Building College-University Partnerships for Nanotechnology Workforce Development

NanoScience and Nanotechnology

NanoScience and Nanotechnology:
How the Smallest Building Blocks are Impacting Life Today and Tomorrow

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Materials Science and Engineering

Pennsylvania State University

Overview

- What is Materials Science and Engineering
  - What is a material
  - Engineering versus Science
  - Example – Turkey Timer

- Impact now and in the Future
  - Interest in Nanotechnology
  - Making materials small generates big changes
  - Products
  - Research

- Questions

Ceramics in General

- Bond metal to a non-metal
- Ionic and covalent bonding
- High stiffness with no toughness
- Insulators
- High temperature and chemical resistivity

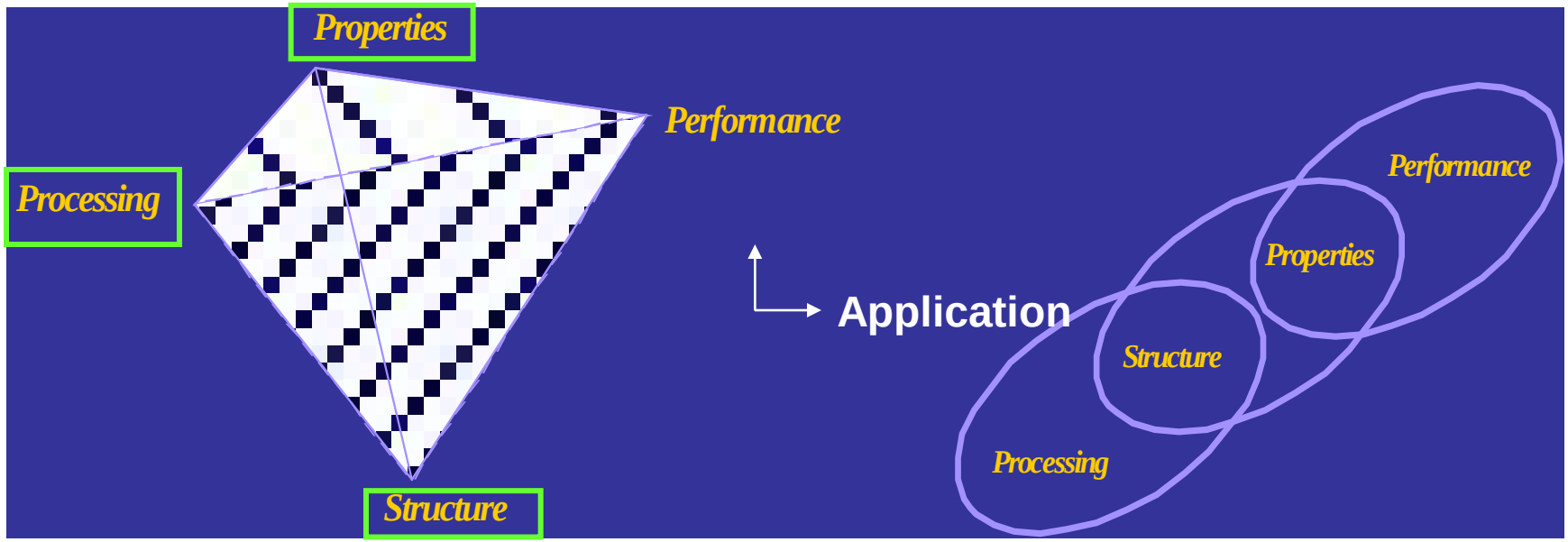
Metals in General

- Metallic bonding – sharing of electrons
- Alloyed with addition of other elements
- High strength, tough/ductile
- Can engineer stiffness and toughness through both atomistic and microstructural manipulations
- Conductors

Polymers in General

- Long carbon chains (does not have to be carbon)
- Covalent bonds within chains with covalent and van der Waals bonds between chains
- Low stiffness and high ductility/toughness
- Low temperature
- Performance highly dependent on molecular weight and degree of crystallinity

THE MATERIALS' SCIENCE TETRAHEDRON

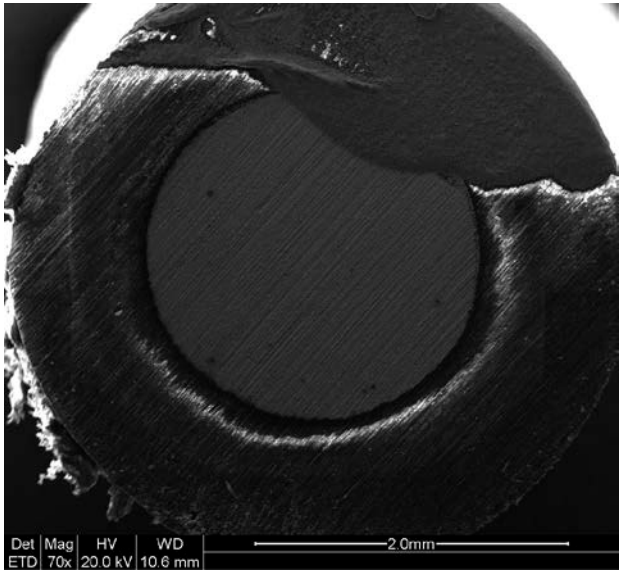


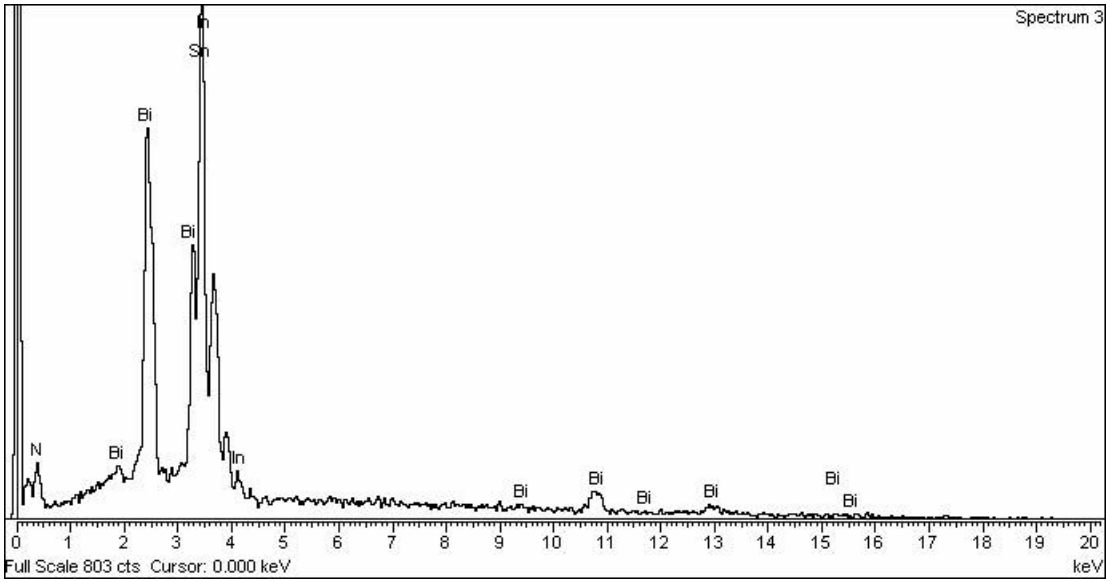
chemistry, thermodynamics, kinetics, transport phenomena crystallography, electron and x-ray diffraction, analytical methods solid state physics, optics, electromagnetics, mechanical properties, chemical stability, etc.

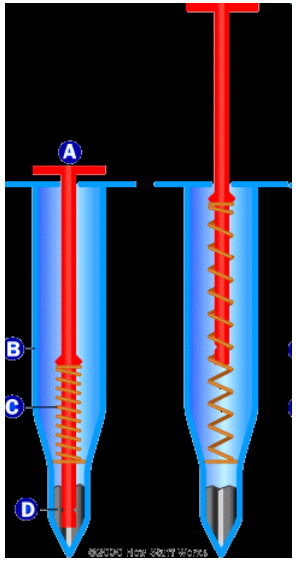
Engineering versus Science

- Engineering answers the question how
- Science answers the question why
- Example: creation of a hard surface to use to hit an object (hammer, golf club, tennis racket, etc.)
- Engineering chooses a metal and develops a setup to generate power
- Science asks what can we change within the components of the engineered system to exact improved properties for better performance

Turkey Day Materials Science





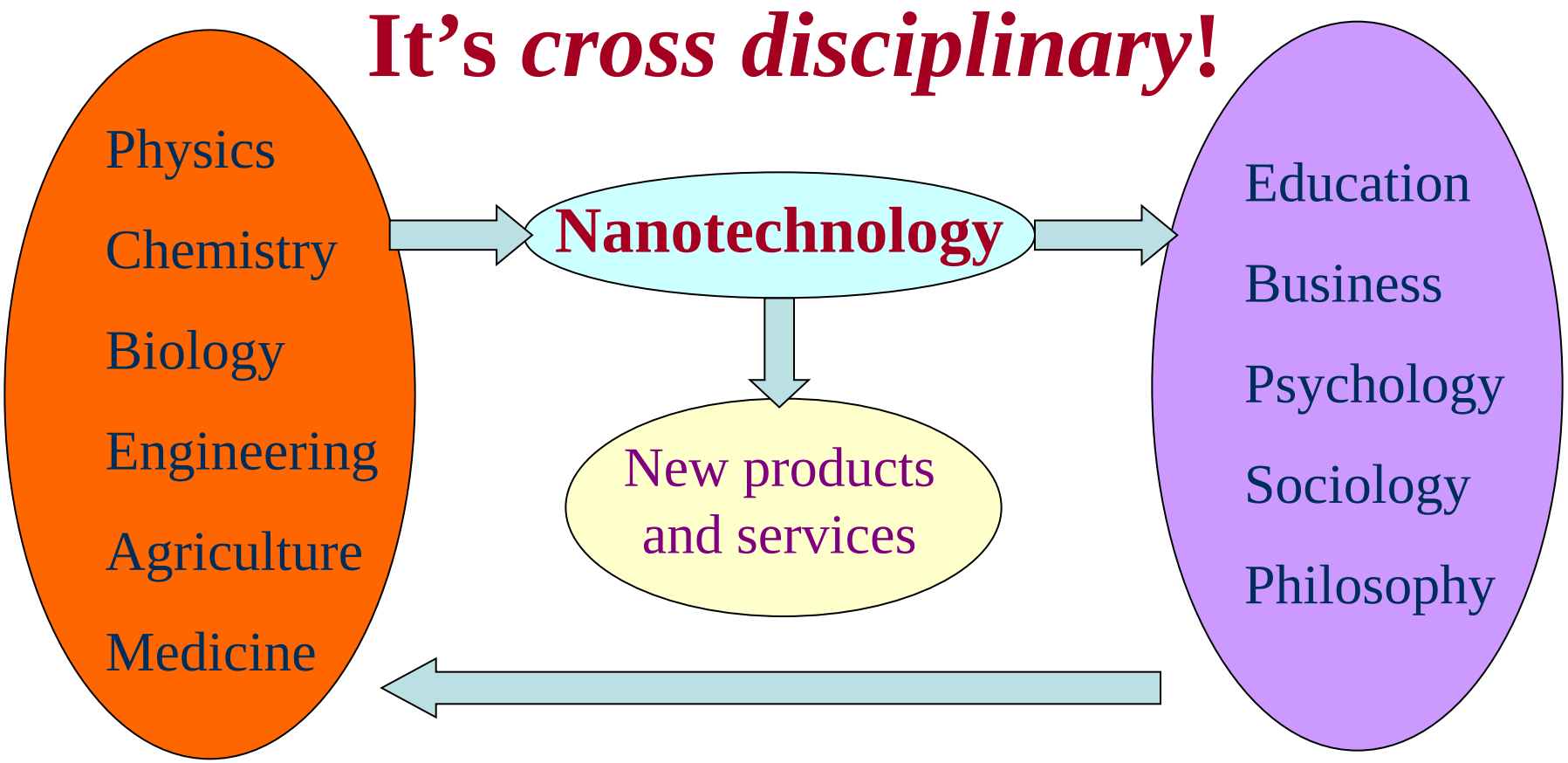


Element	Field's Metal Weight %	Turkey Timer Weight %
Bismuth (Bi)	32.5	32.5
Indium (In)	51	18.7
Tin (Sn)	16.5	48.5
Melting Point Celsius (F)	62 (144)	85 (185)

Nanoscience and Nanotechnology

- **Nano: 10^{-9} meters or 0.000000001 meters**
- **Essentially any material with a defining property determined by a structure at the nanometer scale**
- **Working definition for materials science and engineering is 0.1 – 100 nanometers**

What Makes Nanotechnology Development and Education Challenging and Exciting?



Large Effects of Smallness

- **Nanoparticles: as you DECREASE the diameter of the particles you INCREASE the surface area. (you can get a lot more particles into the same fixed volume of space**

- **Left jar contains 3000 marbles 5/8”in diameter**
- **Right jar contains 5000 marbles ½” in diameter**
- **A reduction of 20% created a gain of 2000 marbles**

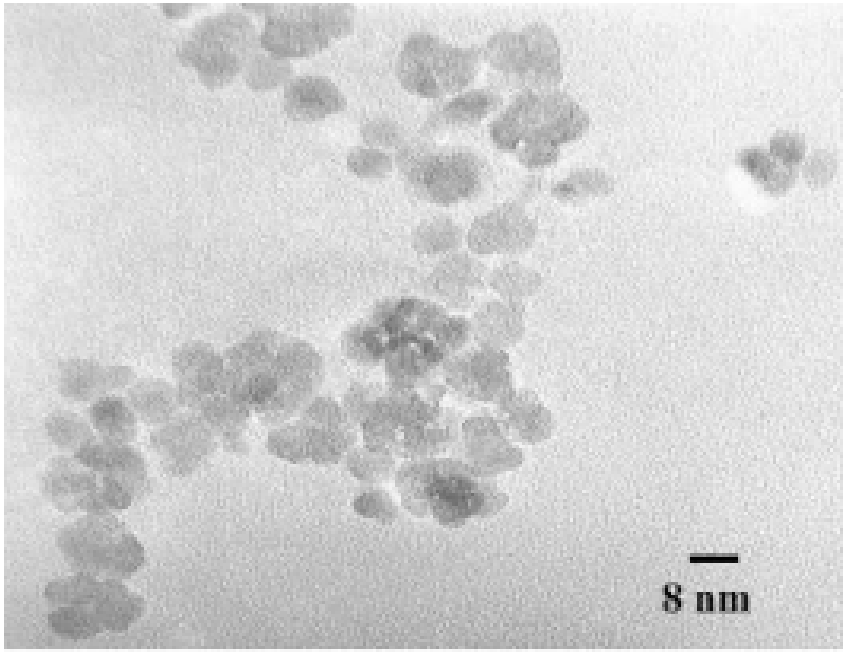
Large Effects of Smallness

- **Sometimes we are just interested in making really small particles**

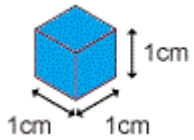
- **Here quantum dots of cadmium selenide (CdSe) are used to create an array of colors**

Large Effects of Smallness

- Surface area: amount of surface available for chemical reaction
- "traditional" ceramic powders are typically around 1 to 10 micrometers in size
- Surface area of <1 m^2/g
- These ceramic particles are around 8 nanometers in size
- A reduction of ~1000 times in size
- Surface area of ~130 m^2/g



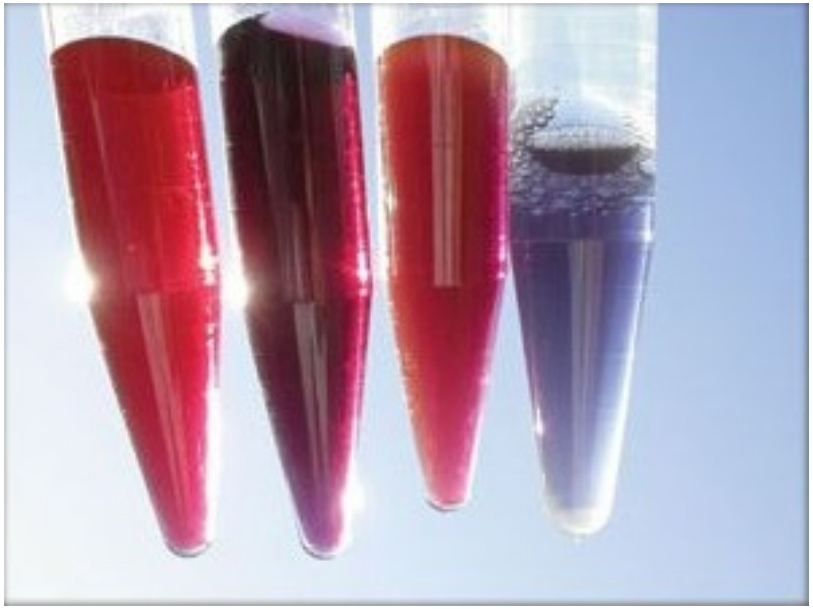
- **What does that mean physically?**



A one centimeter cube full of this 8nm particle size powder would have an equivalent surface area of ~1400 sq ft.!
1cm = 0.40 inches

A Little History

- **Nanotechnology has been around for a long time – 2000 years ago nano-gold particles were used in coloring of glass**
- **The left picture shows the array of colors possible with gold nanoparticles**



Career Pathways

- **Business**
- **Communications**
- **Human Services**
- **Engineering and Industrial**
- **Science**

Making Things Smaller and Cheaper

Portable music player

Portable telecommunication

Portable GPS

Pocket calculator

Portable video camera

Portable gaming device

Portable camera

System Integration

Portable music player

Portable telecommunication

Portable GPS

Pocket calculator

Portable video camera

Portable gaming device

Portable camera

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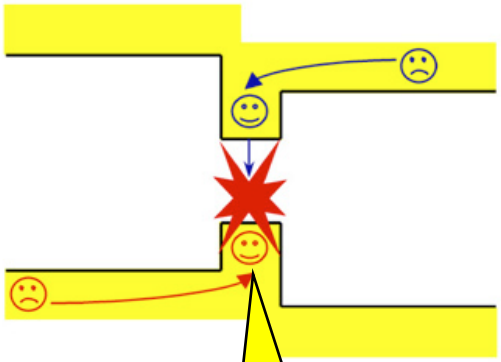
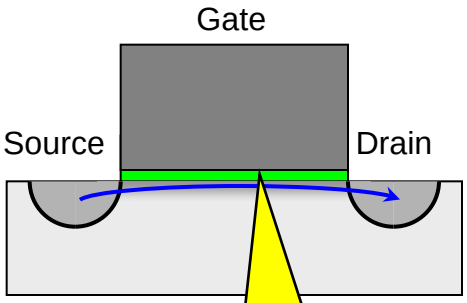
Nanotechnology on our Desktops

Quantum Well Laser



Well
6 nm

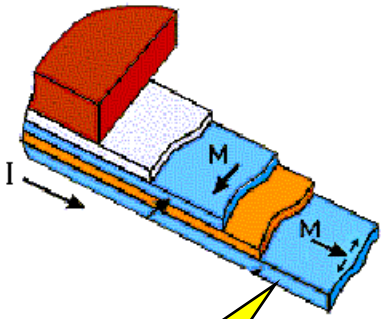
Transistor



Gate oxide
4 nm

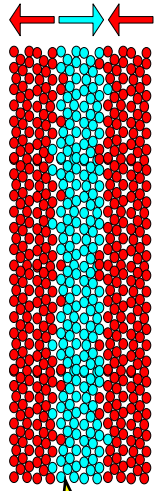
Hard Disk

Sensor



Switching layer
5 nm

Medium



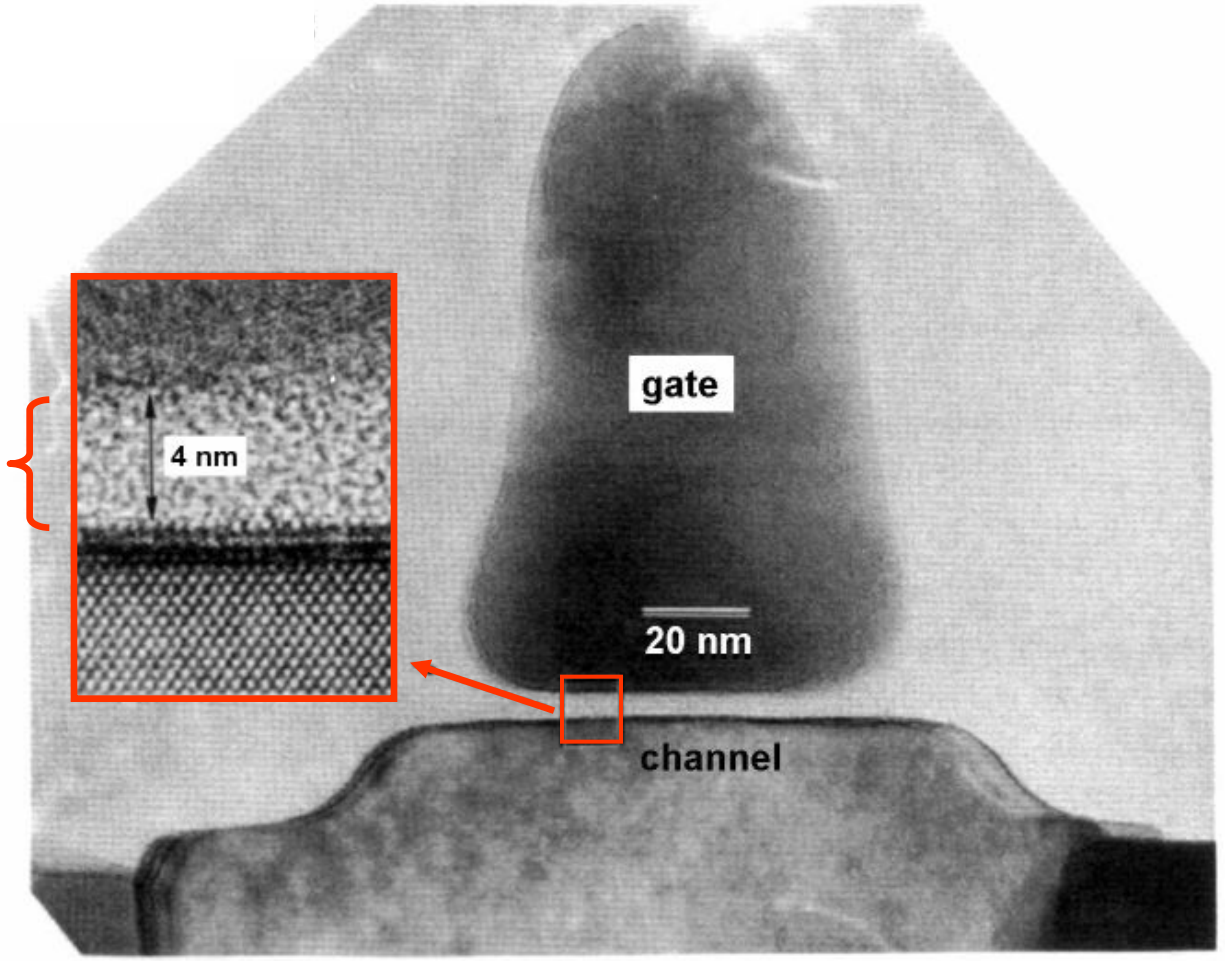
Magnetic grain
10 nm

Power consumption by a leaky gate oxide: A show-stopper for Moore's Law ?

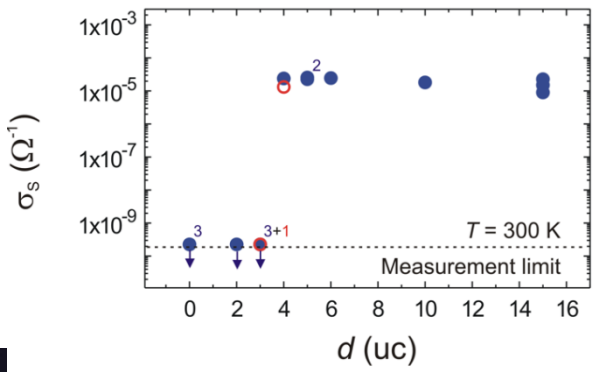
Gate oxide has shrunk to < 2nm, < 10 atom layers.

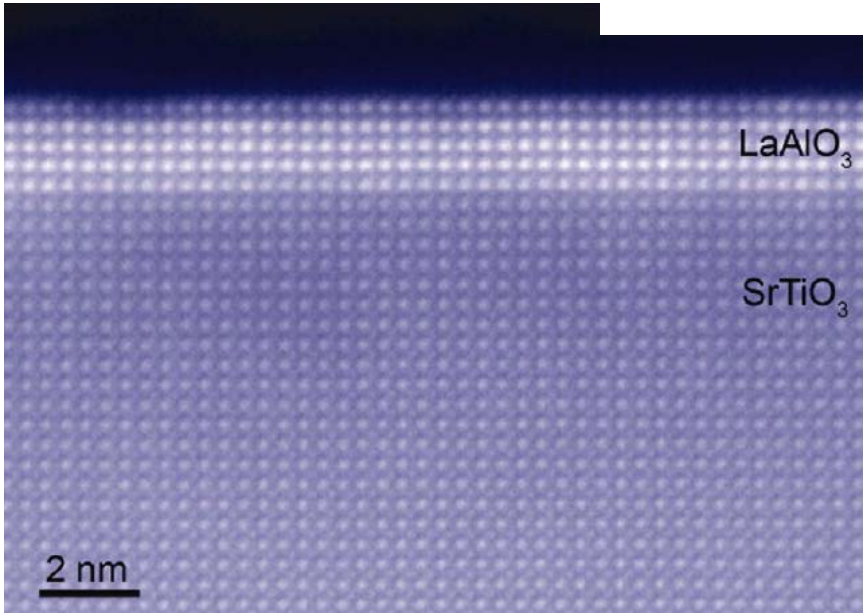
Electrons can tunnel through when applying a gate voltage.

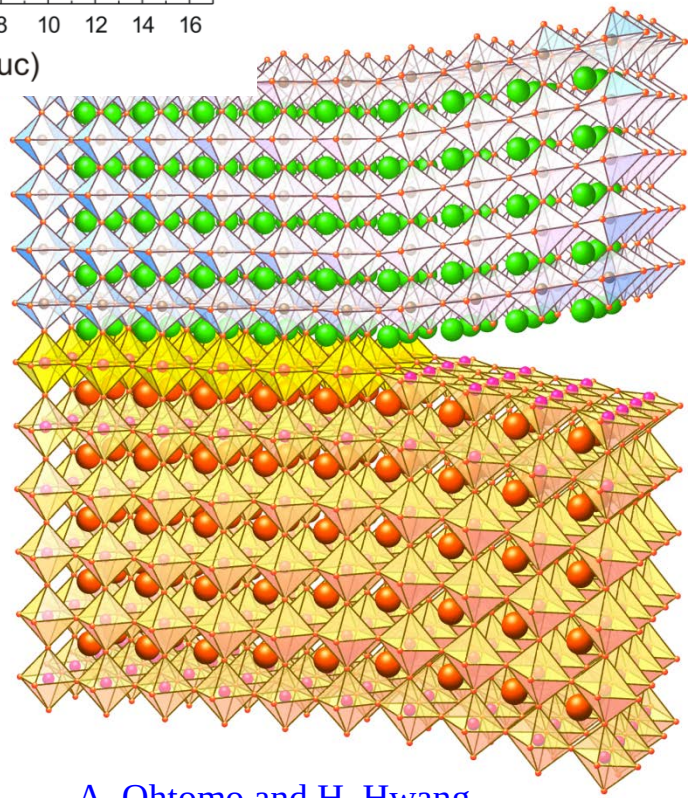
Uses up to $^1/_3$ of the power.



Surprising phenomena at oxide-oxide interfaces: formation of a 2dimensional electron gas between two bulk insulators



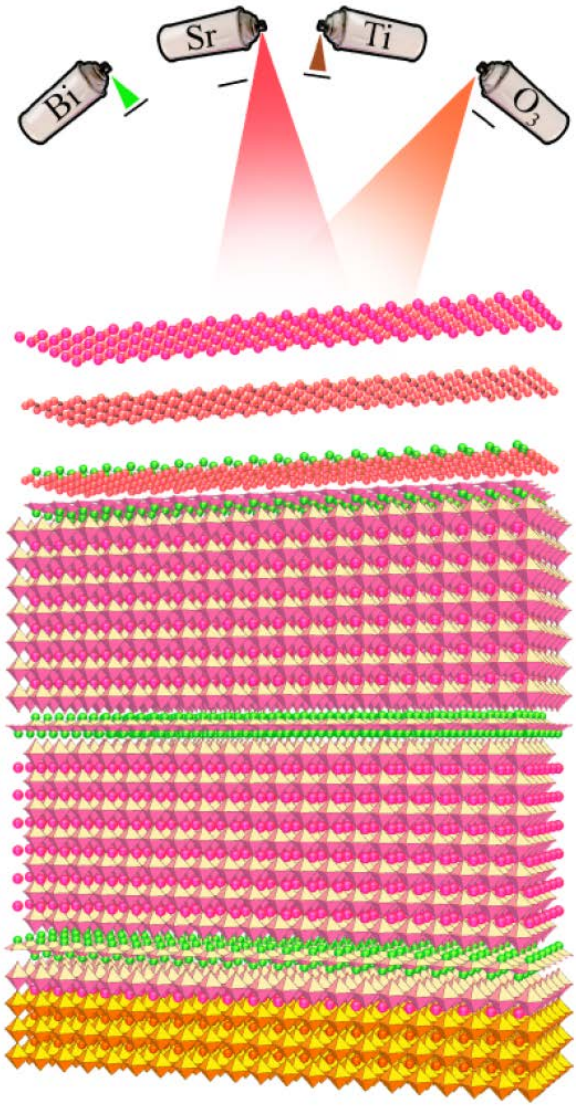




J. Mannhart[1],* and D. G. Schlom[2],*
Science 327, 1607 (2010)

A. Ohtomo and H. Hwang
Nature **427** (2004) 423-426

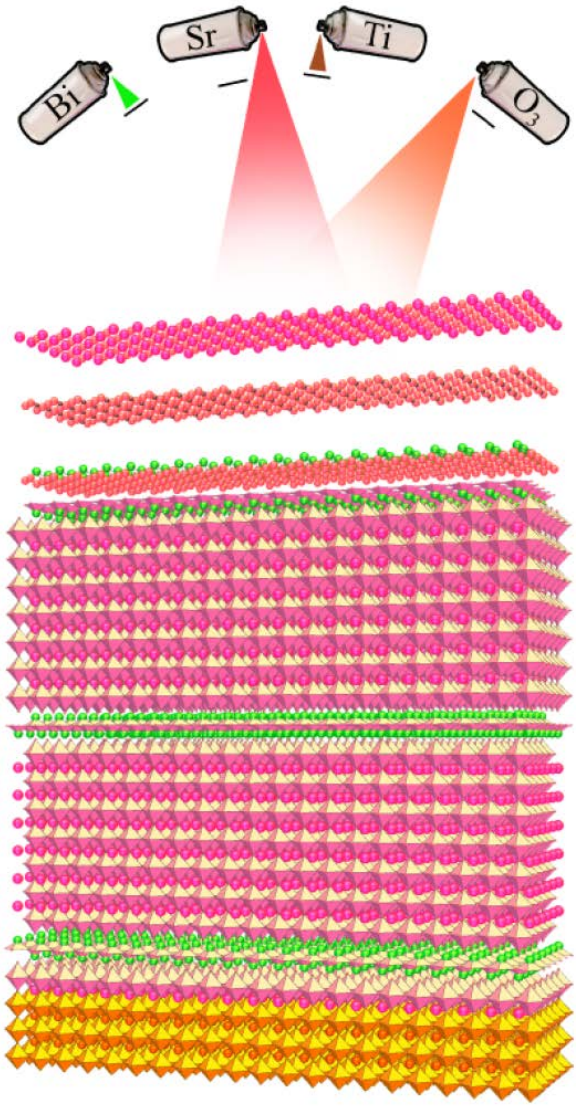
How Do We Arrange Them?



- atomic spray painting approach

J. Am. Cer. Soc. **91**, 2429 (2008).

How Do We Arrange Them?



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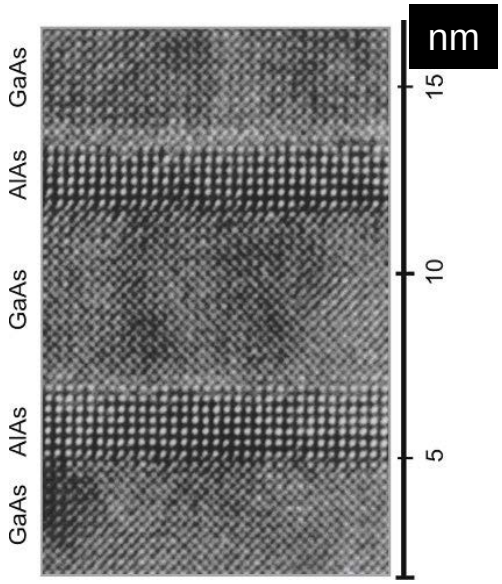
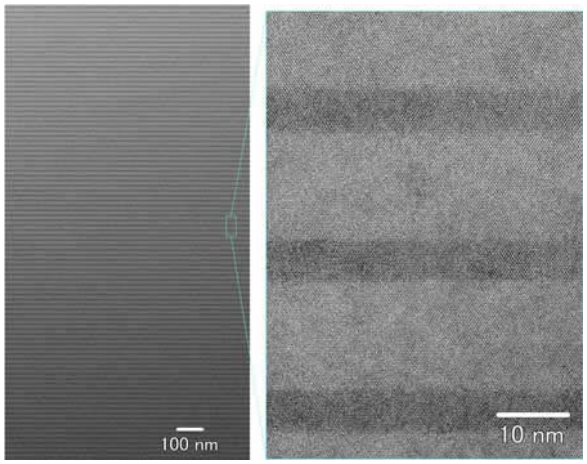
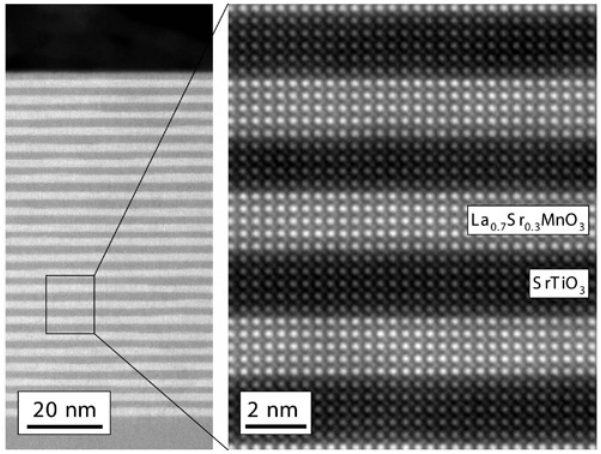


AlAs/GaAs superlattices, atomically sharp interfaces, perfect atomic registry across interfaces, nanoscale arrangement of two structurally similar materials with entirely different electronic properties



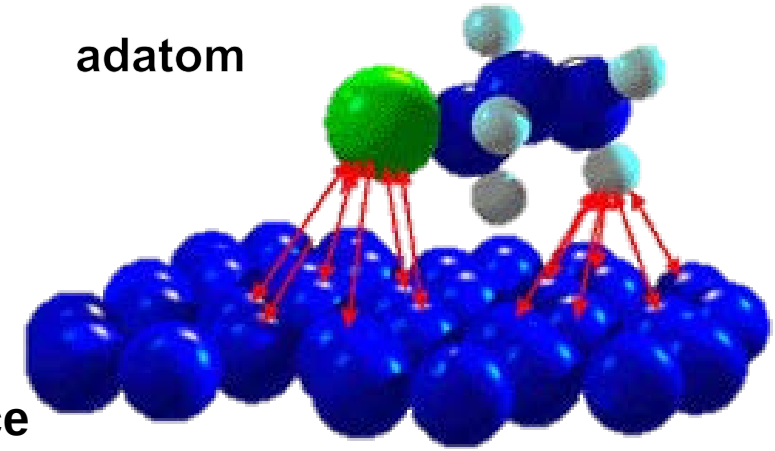
InGaAsP superlattice for high-efficicency solar cells, Sugiyama Lab, U of Tokyo



D. Muller group, Cornell

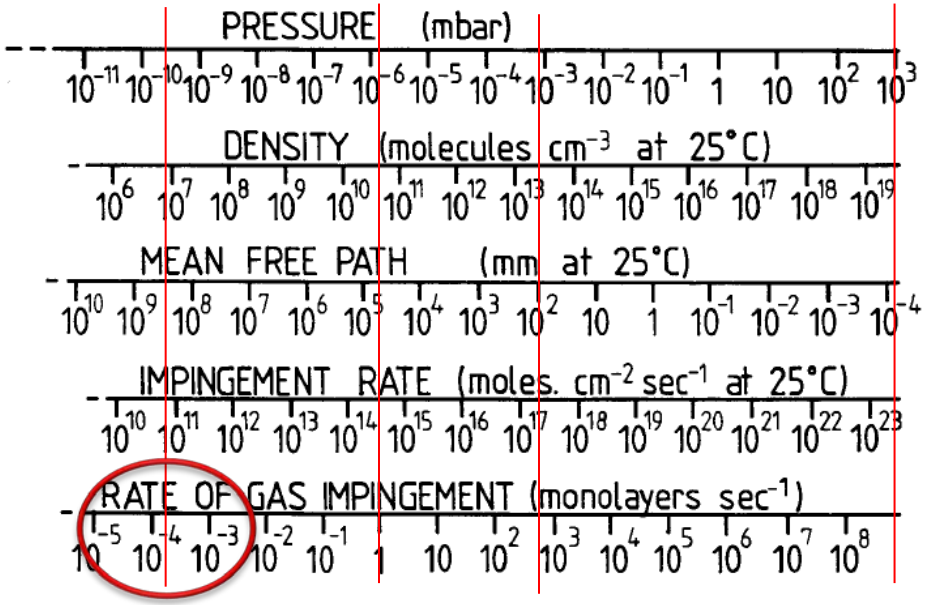
Ingredients for Atomic Scale Control

- Keep the growth environment clean!



Ultrahigh vaccum is the choice!

enough time to build up the crystal layer by layer without incorporating gas molecules

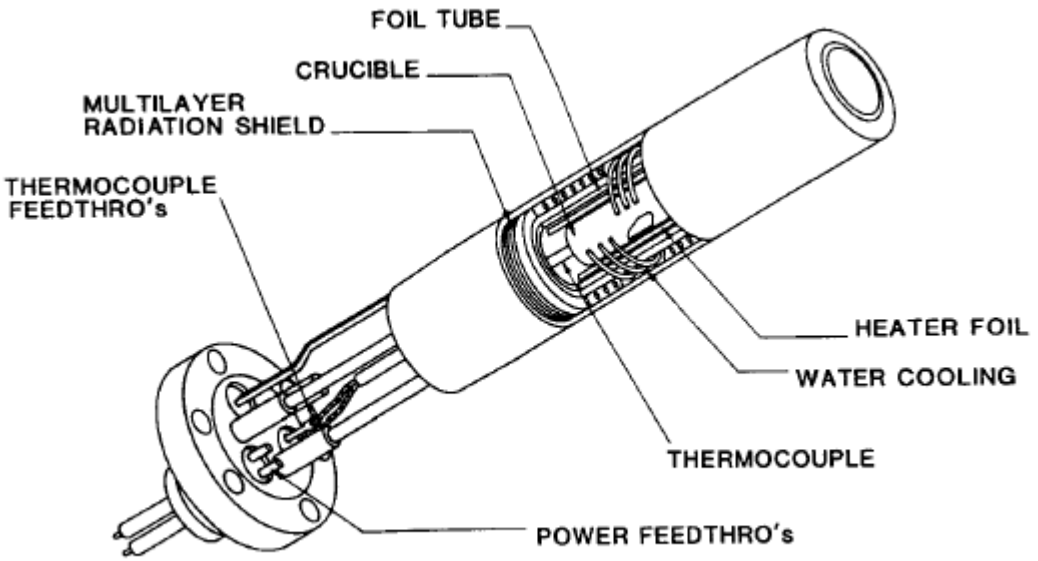


Grow Slowly to Maintain Control

- We want to grow atomic layer by atomic layer
  - How many atoms will form a monolayer?
  - How do I generate this this much flux?

$$J_i = \frac{p_i N_A}{\sqrt{2\pi M_i RT}}$$

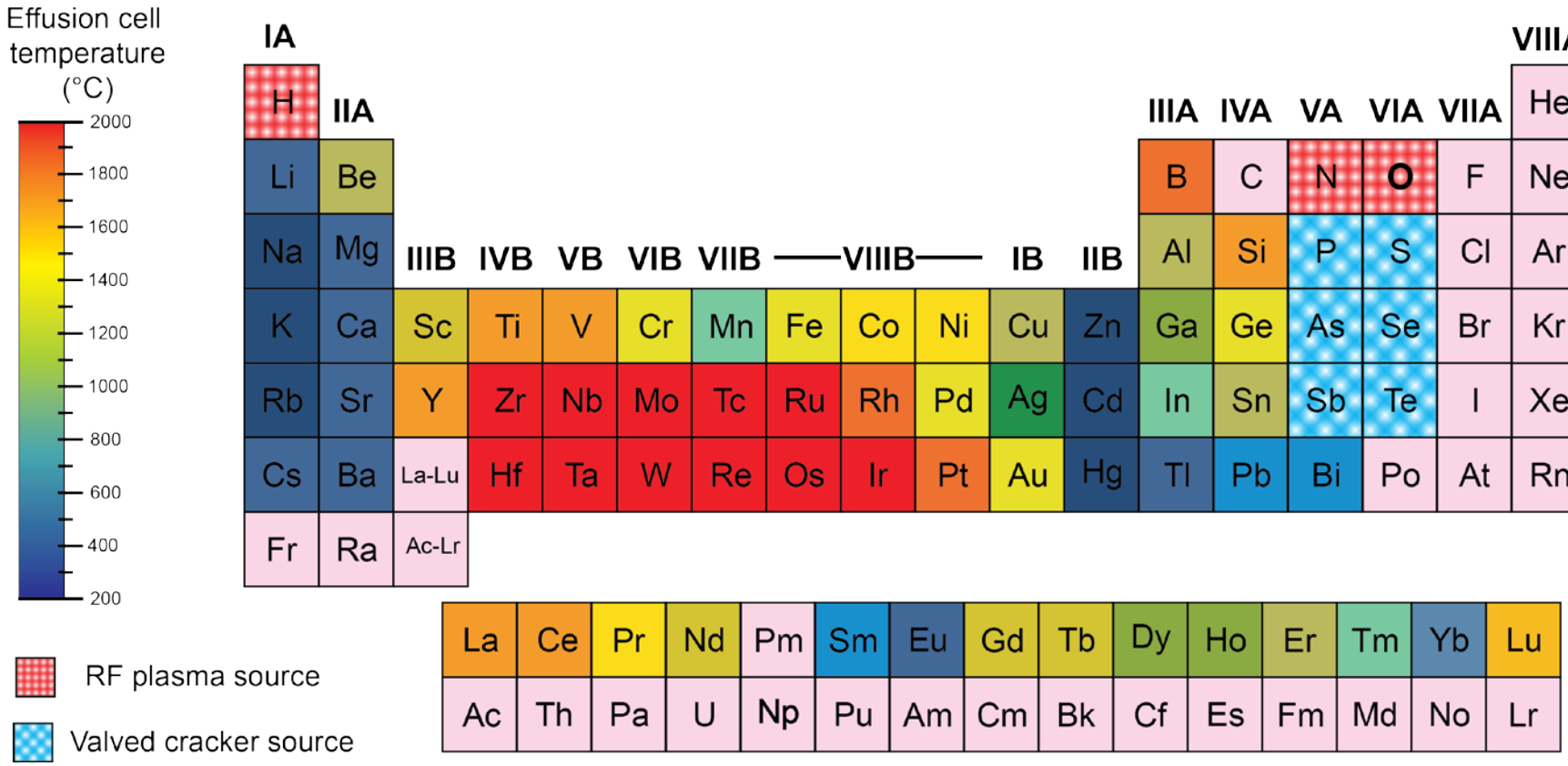
Knudsen



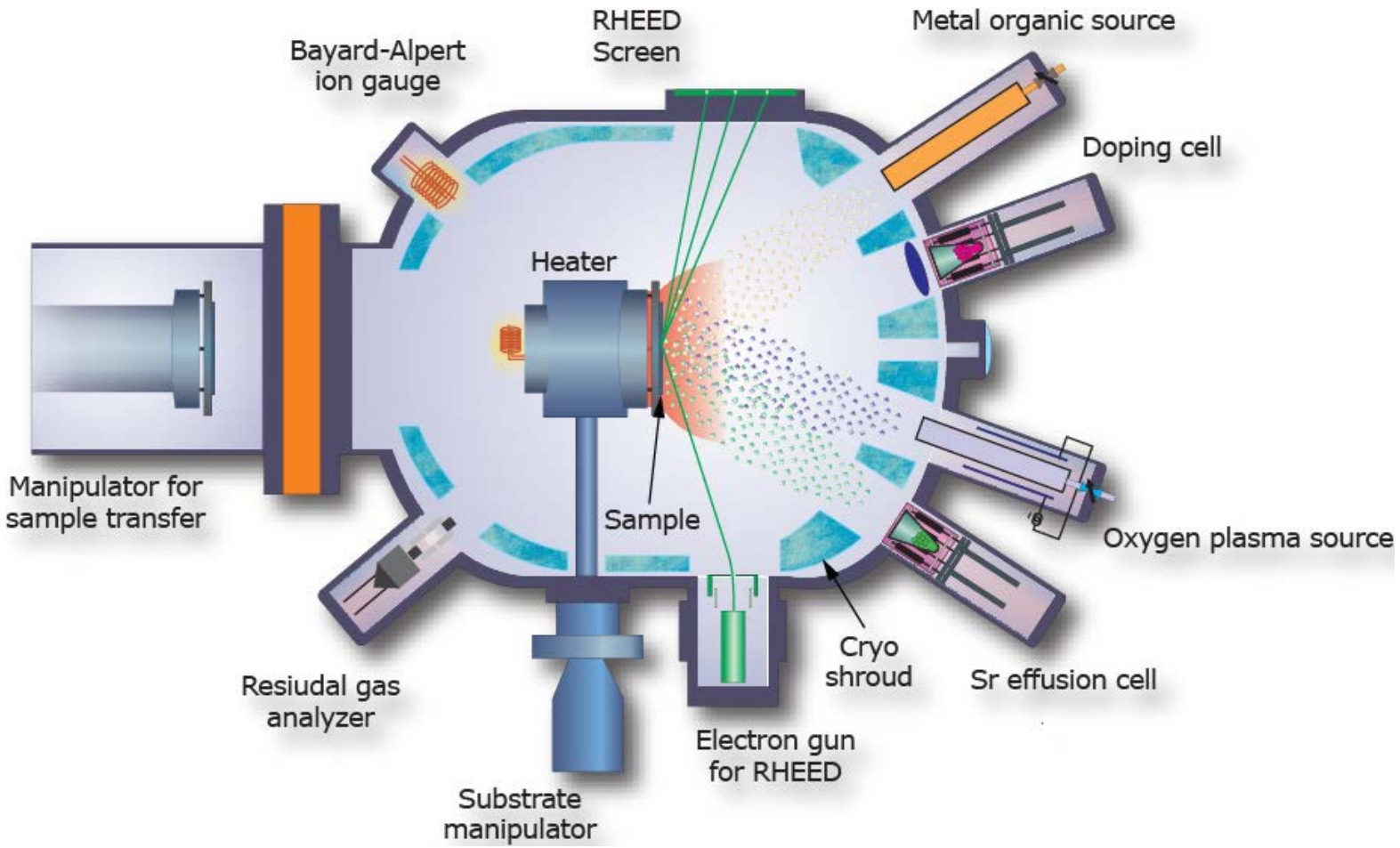
Effusion cell

Is This Feasible?

- What are the vapor pressures of elements?



Put Everything Together into a System: MBE



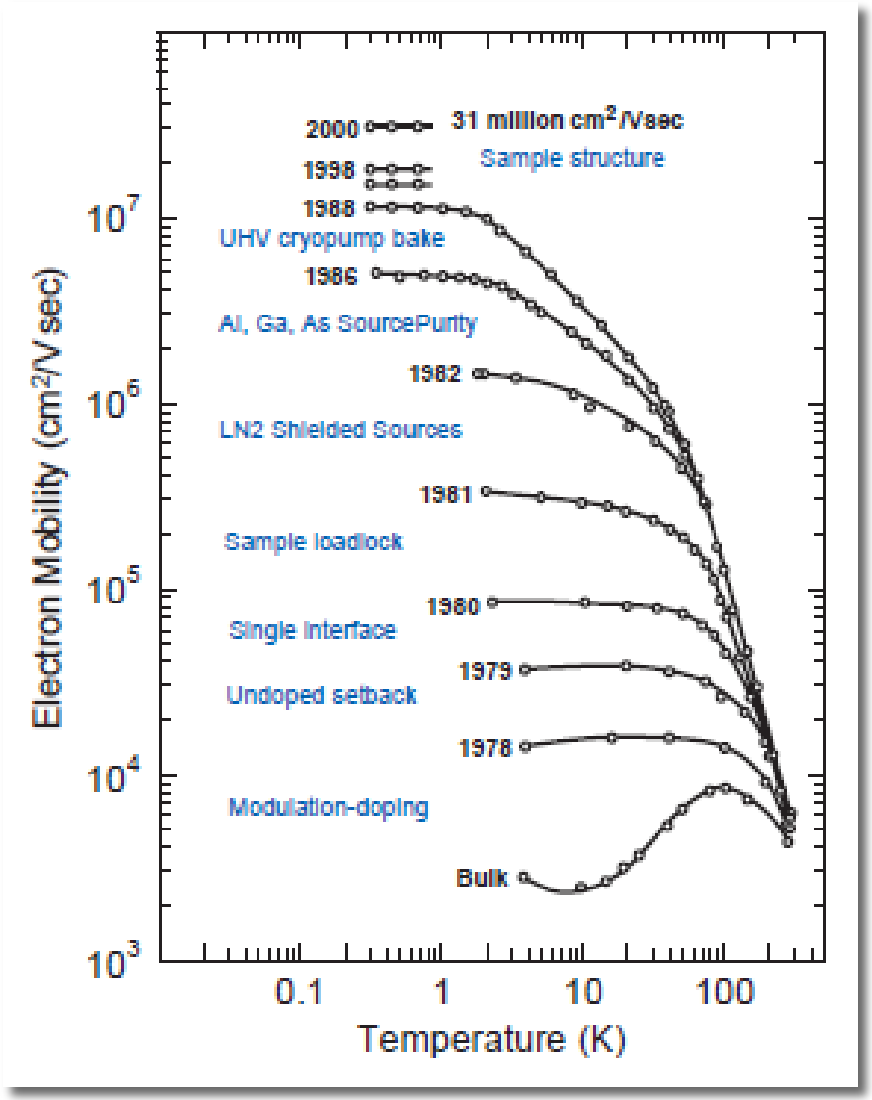
Can We Do Nanoscience with this Last Century Technology?

- **Pioneering work in the U.S.: Al Cho and Art Gossard**

- **Pioneering work in Germany: Klaus Ploog**

Paul-Drude-Insitute
for Solid State Electronics

How Good is Good?



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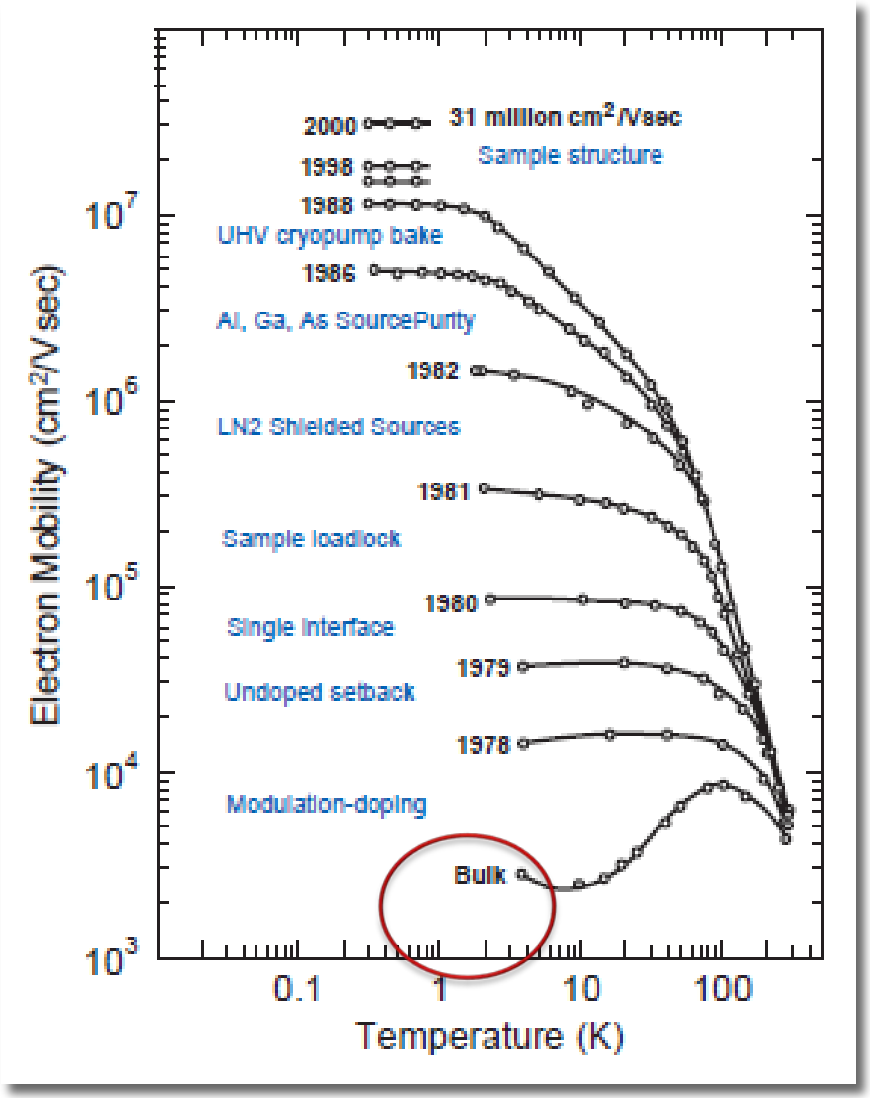
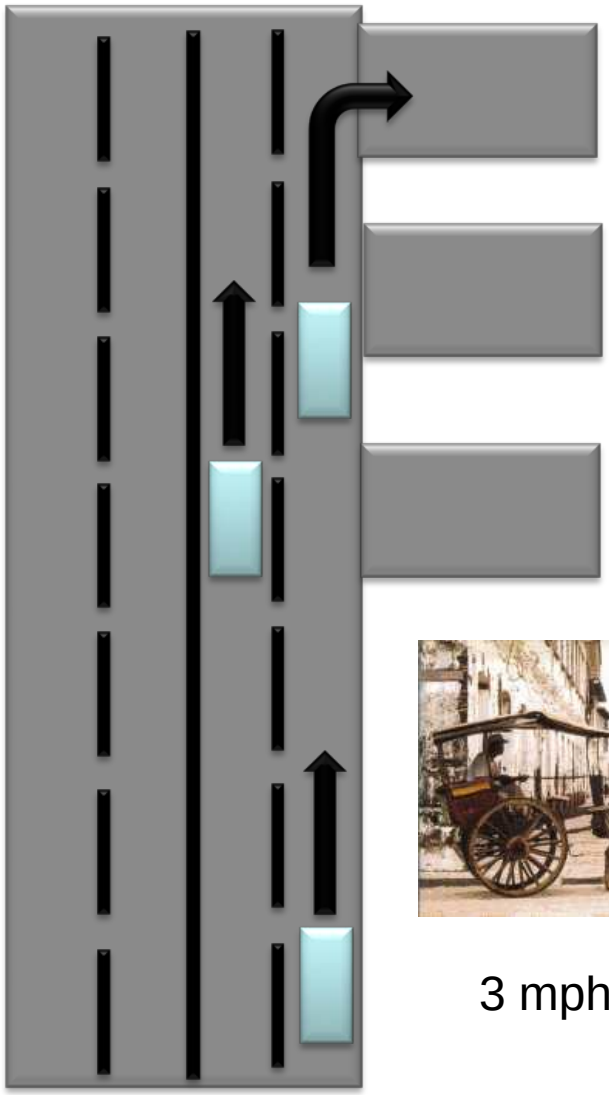
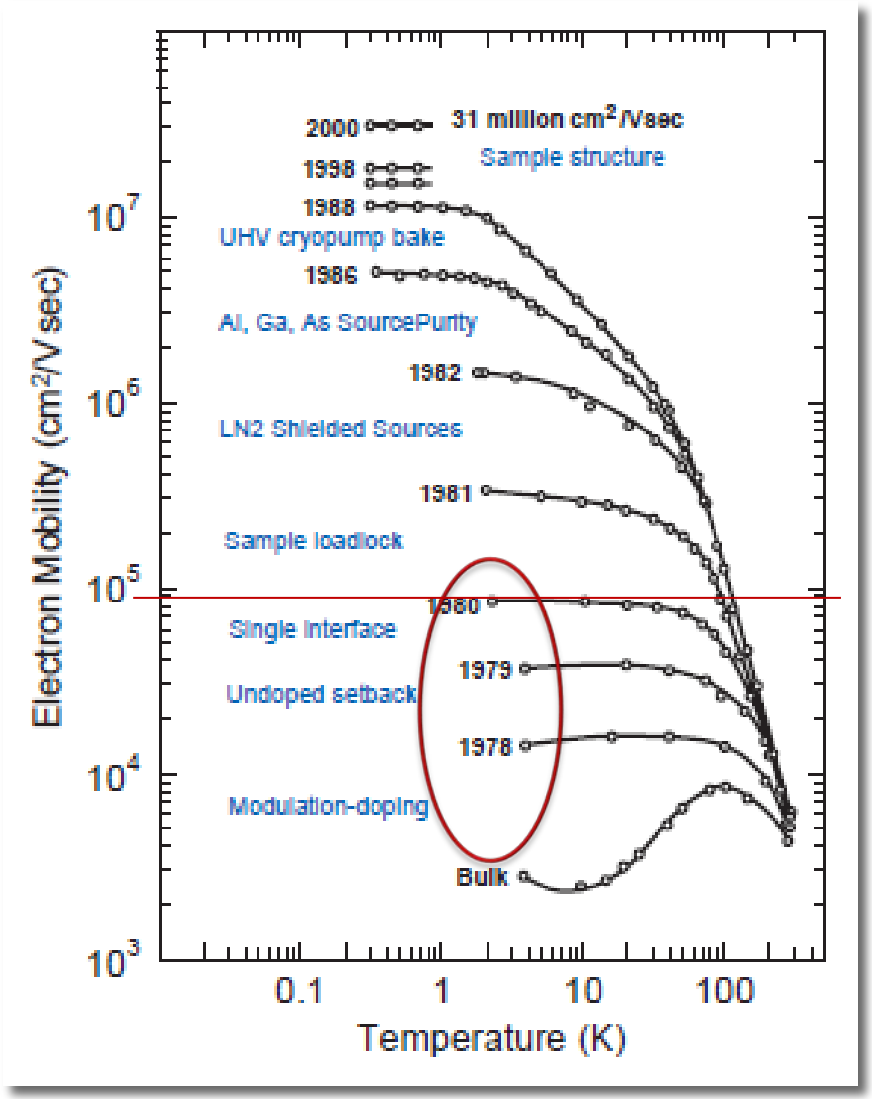
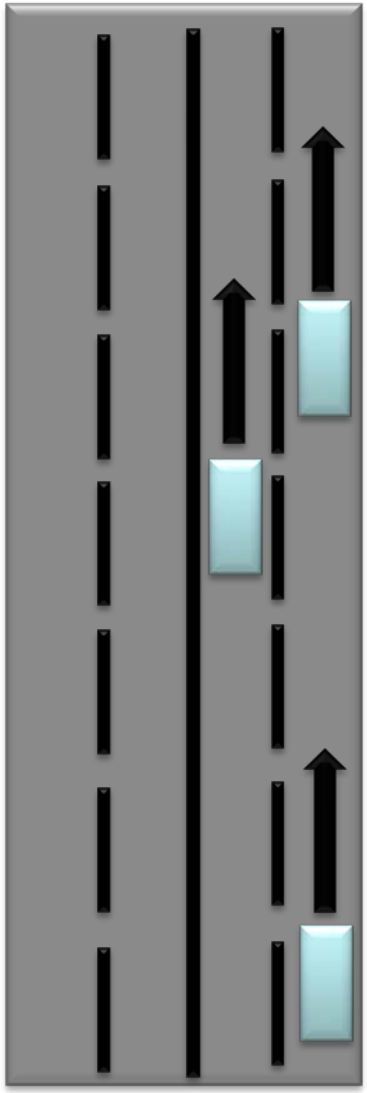




3 mph

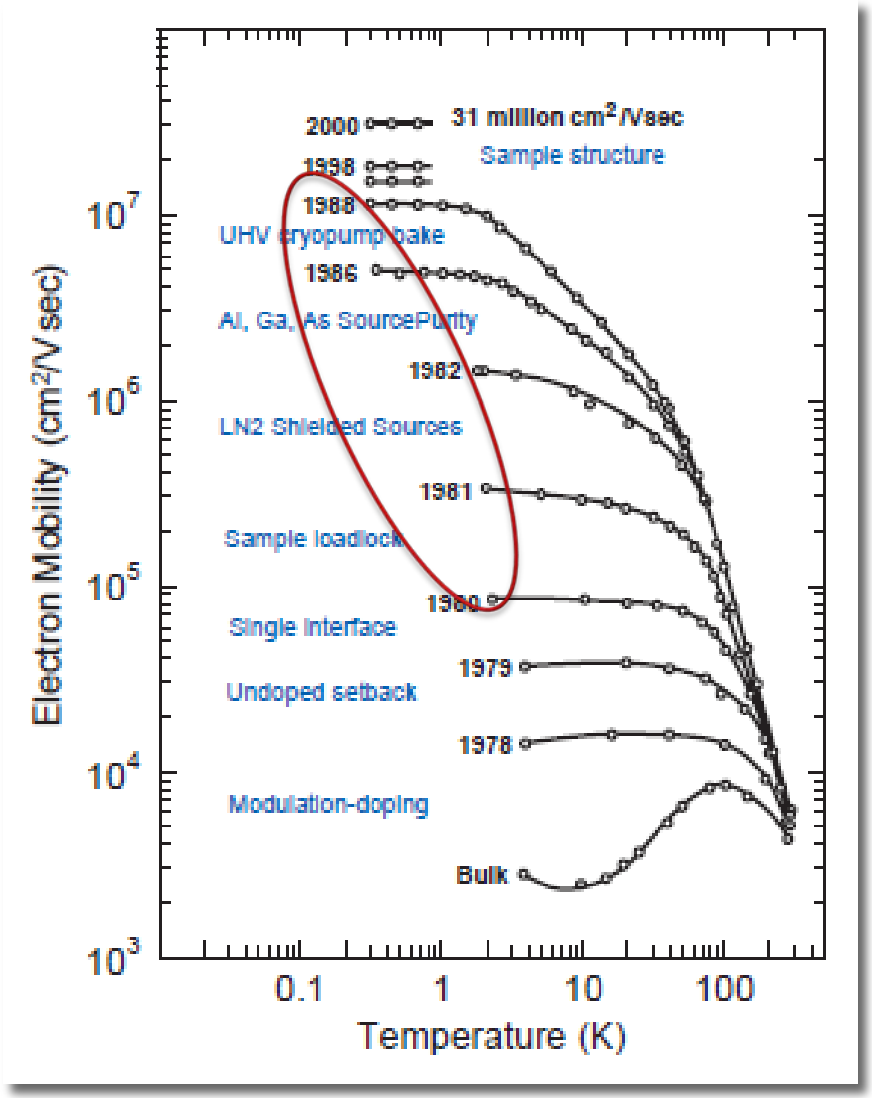
Separate Scatters from Transport

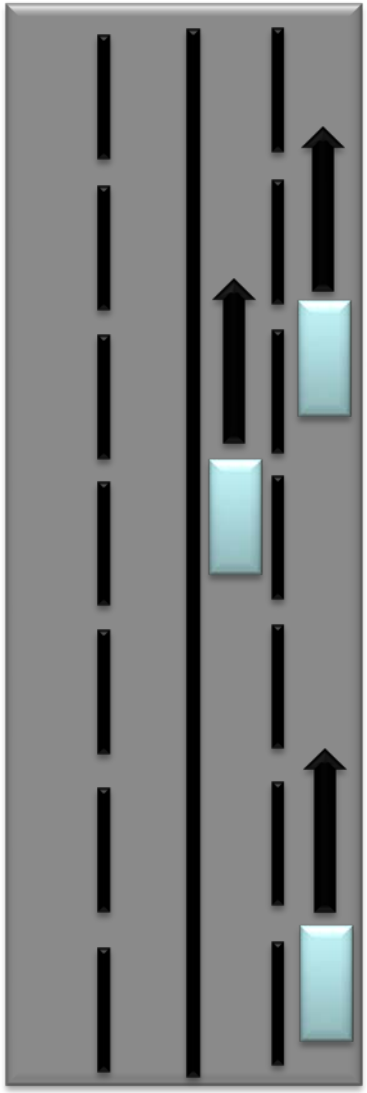




65 mph

Materials Perfection: Impurity Control

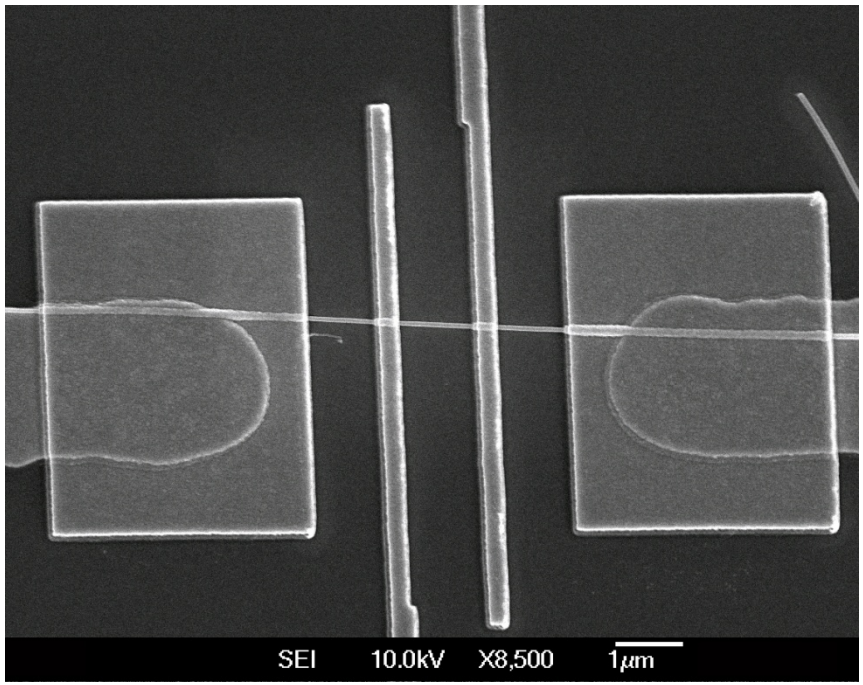




10000 mph

hypersonic scram jet

Semiconductor Nanowires



- Less than 5nm in diameter
- Increase speed of electrons in nanowires – faster computing, improve efficiency of solar cells
- Large surface area attractive for chemical sensing – homeland security

The Many Uses of Gold Nanoparticles

- First Response home pregnancy test

- Gold nanoparticles with complementary DNA base pair sequence for HcG
- The gold nanoparticles allow for more base pair detectors to be present on the applicator – thus heighten sensitivity to elevated levels of HcG

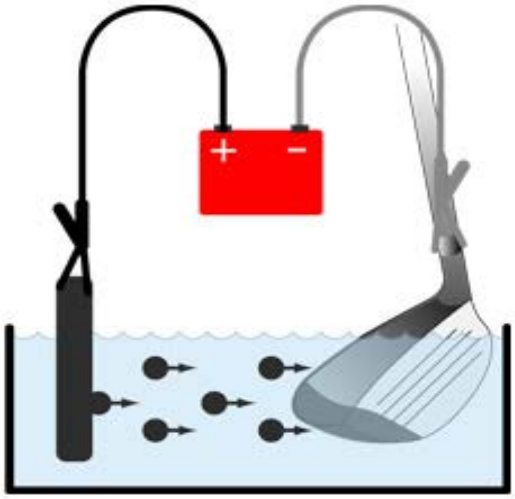
Nano-Sun block

- Keys incorporates nanosized ZnO particles into a cream
- ZnO nanoparticles adsorb UVA and UVB radiation wavelengths
- However, because of the small size of the ZnO particles (around 25 nm) the particles do not scatter visible light
- No white appearance

Easton Sports Stealth CNT Bat

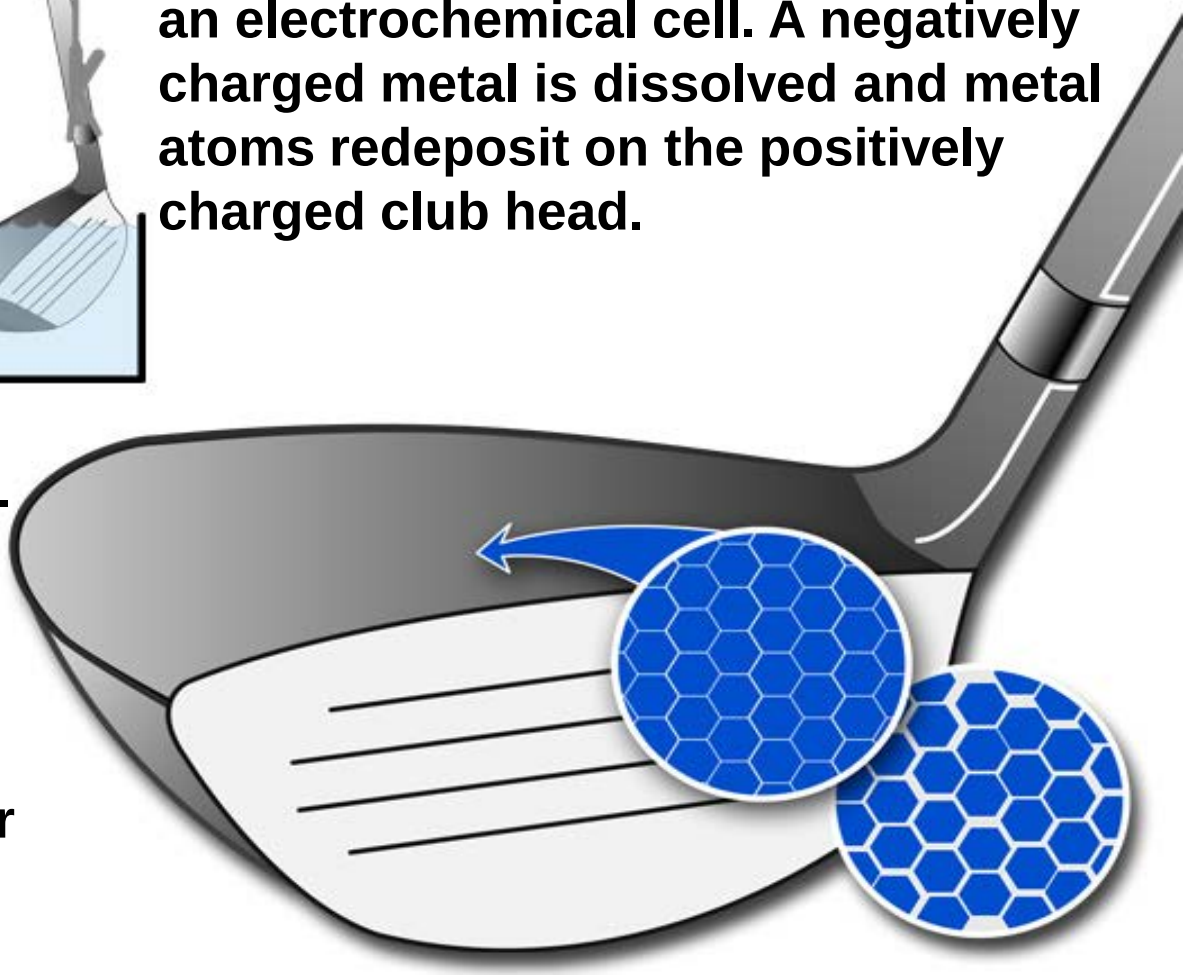
- Combines carbon fiber technology with carbon nanotube (CNT) technology
- In between the carbon fibers is a polymer resin containing CNT
- Optimizes stiffness of bat for maximum energy transfer to the ball

Nanotechnology in Golf



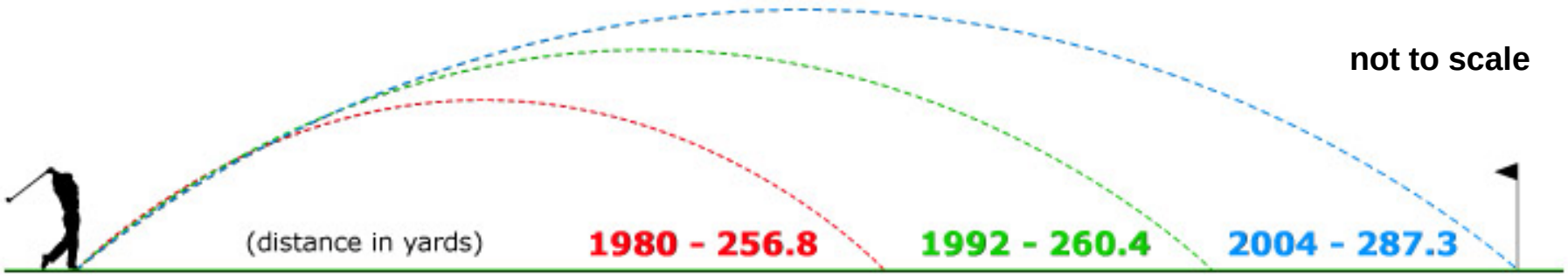
Electrodeposition is performed using an electrochemical cell. A negatively charged metal is dissolved and metal atoms redeposit on the positively charged club head.

Dense layer of a nano-grained metal on the surface of the club head. This leads to a lighter and stronger club face with a bigger "sweet spot"



The Result of Materials Improvements

- **Distances are average drive lengths (in yards) for PGA Tour players over the last 25 years**
- **Note the substantial increase in the last decade (over 25 yards)**



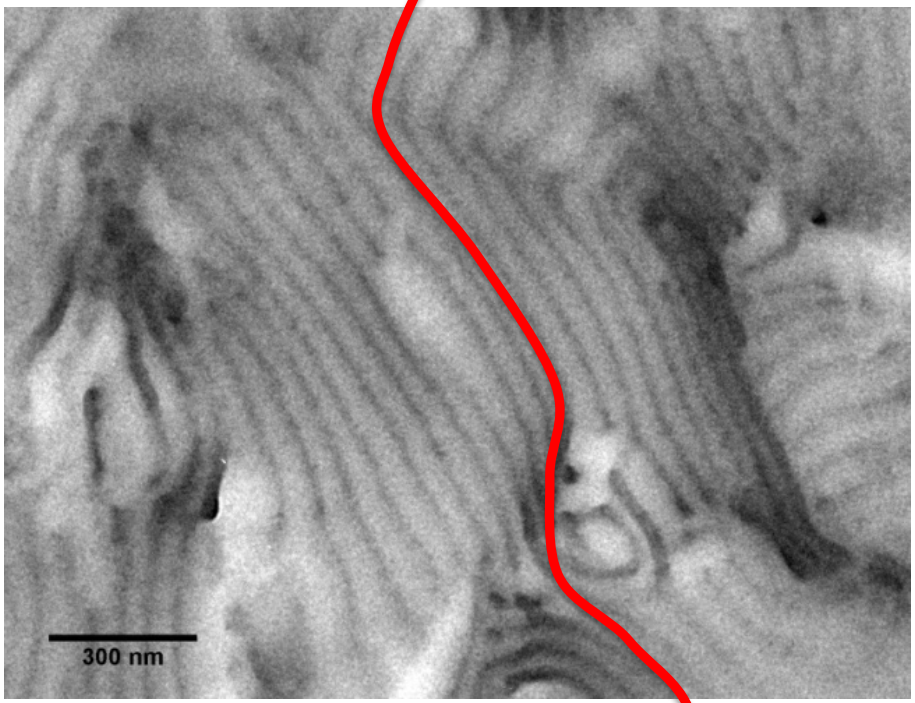
NEW TECHNOLOGY has helped golfers increase the distance a ball travels. Here is a look at the increase in PGA Tour driving distance from 1980 to 2004:

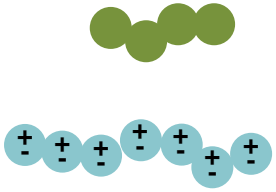
ARC Outdoors - ArcticShield Socks

- Silver is known for its antimicrobial properties
- Attempts have been made to incorporate silver into linen socks via metal threads
- Through the use of silver nanoparticles ARC has incorporated the silver into the polymer fibers
- ARC claims permanent resistance to odor or fungus

Block Copolymer Assemblies to Form Ionic Channels

Transmission electron micrograph of a block copolymer with hydrophobic and ionic phases. The ionic phases for channels for transport of ions and water.

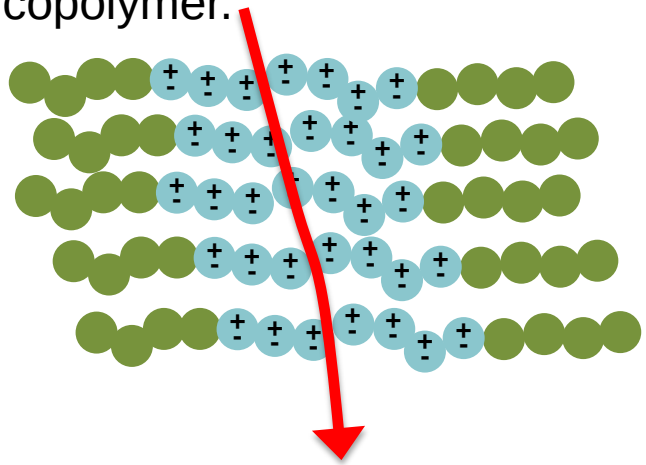




Hydrophobic part of the polymer provides mechanical strength.

Ionic part of the polymer is hydrophilic and conducts ions and water.

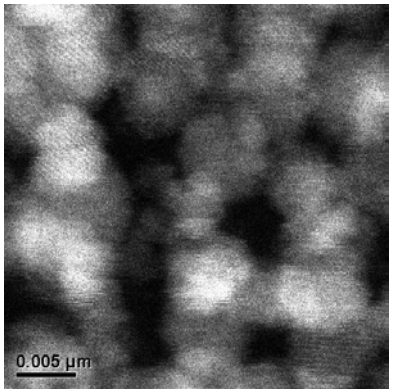
Schematic of the self-assembly of like parts of the block copolymer.



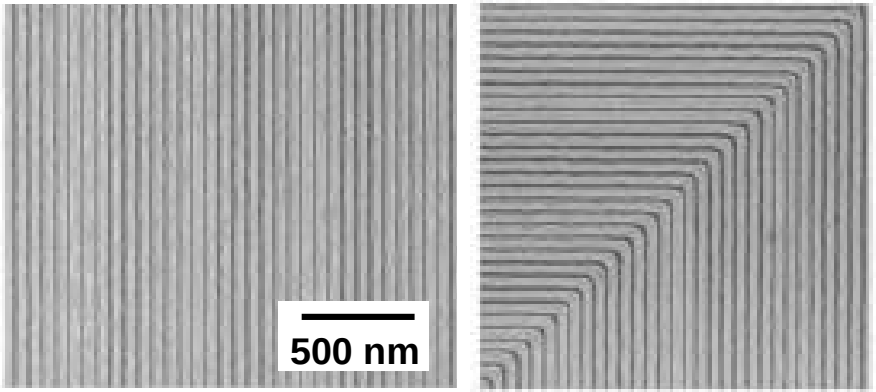
Elabd and Hickner, *Macromolecules* **2011**.

Block Copolymers can Form Many Different Structures

5 nm phases

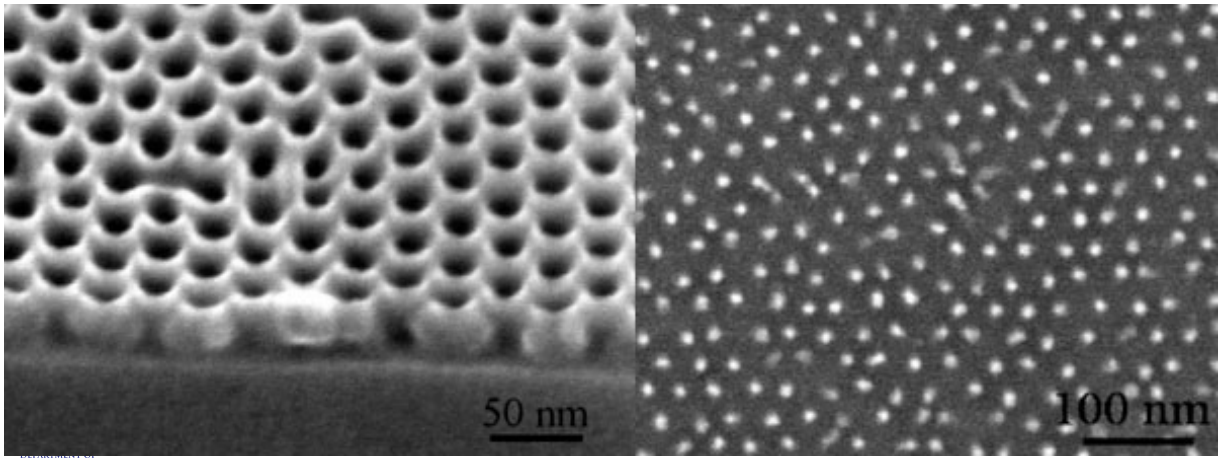


High aspect ratio lines and corners

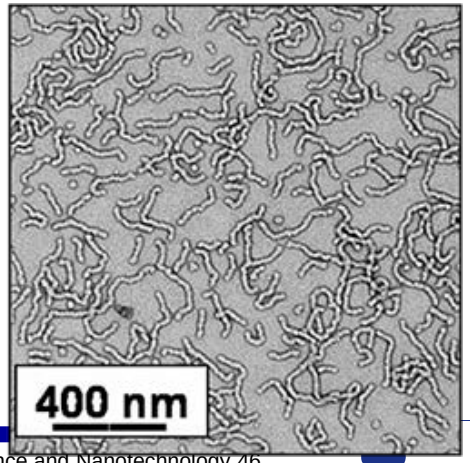


Selective patterning

Holes and isolated dots

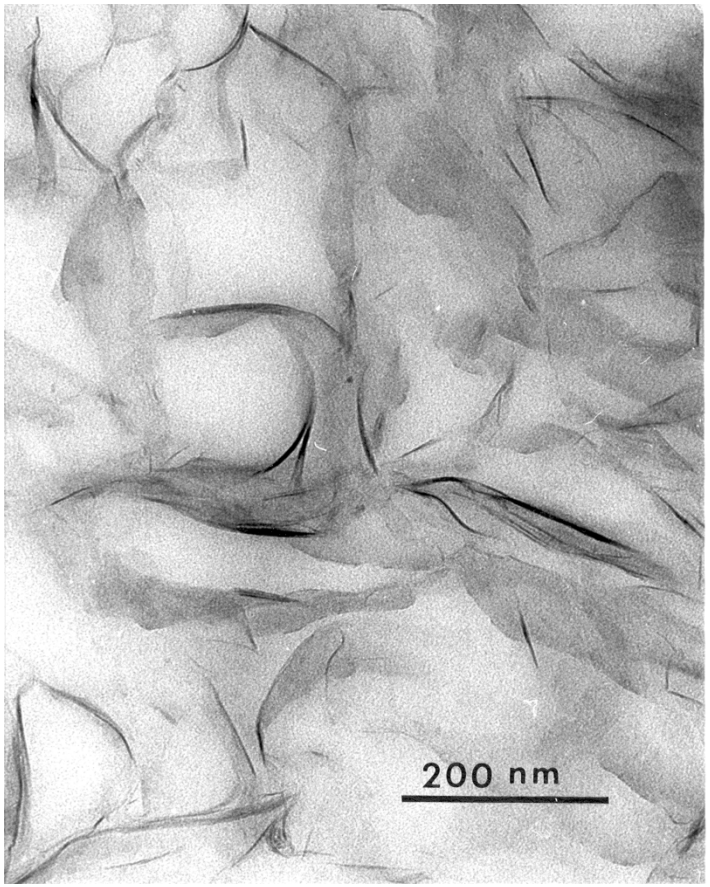


Wormlike micelles in solution

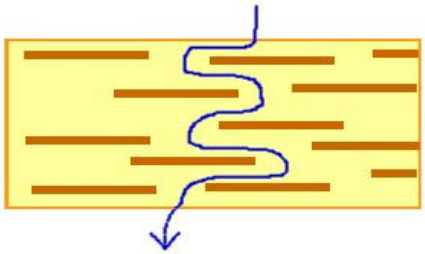


Bates and Fredrickson, *Physics Today* **1999**.

Polymer Nanocomposites



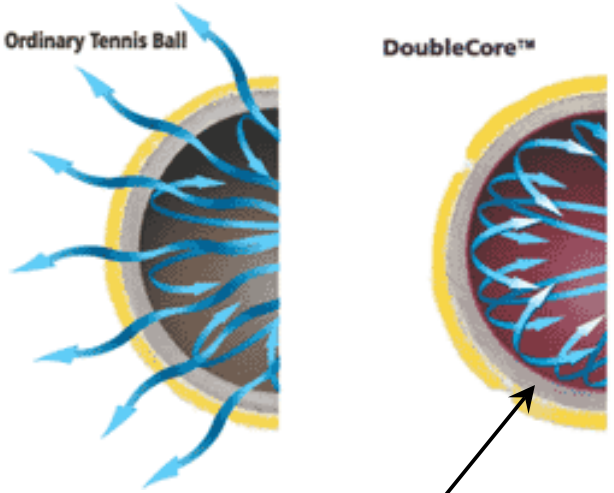
- Addition of a small amount of nanoparticles gives large change in properties of polymer



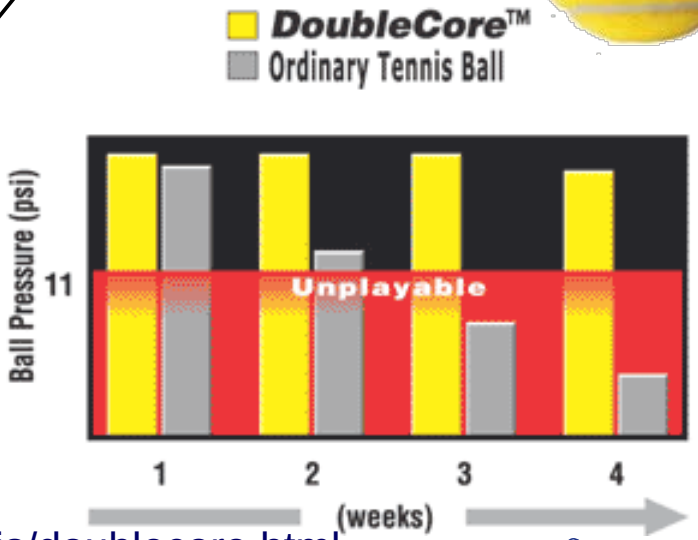
- However, important polymer properties such as optical transparency, flexibility, and low weight remain

Imagine this 10's of 1000's of times over

Wilson high performance tennis balls



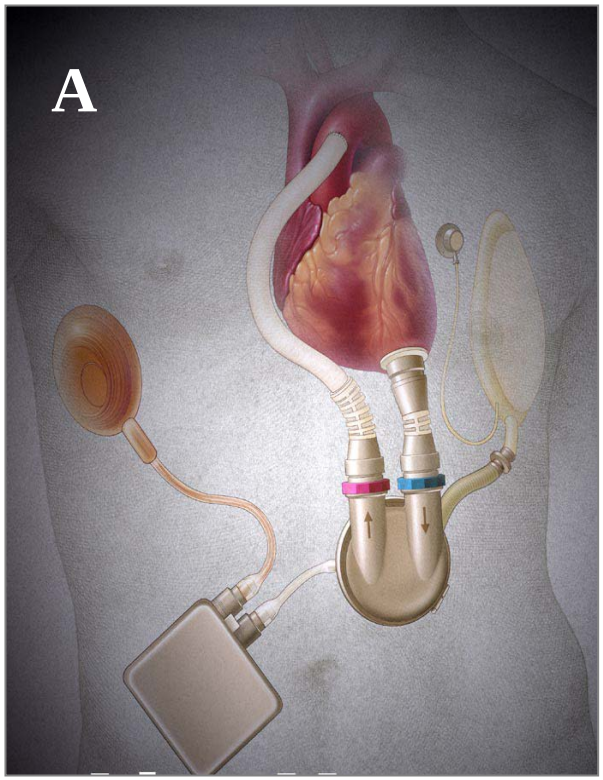
inner core (barrier)
butyl-rubber + clay



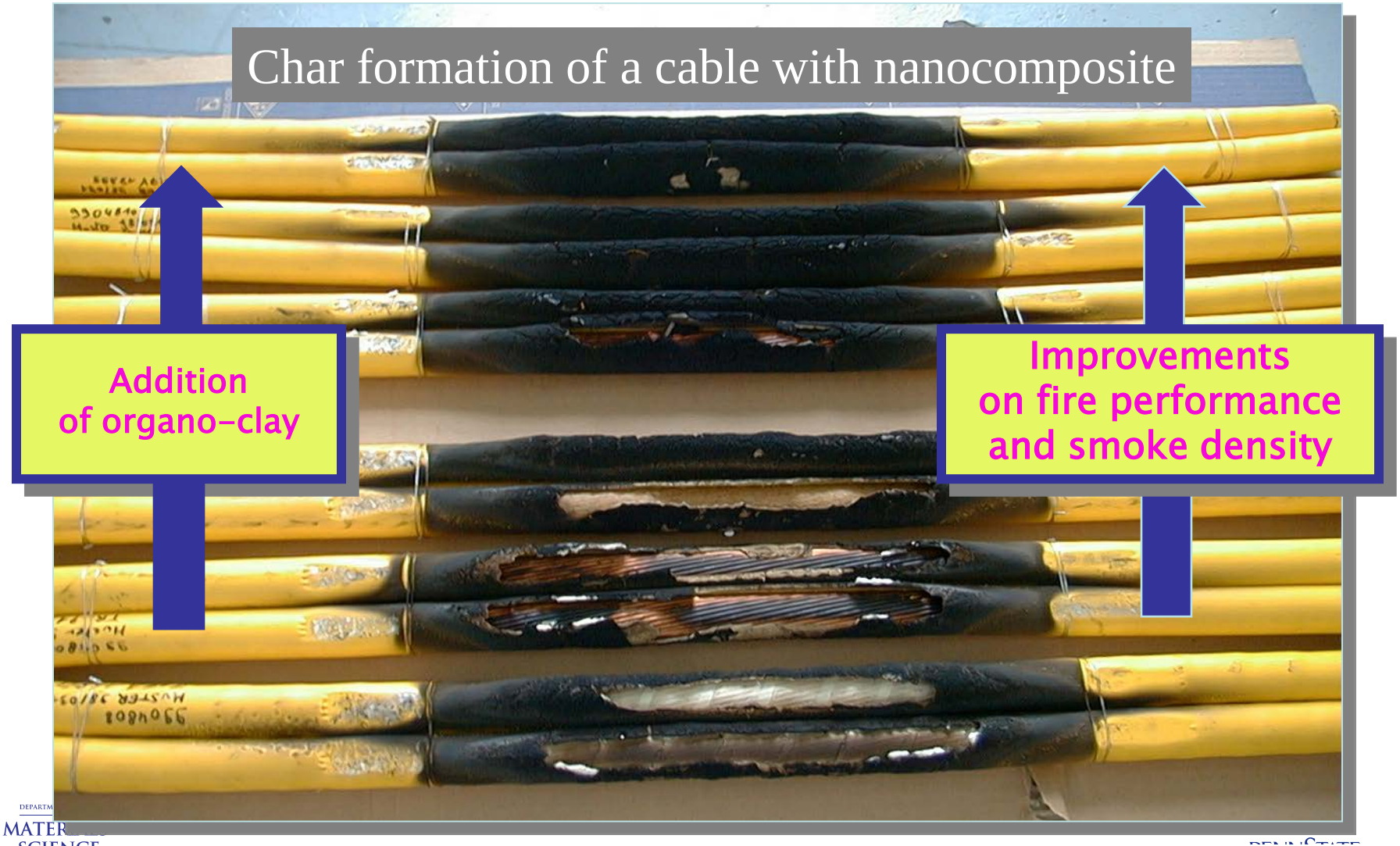
http://www.wilsonsports.com.au/tennis/doublecore.html

Application of Nanocomposite Polymer Materials

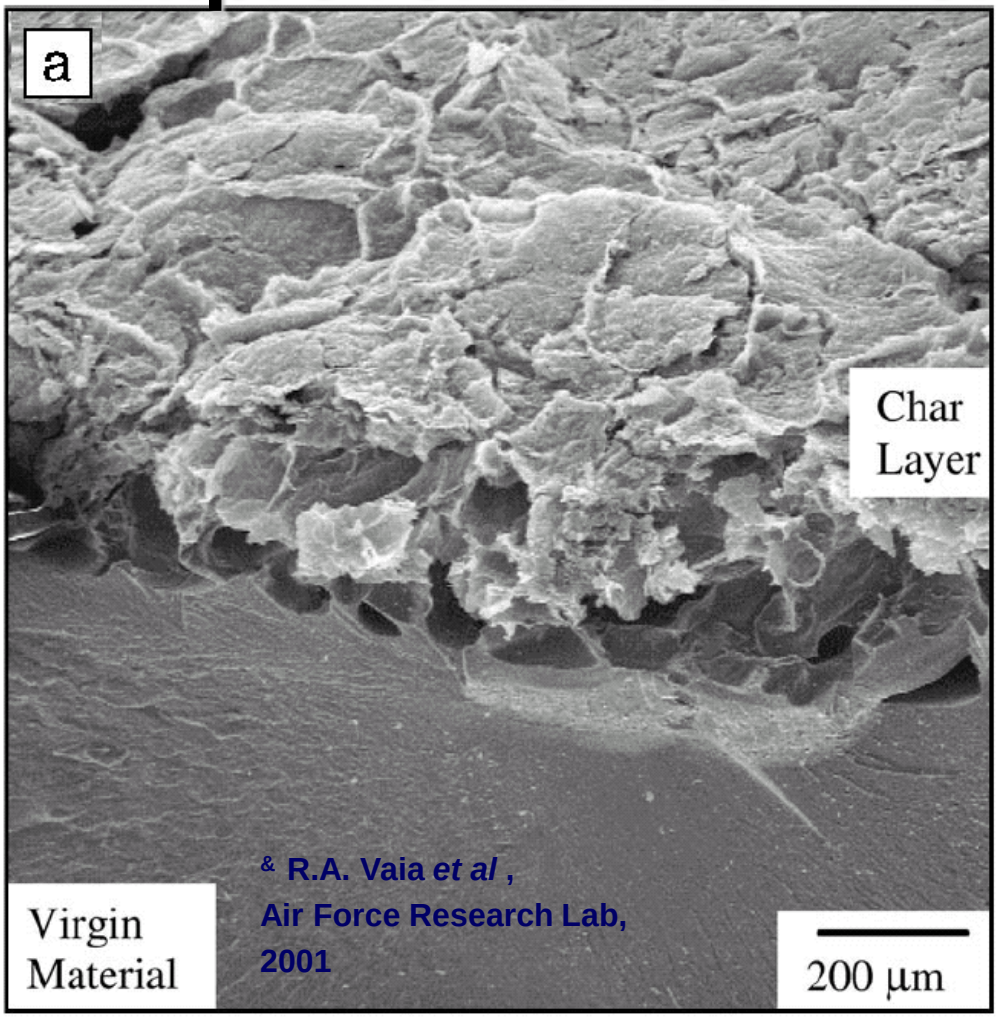
A. Pump for artificial heart
B. Decrease sneaker weight, increase response
C. Running boards and body panels for cars



Non-halogen, low flammability cables



Improvement of Thermal Properties



& R.A. Vaia *et al* , Air Force Research Lab, 2001

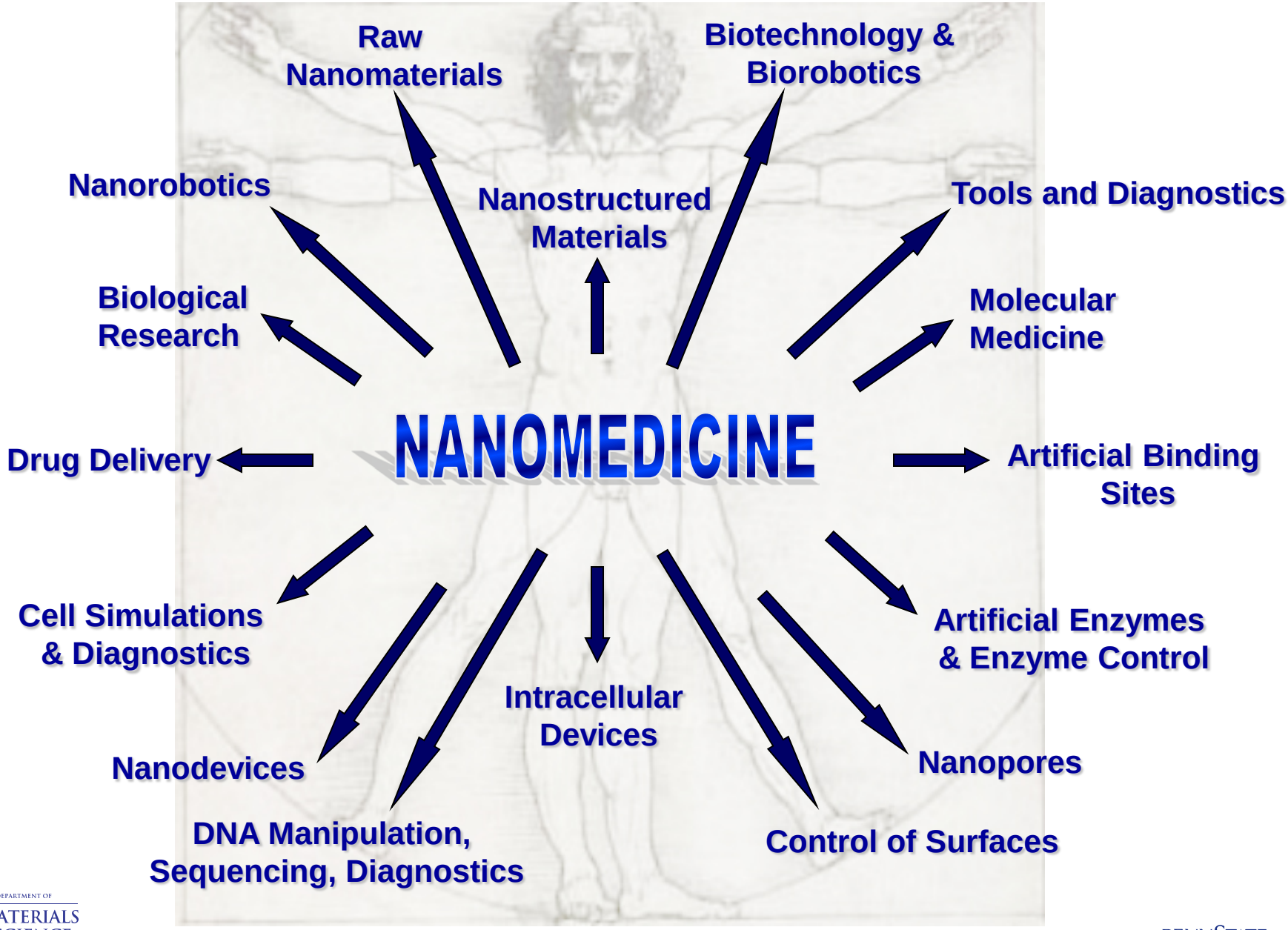
SEM of nylon-6/5wt% clay nanocomposite after exposure to simulated solid-rocket motor exhaust &

Thermal Conductivity

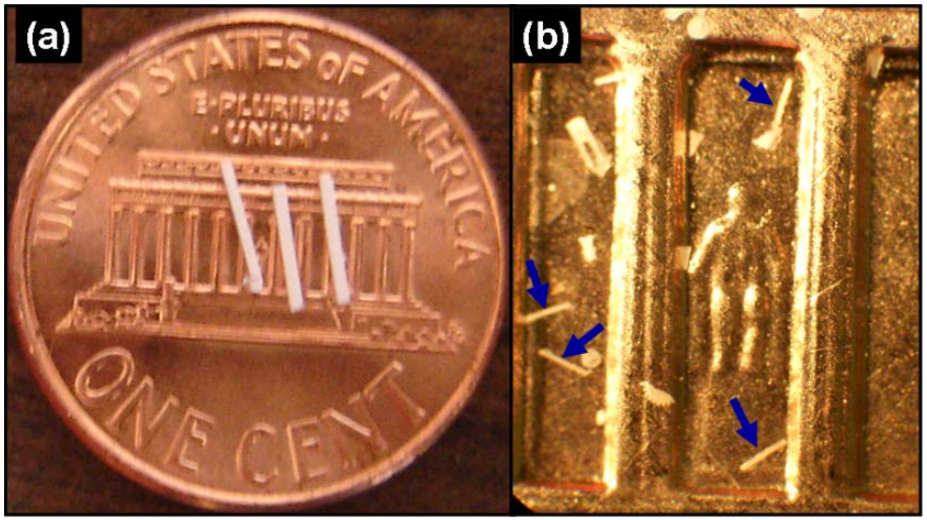
PC with 5wt% clay nanocomposite

O'Lala Foods - Choco'la Chewing Gum

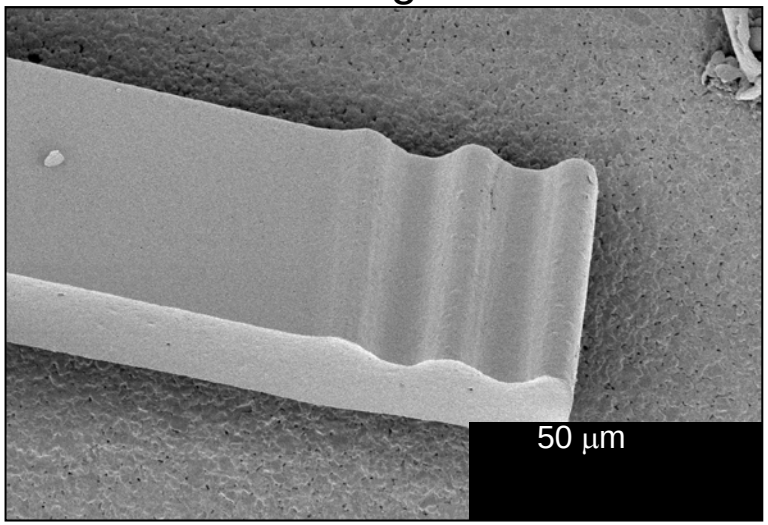
- Incorporating chocolate into chewing gum has actually been challenging because the cocoa butter fats in chocolate cause the gum to lose its elastic nature
- O’Lala has incorporated nano-crystals that change the surface characteristics of the gum allowing for the incorporation of chocolate flavoring


Raw Nanomaterials
Biotechnology & Biorobotics
Nanorobotics
Nanostructured Materials
Tools and Diagnostics
Biological Research
Molecular Medicine
NANOMEDICINE
Drug Delivery
Artificial Binding Sites
Cell Simulations & Diagnostics
Artificial Enzymes & Enzyme Control
Intracellular Devices
Nanodevices
Nanopores
DNA Manipulation, Sequencing, Diagnostics
Control of Surfaces

Surgical Tools

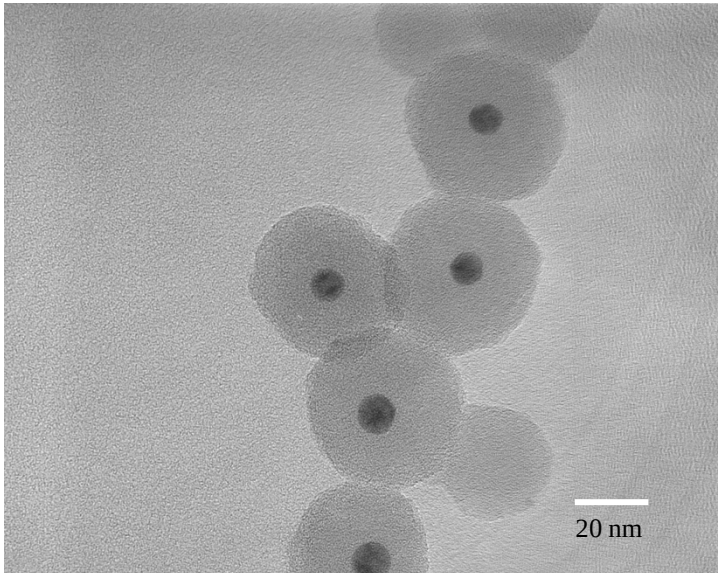


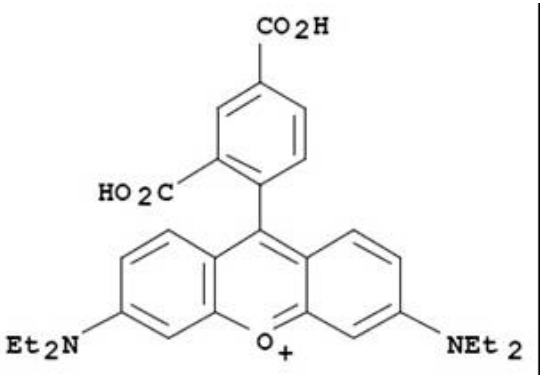
A) Bend bars made using 400 micron thick molds
B) Bend bars made using 25 micron thick molds



Nanocomposite Particles

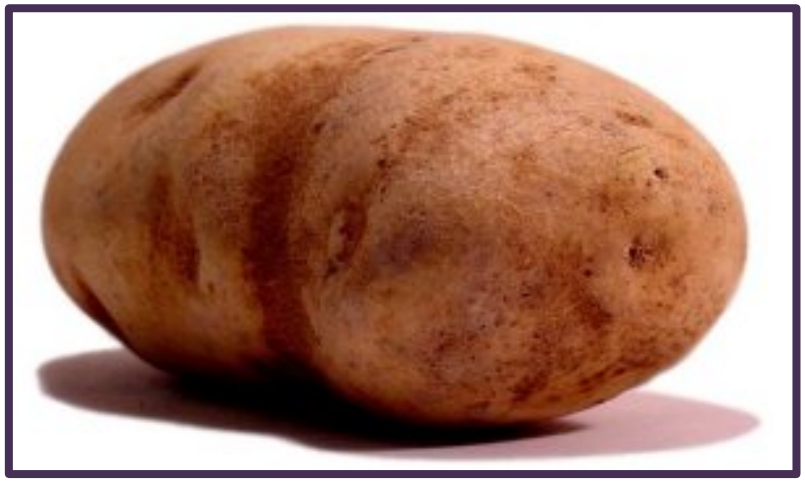
Silica shell with rhodamine WT core

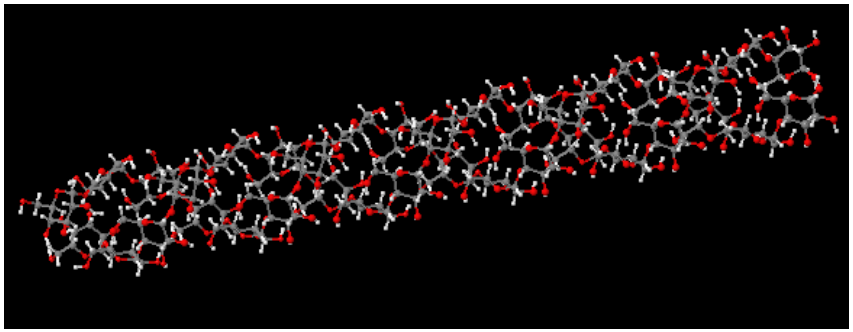


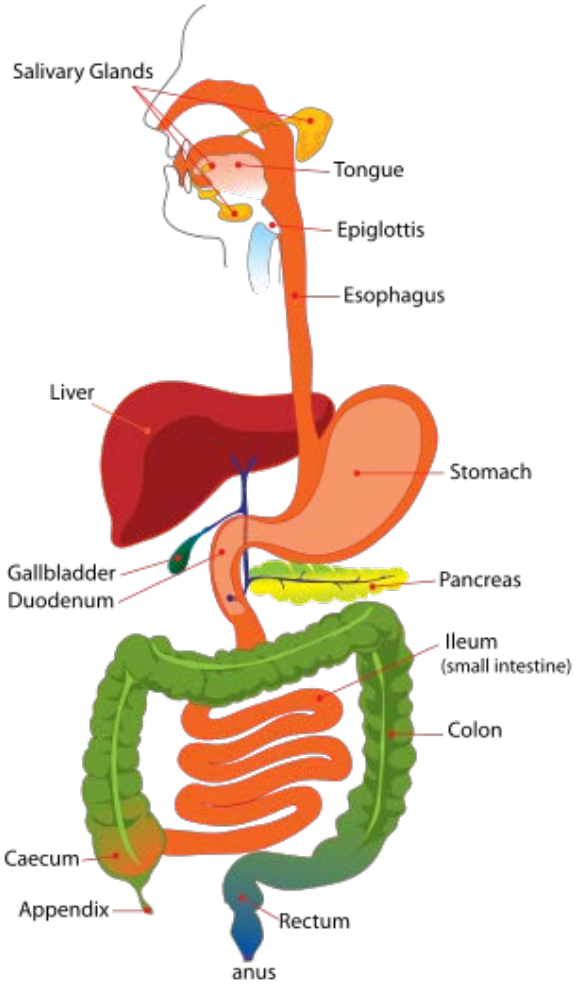


- Particles on the order of 1 – 100 nm in diameter
- Shell and core of particle are two different materials
- Can be tailored to absorb specific radiation frequencies – military application
- Can be designed to emit specific wavelengths of light – flat panel displays
- Can be designed with any desired surface – biomedical imaging and drug delivery

Drug Delivery Systems







Erica Marden Senior Honors Thesis, 2012