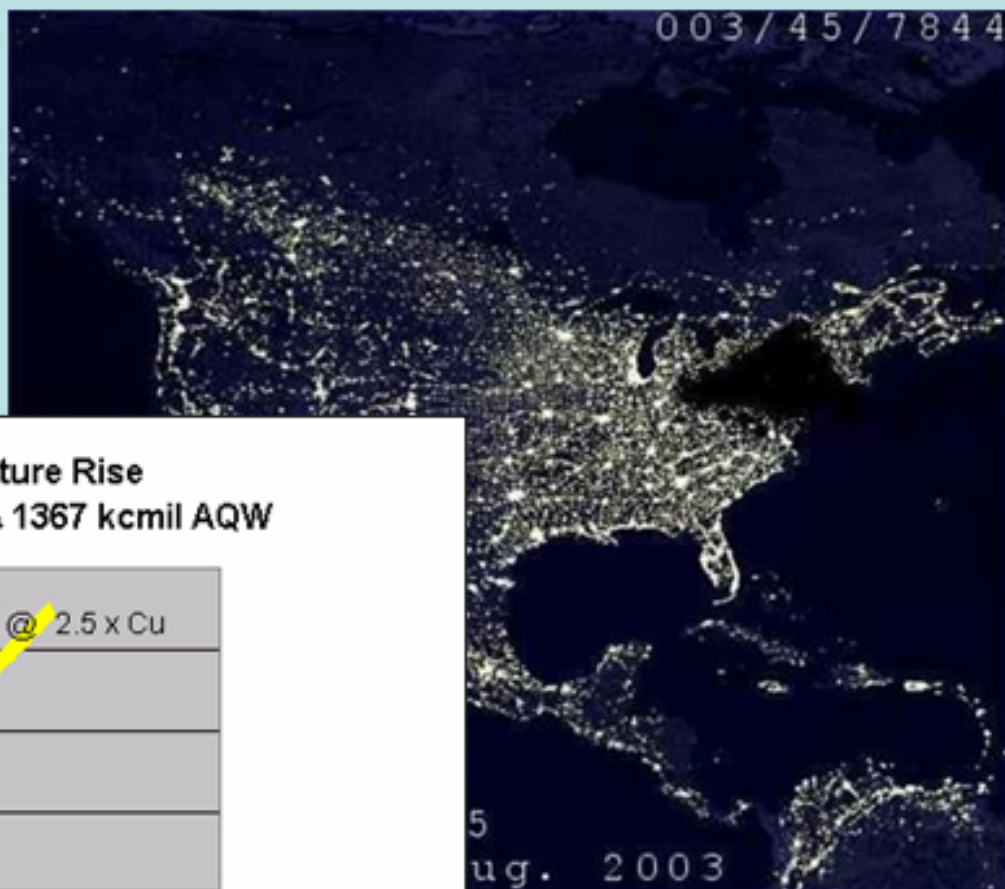
Grid Applications & Benefits

- Eliminate Thermal-Sag Failure: Now a $100B+ a year problem.

- Short-Distance AC: AQW* could increase throughput up to ten-fold without increasing losses while using only existing towers and rights-of-way. Avoid new construction in congested urban areas – estimated over $100M per mile.

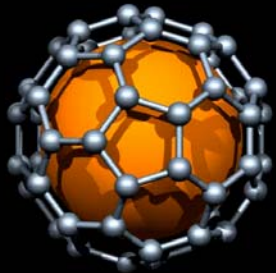- Medium-Distance AC: AQW* could decrease resistive losses and voltage drop ten-fold if amperage were not increased. This would improve grid dynamics significantly in the range between 100 and 300 miles, where voltage stability limits deliverable power.

- Long-Distance HVDC: AQW* could permit amperage throughput ten fold or reduce losses ten-fold. New conventional lines cost $1M to $2M per mile, plus about $250M per AC/DC converter station.

- Remote Power: Could enable utilization of large-scale renewables and remote nuclear.

* AQW = Armchair Quantum Wire

Conclusions

- The control of the matter produced, at the end of the 18th century, a first technological and industrial revolution

- In the middle of the 20th century, the control of the matter on a micrometer scale was at the origin of a second technological revolution, which was concretized by the development of micro electronics

- It is probable that the nanosciences and the nanotechnologies, will constitute, during the 21st century, the third technological and industrial revolution

The End

Thank you for your attention