

# Introduction to Material Science and Engineering



# Introduction

## What is material science?

**Definition 1:** A branch of science that focuses on materials; interdisciplinary field composed of physics and chemistry.

**Definition 2:** Relationship of material properties to its composition and structure.

## What is a material scientist?

A person who uses his/her combined knowledge of physics, chemistry and metallurgy to exploit property-structure combinations for practical use.

# What are materials?

## What do we mean when we say “materials”?

### 1. Metals

- aluminum
- copper
- steel (iron alloy)
- nickel
- titanium

### 2. Ceramics

- clay
- silica glass
- alumina
- quartz

### 3. Polymers

- polyvinyl chloride (PVC)
- Teflon
- various plastics
- glue (adhesives)
- Kevlar

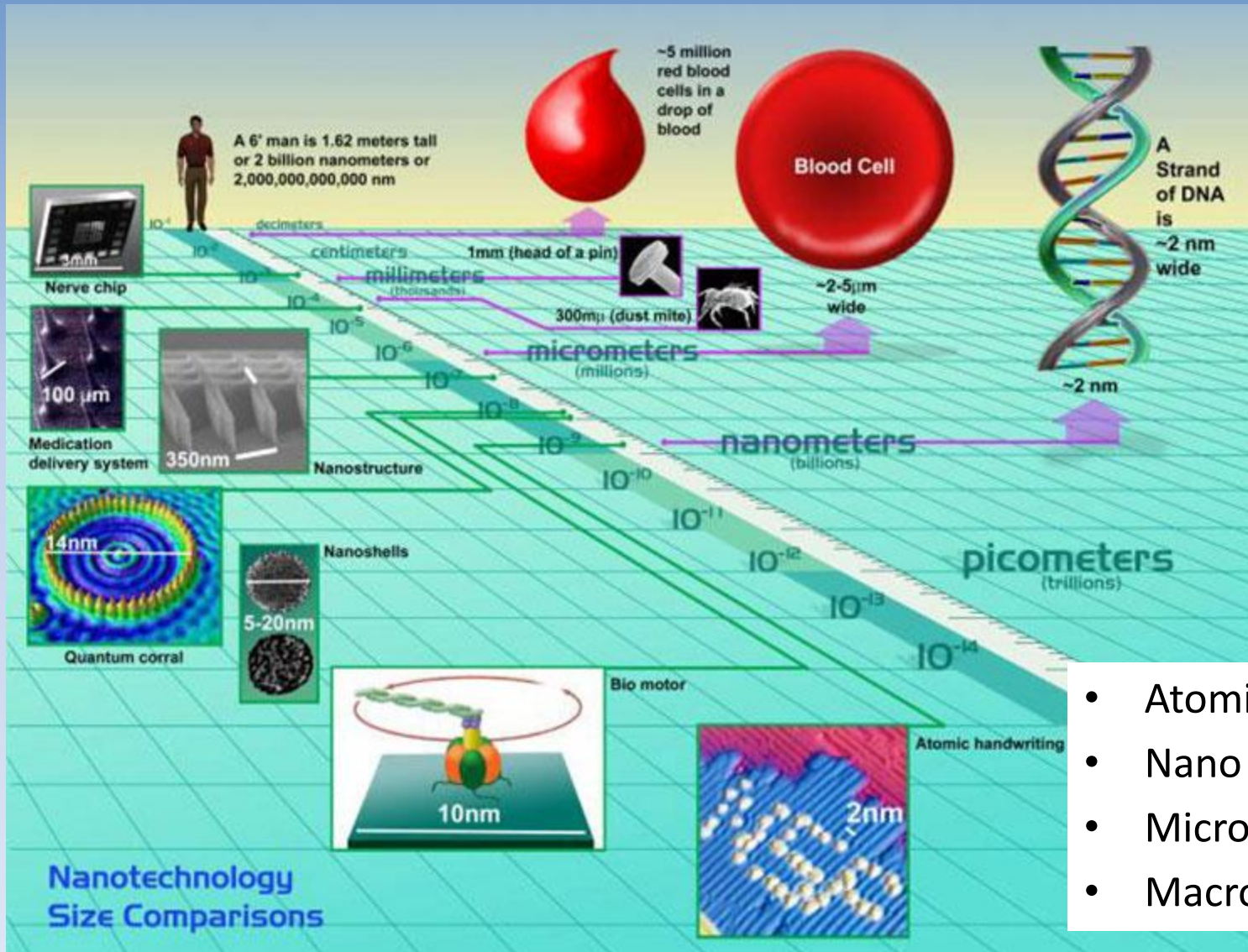
### 4. Composites

- wood
- carbon fiber resins
- concrete

***semiconductors (computer chips, etc.) = ceramics, composites***

***nanomaterials = ceramics, metals, polymers, composites***

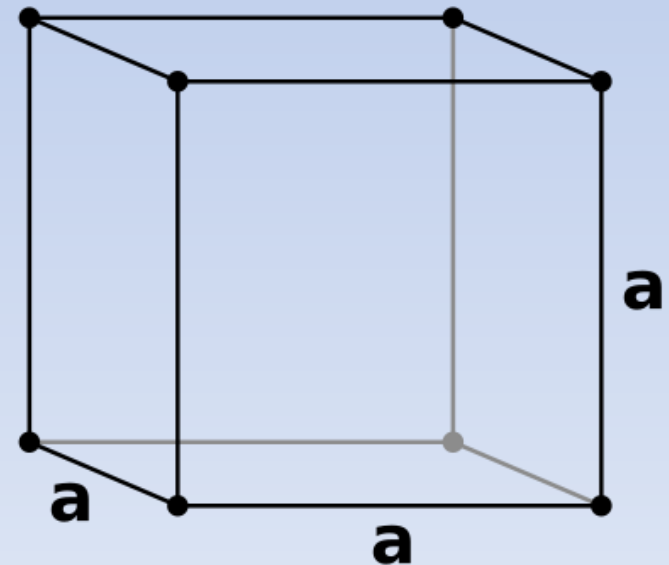
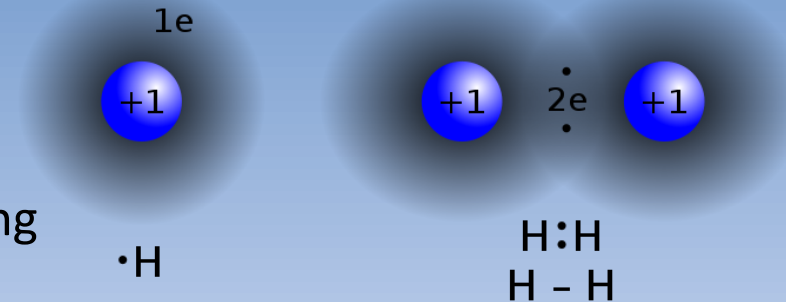
# Length Scales of Material Science



- Atomic –  $< 10^{-10}$  m
- Nano –  $10^{-9}$  m
- Micro –  $10^{-6}$  m
- Macro –  $> 10^{-3}$  m

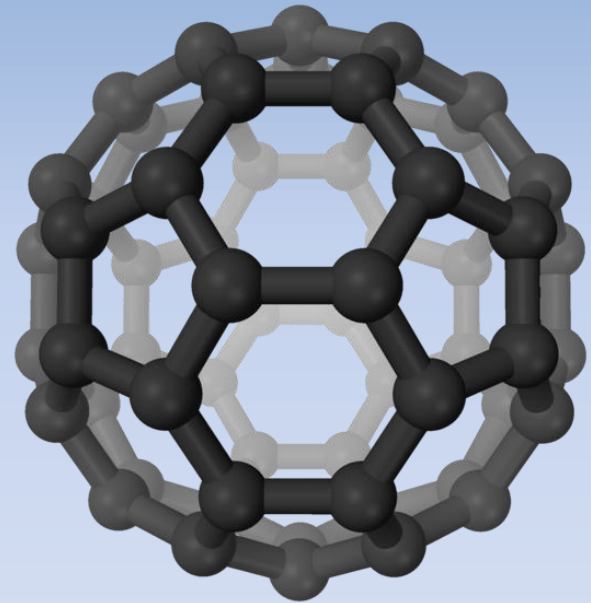
# Atomic Structure – $10^{-10}$ m

- Pertains to atom electron structure and atomic arrangement
- Atom length scale
  - Includes electron structure – atomic bonding
    - ionic
    - covalent
    - metallic
    - London dispersion forces (Van der Waals)
  - Atomic ordering – long range (metals), short range (glass)
    - 7 lattices – cubic, hexagonal among most prevalent for engineering metals and ceramics
    - Different packed structures include: Gives total of 14 different crystalline arrangements (Bravais Lattices).
      - Primitive, body-centered, face-centered



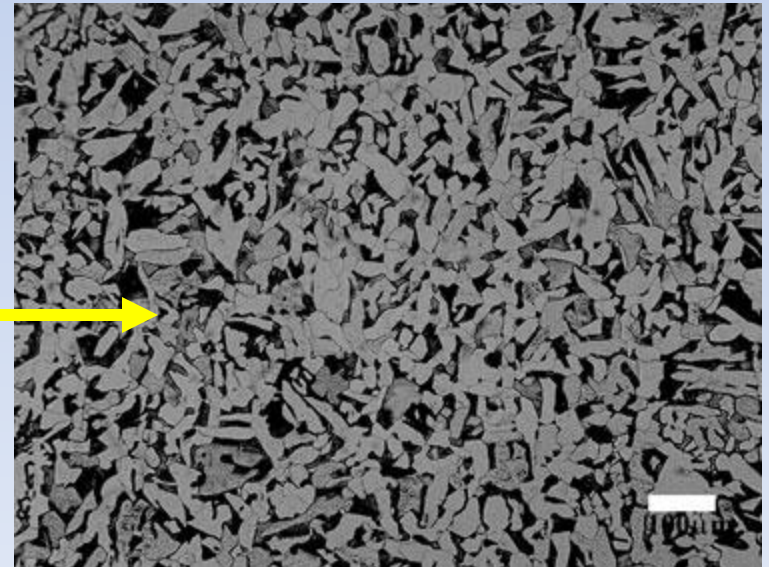
# Nano Structure – $10^{-9}$ m

- Length scale that pertains to clusters of atoms that make up small particles or material features
- Show interesting properties because increase surface area to volume ratio
  - More atoms on surface compared to bulk atoms
  - Optical, magnetic, mechanical and electrical properties change



# Microstructure – $10^{-6}$

- Larger features composed of either nanostructured materials or periodic arrangements of atoms known as crystals
- Features are visible with high magnification in light microscope.
  - Grains, inclusions other micro-features that make up material
  - These features are traditionally altered to improve material performance



# Macrostructure – $10^{-3}$ m

- Macrostructure pertains to collective features on microstructure level
- Grain flow, cracks, porosity are all examples of macrostructure features





# Classes of Materials

- metals
- polymers
- ceramics
- composites



# Metals

- Metals consist of alkaline, alkaline earth, metalloids and transition metals
- Metal alloys are mixtures of two or more metal and nonmetal elements (for example, aluminum and copper, Cu-Ni alloy, steel)
- Bonding: Metallic
  - No particular sharing or donating occurs. Electron cloud is formed (that is, free electrons)
  - Strong bonds with no hybridization or directionality
- Properties:
  - Electrically conductive (free electrons)
  - Thermally conductive
  - High strength – large capacity to carry load over x-section area (stress)
  - Ductile – endure large amounts of deformation before breaking.
  - Magnetic – ferromagnetism, paramagnetic
  - Medium melting point

# Metal Applications

- Electrical wire: aluminum, copper, silver
- Heat transfer fins: aluminum, silver
- Plumbing: copper
- Construction beams (bridges, sky scrapers, rebar, etc.): steel (Fe-C alloys)
- Cars: steel (Fe-C alloys)
- Consumer goods:
  - soup cans
  - appliances (stainless steel sheet metal)
  - utensils
  - tools
  - Many, many, many more...

# Polymers

- Polymers consist of various hydro-carbon (organic elements) with select additives to elucidate specific properties
- Polymers are typically disordered (amorphous) strands of hydrocarbon molecules.
- Bonding: Covalent-London Dispersion Forces
- Properties:
  - ductile: can be stretched up to 1000% of original length
  - lightweight: Low densities
  - medium strength: Depending on additives
  - chemical stability: inert to corrosive environments
  - low melting point

# Polymer Applications

- Car tires: vulcanized polymer (added sulfur)
- Ziploc bags
- Food storage containers
- Plumbing: polyvinyl chloride (PVC)
- Kevlar
- Aerospace and energy applications: Teflon
- Consumer goods:
  - calculator casings
  - TV consuls
  - shoe soles
  - cell phone casings
  - Elmer's Glue (adhesives)
  - contact lenses
  - Many, many. many more...

# Ceramics

- Consist of metal and non metal elements
- Typically a mixture of elements in the form of a chemical compound , for example  $\text{Al}_2\text{O}_3$  or glass
- Three types: composites, monolithic and amorphous ceramics
- Bonding covalent – ionic
  - Typically covalent. In some cases highly direction covalent bonding
  - Ionic in case of  $\text{SiO}_2$  glasses and slags
- Properties:
  - wear resistant (hard)
  - chemical stability: corrosion resistant
  - high temperature strength: strength retention at very high temperatures
  - high melting points
  - good insulators (dielectrics)
  - adhesives
  - good optical properties

# Ceramic Applications

- Window glass:  $\text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{MgO} - \text{CaO}$
- Aerospace, energy and automotive industry
  - heat shield tiles
  - engine components
  - reactor vessel and furnace linings
- Consumer products:
  - pottery
  - dishes (fine china, plates, bowls)
  - glassware (cups, mugs, etc.)
  - eye glass lenses

# Composites

- A mixture of two different materials to create a new material with combined properties
- Types of composites:
  - Particulate reinforced – discontinuous type with low aspect ratio
  - Whisker/rod reinforced - discontinuous type with high aspect ratio
  - Fiber reinforced - continuous type with high aspect ratio (naturally)
  - Laminated composites - layered structures (surf boards, skate boards)
- Bonding: depends on type of composite (strong-covalent, medium-solid solution, weak-tertiary phase layer)
- Properties: Depends on composites
  - High melting points with improved high temperature strength: ceramic-ceramic
  - High strength and ductile with improved wear resistance: metal-ceramic
  - High strength and ductile: polymer-polymer



# Composites: Applications

- **Wood:** naturally occurring biological material consists of very strong fibers imbedded in a soft matrix
- **Plywood:** laminated wood for buildings
- **Concrete:** basements, bridges, sidewalks
- **Fiberglass:** boats
- **Carbon fiber resins:** bicycle frames

# Advanced Applications Ceramics & Composites

- Aerospace and Defense Applications
  - Structural materials used for missiles, aircraft, space vehicles
  - What type of materials may be used?
- Ultrahigh Temperature Ceramic-Composites (UHTCs)
  - Metal-nonmetal, Covalent bonded compounds ( $\text{ZrB}_2$  –  $\text{SiC}$ )
  - High melting point materials; strong materials at temperature; excellent oxidation resistance
- Why these materials?
  - Service temperatures are in excess of  $2000^\circ\text{C}$  ( $\sim 1/3$  surface temperature of our sun)
  - Materials have high melting points ( $>3000^\circ\text{C}$ )
  - Excellent strength retention at services temperatures
  - Relative chemical stability at service temperatures
  - Light weight

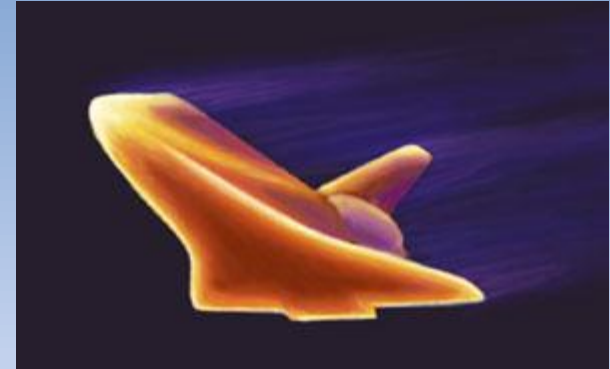
# Advanced Applications Ceramics & Composites

*Structural materials for use in hypersonic aircraft  
Next-generation re-entry vehicles*



**Why is the space shuttle shaped the way it is?**

*To reduce the amount of heat generated upon re-entry.*



**UHTC materials can change the shape of next-generation space planes because of their unique combinations of properties**

# Advanced Applications Polymers

- Self-decontaminating polymers
  - medical, military, security and environmental applications
  - current applications: look for attachment to textiles for self toxin cleaning fabrics (that is, chemical scavenging and cleaning clothing)
- Sulphonated polyether polyetherketone (SPEEK) and polyvinyl alcohol (PVA) aqueous solutions
- Excite solutions with light to form strong reducing benzophenyl ketyl (BPK) radicals; helps break down organic toxic chemicals

Little, Brian, *“Materials for Advanced Applications: Self-Decontaminating Polymers, photofunctional composites, and electroconductive fibers,”* Chemistry and Biochemistry Dissertation, University of Auburn (2012)

# Advanced Applications Metals

- Hydrogen-absorbing metal alloys for energy transportation or batteries
  - Electrolyzed hydrogen from water (fuel cell technology) can be stored in tanks fabricated from Hydrogen-absorbing metal alloys (HAMA)
  - Nickel Metal Hydride (Ni-MH) batteries use the same principle, but to improve battery self discharge
  - Volume density is significantly higher for gaseous hydrogen; more hydrogen per tank
- Typical alloys consist of Mn-Ti-V, Mg-Ni, Zr-Mn/Ti/V, Mn-Ni, La-Ni.
- BCC metals show higher storage and desorption properties
- Some metals can absorb a gas densities equivalent to liquid hydrogen densities

T. Mouri, H. Iba, "Hydrogen-absorbing alloys with a large capacity for a new energy carrier," *Materials Science and Engineering A*, Vol 329-331, 346-350 (2002).

"Light Weight Hydrogen 'Tank' Could Fuel Hydrogen Economy", Science Daily, <http://www.sciencedaily.com/releases/2008/11/081104084215.htm>

# Other well known materials

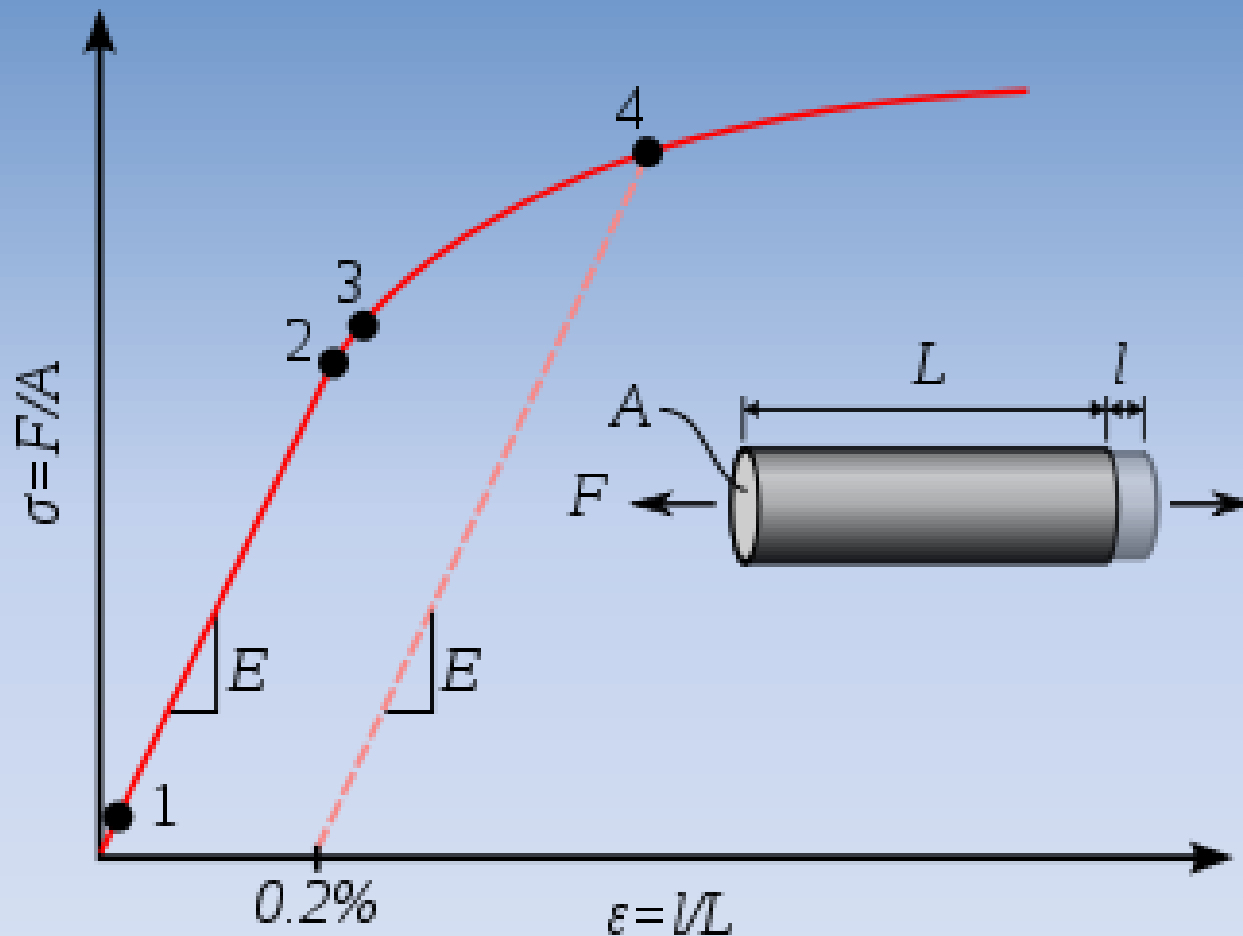
- Semiconductors – ceramics
  - computer chips
  - memory storage devices
  - solar cells
  - image screens
- Nanomaterials – ceramics, metals, polymers
  - gold nanoshells
  - quantum dots
  - ferrofluids
  - medical devices

# How do we test materials?

## We use mechanical, chemical and optical methods

- Mechanical testing gives strength, ductility and toughness material information
  - tensile tests
  - bend tests
  - compressive tests
  - fracture testing
- Chemical testing tells us about composition and chemical stability
  - x-ray diffraction and fluorescence – composition testing
  - corrosion testing
- Optical testing is more of a way to view atomic, nano and microstructures, and gives us insight to structure property relationships
  - light optical microscope – microstructure
  - scanning electron microscope – microstructure and nano structure
  - transmission electron microscope – nanostucture and atomic structure
  - scanning tunneling electron microscope – atomic structures

# Mechanical Testing



Schematic stress-strain curve created from experiments using universal test frame



# Mechanical Testing



universal testing machines



# Mechanical Testing

- What is ***stress*** and ***strain***?  
Is it like force and length change (displacement)?
- Stress is defined as the force per unit cross-section area;  $S = \text{Force}/\text{Area}$
- Strain is defined as the ratio of length change to original length;  
 $e = (L_f - L_i)/(L_i)$  (normalizes the length change)
- Why these terms?

*Stress Scenario: If I apply a force on the eraser of a pencil and apply the same force on a table top, how does each material behave? Can you distinguish which material is stronger?*

Force as a strength description is inadequate because different sized objects accommodate the force differently. Just because both objects could handle the same force does not mean they are the same **STRENGTH!**

*Strain Scenario: If I pull on a 1 inch long piece of taffy and apply the same pulling force on a piece of 2 inch long putty and both lengthen (both have equal diameters), with the taffy and putty stretching the same distance, what does this say about the two materials? They both stretched the same distance.*

Displacement only cannot distinguish materials that can accommodate large deformations or changes in shape. Thus, the taffy can accommodate larger shape change because the ratio of length change to original length is larger than the putty.

# Chemical Methods

x-ray diffraction

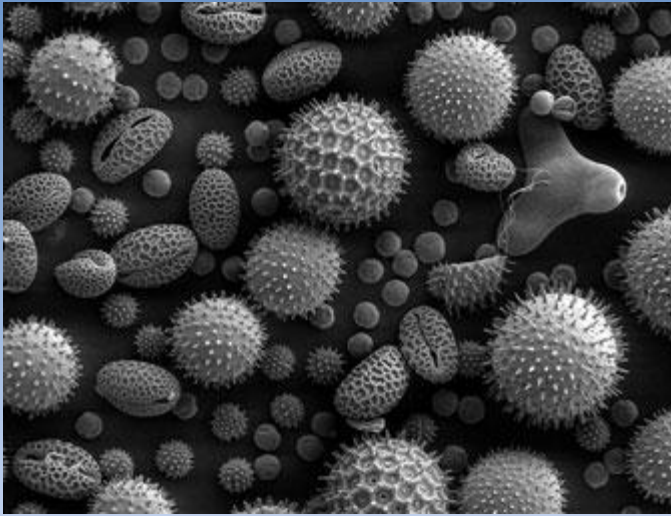
mass spectroscopy

gas chromatography

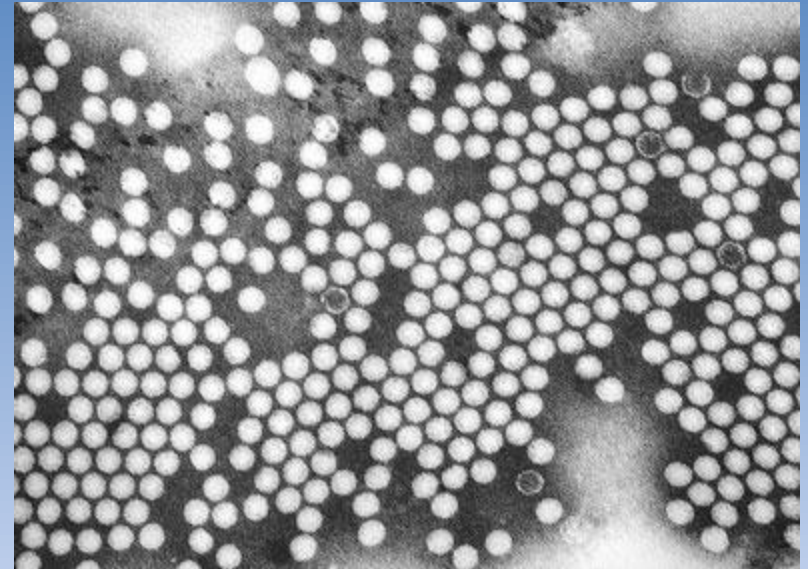
x-ray fluorescence

# Viewing Methods

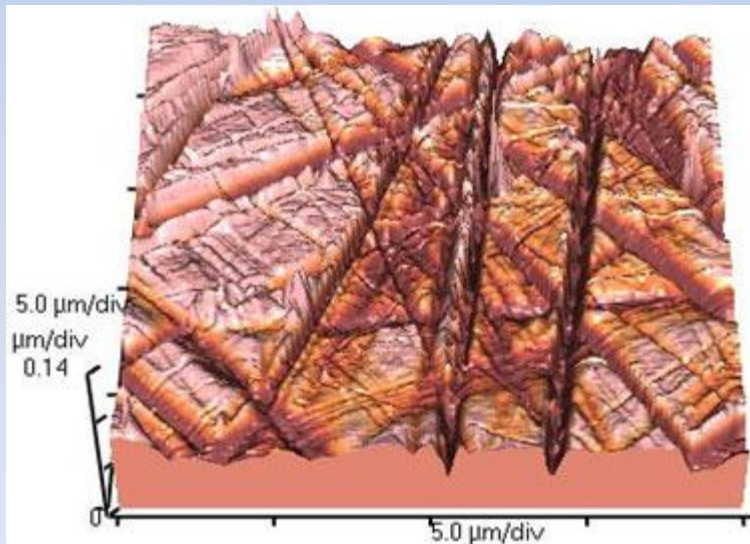
## Scanning Electron Microscope



## Transmission Electron Microscope



## Atomic Force Microscope



## Optical (Light) Microscope

