MATERIALS SCIENCE

SSP 2412

INTRODUCTION TO MATERIALS SCIENCE

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Introduction

- **Historical Perspective**
  Stone → Bronze → Iron → Advanced materials
- **What is Materials Science (and Engineering) ?**
  Processing → Structure → Properties → Performance
- **Classification of Materials**
  Metals, Ceramics, Polymers, Semiconductors
- **Advanced Materials**
  Electronic materials, superconductors, etc.
- **Modern Material's Needs, Material of Future**
  Biodegradable materials, Nanomaterials, “Smart” materials

Historical Perspective

- Beginning of the Material Science - People began to make tools from stone – Start of the Stone Age about two million years ago.
  Natural materials: stone, wood, clay, skins, etc.

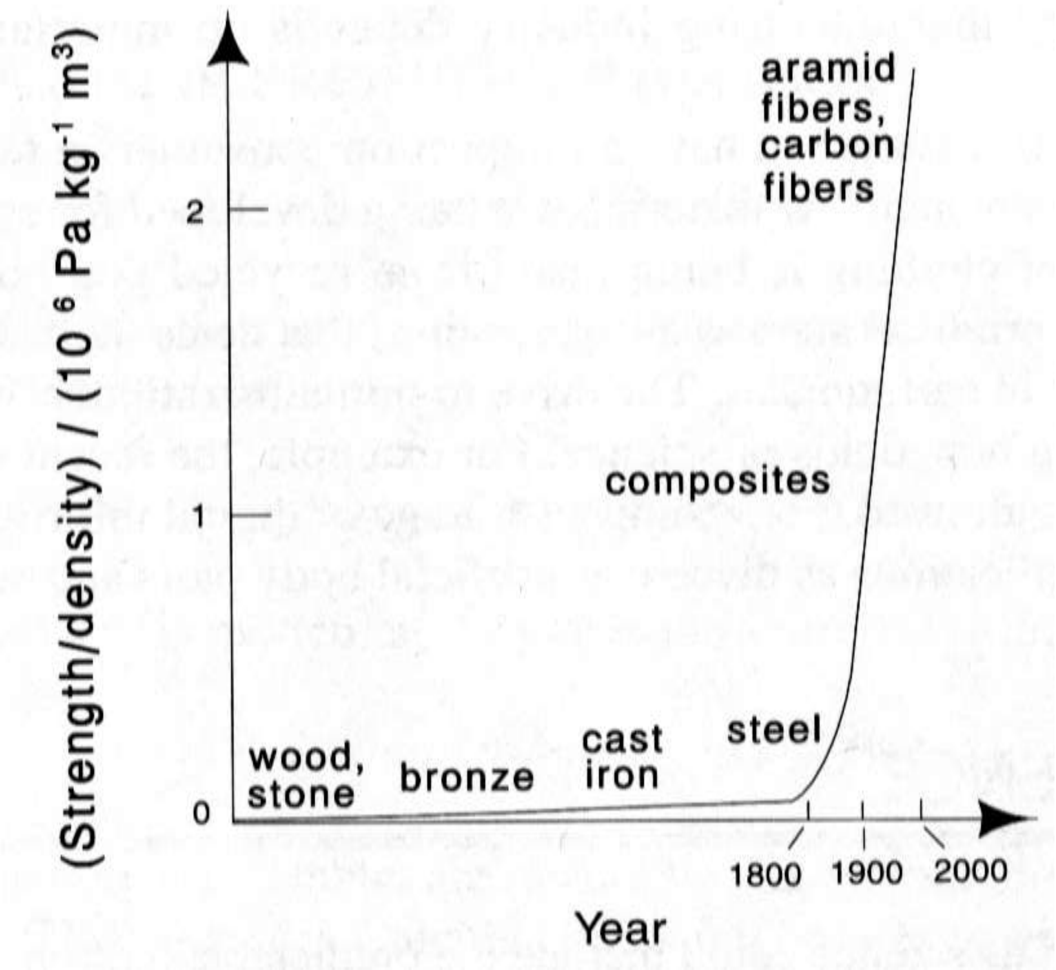
- The Stone Age ended about 5000 years ago with introduction of Bronze in the Far East. Bronze is an **alloy** (a metal made up of more than one element), copper + < 25% of tin + other elements.
  Bronze: can be hammered or cast into a variety of shapes, can be made harder by alloying, corrode only slowly after a surface oxide film forms.

- The Iron Age began about 3000 years ago and continues today. Use of iron and steel, a stronger and cheaper material changed drastically daily life of a common person.

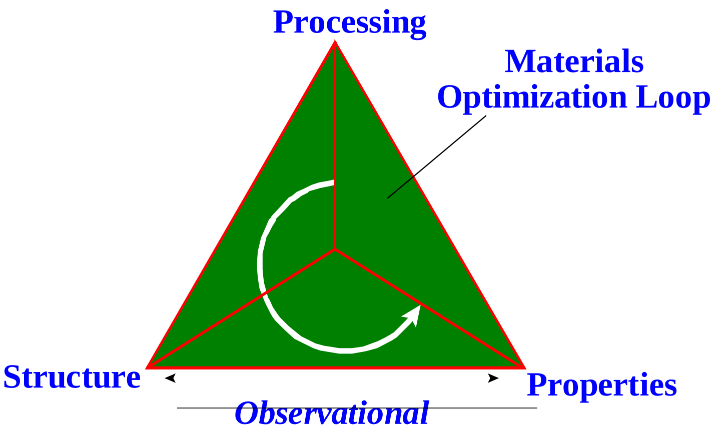
- Age of Advanced materials: throughout the Iron Age many new types of materials have been introduced (ceramic, semiconductors, polymers, composites…). Understanding of the **relationship among structure, properties, processing, and performance of materials**. Intelligent design of new materials.

A better understanding of structure-composition-properties relations has lead to a remarkable progress in properties of materials. Example is the dramatic progress in the strength to density ratio of materials, that resulted in a wide variety of new products, from dental materials to tennis racquets.

Strength to Density Ratio of Materials

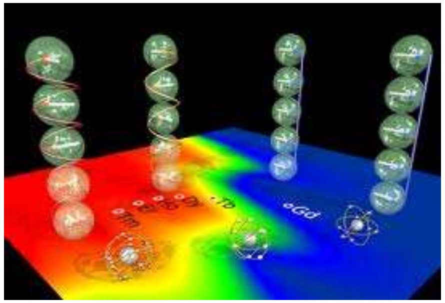


What is Materials Science?

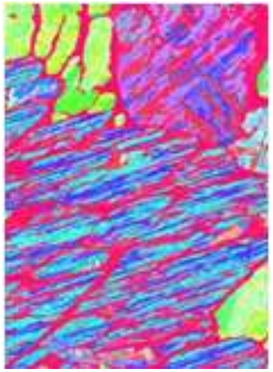


Material science is the investigation of the relationship among processing, structure, properties, and performance of materials.

Structure

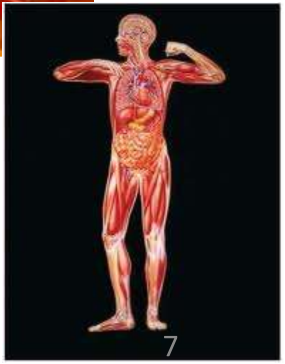


- **Subatomic level (Chapter 2)**
  Electronic structure of individual atoms that defines.. interaction among atoms (interatomic bonding).



- **Atomic level (Chapters 2 & 3)**
  Arrangement of atoms in materials (for the same atoms can have different properties, e.g. Steel structures of golf stick)

- **Microscopic structure (Ch. 4)**
  Arrangement of small grains of material that can be by microscopy (e.g. brass grains).



- **Macroscopic structure**
  Structural elements that may be viewed with the naked eye.

Length-scales; Units

Angstrom = 1Å = 1/10,000,000,000 meter = 10^{-10} m

Nanometer = 10 nm = 1/1,000,000,000 meter = 10^{-9} m

Micrometer = 1µm = 1/1,000,000 meter = 10^{-6} m

Millimeter = 1mm = 1/1,000 meter = 10^{-3} m

- Interatomic distance ~ a few Å
- A human hair is ~ 50 µm
- Elongated bumps that make up the data track on CD are ~ 0.5 µm wide, minimum 0.83 µm long, and 125 nm high

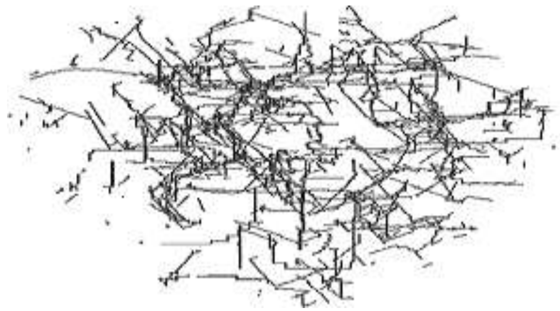
UTM

Length and Time Scales from the point of view of Materials Modeling

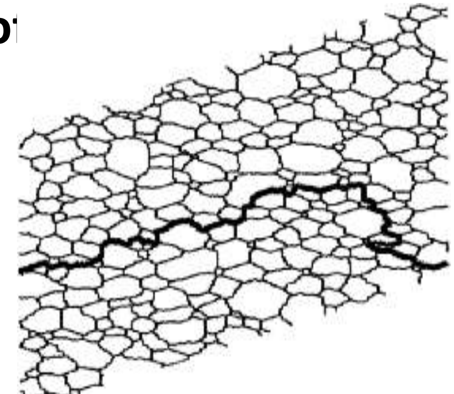
Length Scale, meters: 10^{-9} 0.1, 10^{-8}, 10^{-7}

Length Scale, number of atoms: 10^{3}, 10^{6}, 10^{9}, 10^{27}

Mesoscopic

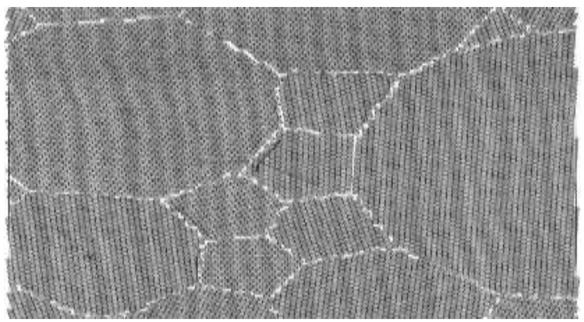


Dislocation Dynamics
Nature, 12 February, 1998

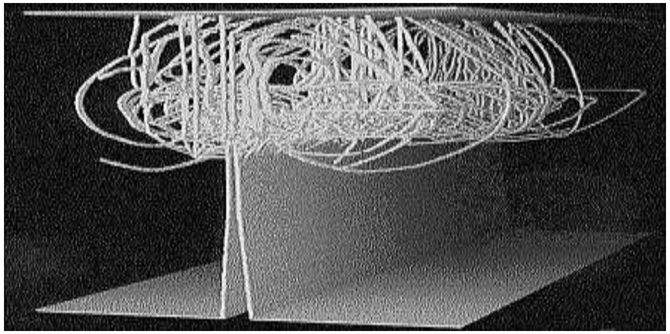


Elizabeth Holm, Sandia
Intergranular fracture
Monte Carlo Potts model

Microscopic

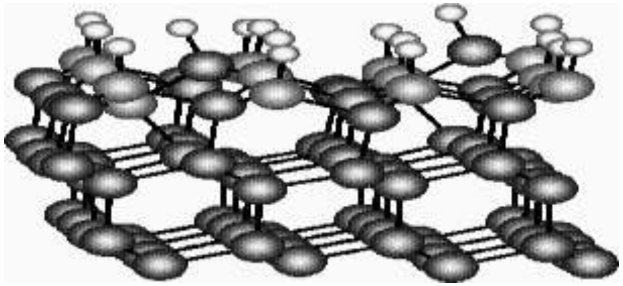


Mo Li, JHU, Atomistic
model of a nanocrystalline



Farid Abraham, IBM
MD of crack propagation

Nanoscopic

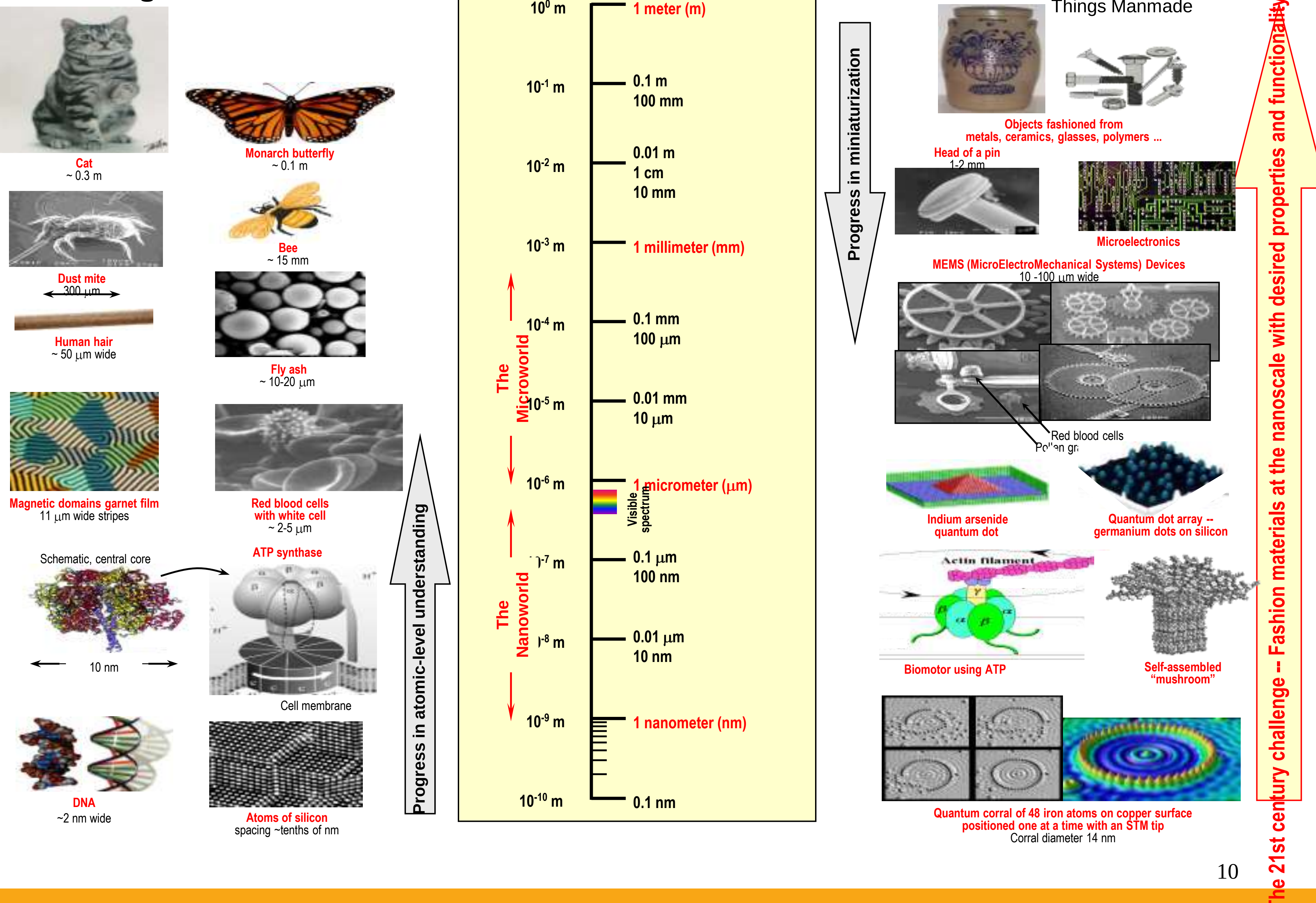


Leonid Zhigilei, UVA
Phase transformation on diamond surfaces

Time Scale, seconds: 10^{-12}, 10^{-9}, 10^{-7}, 1

THE SCALE OF THINGS

Things Natural



Properties

Properties are the way the material responds to the environment and external forces.

Mechanical properties – response to mechanical forces, strength, etc.

Electrical and **magnetic** properties - response electrical and magnetic fields, conductivity, etc.

Thermal properties are related to transmission of heat and heat capacity.

Optical properties include to absorption, transmission and scattering of light.

Chemical stability in contact with the environment - corrosion resistance.

Classes of Materials

- Polymers
  - Plastics
  - Liquid crystals
  - Adhesives
- Metals/Alloys
  - All metals
  - Mixed of different metals
- Electronic Materials /Semiconductors
  - Silicon and Germanium
  - III-V Compounds (e.g. GaAs)
  - Photonic materials (solid-state lasers, LEDs)
- Composites
  - Particulate composites (small particles embedded in a different material)
  - Laminate composites (golf club shafts, tennis rackets, Damaskus swords)
  - Fiber reinforced composites (e.g. fiberglass)
- Biomaterials (really using previous 5, but bio-mimetic)
  - Man-made proteins (cytoskeletal protein rods or "artificial bacterium")
  - Biosensors (Au-nanoparticles stabilized by encoded DNA for anthrax detection)
  - Drug-delivery colloids (polymer based)

General Properties of Materials

Let us classify materials according to the way the atoms are bound together

Metals: valence electrons are detached from atoms, and spread in an 'electron sea' that "glues" the ions together. Strong, ductile, conduct electricity and heat well, are shiny if polished.

Semiconductors: the bonding is covalent (electrons are shared between atoms). Their electrical properties depend strongly on minute proportions of contaminants. Examples: Si, Ge, GaAs.

Ceramics: atoms behave like either positive or negative ions, and are bound by Coulomb forces. They are usually combinations of metals or semiconductors with oxygen, nitrogen or carbon (oxides, nitrides, and carbides). Hard, brittle, insulators. Examples: glass, porcelain.

Polymers: are bound by covalent forces and also by weak van der Waals forces, and usually based on C and H. They decompose at moderate temperatures (100 – 400 C), and are lightweight. Examples: plastics rubber.

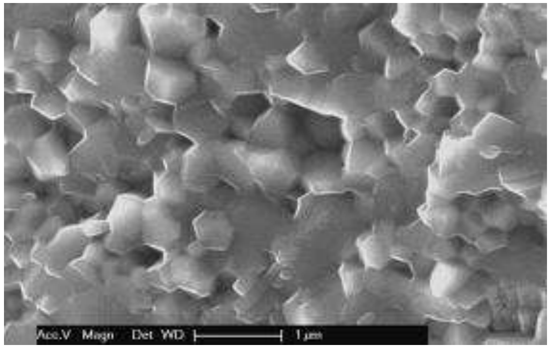
Metals/Alloys

Several uses of steel and alloys in making a car

Semiconductors/Devices

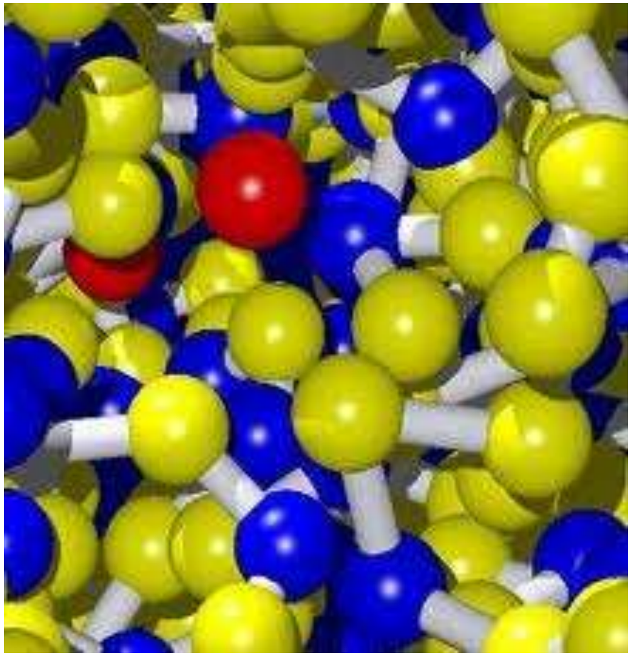
Micro/nano chips electronic devices
(monitor, camera, mobile phone, etc.

Ceramics/Composites



Microstructures of ceramics; Examples of ceramics/composites materials ranging from household to aerospace applications.

Polymers



Polymers include “Plastics” and rubber materials

Criteria for materials selection

- In-service conditions must be characterized
- Deterioration of properties must be evaluated
- The consideration of economics

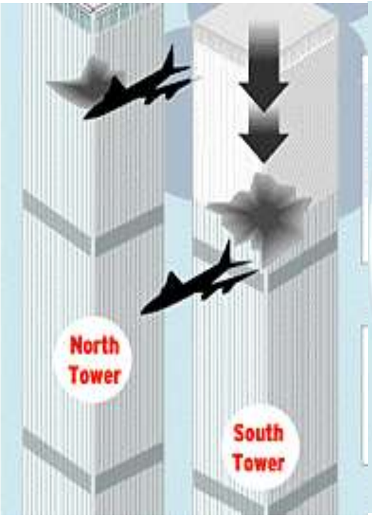
Materials and Failure

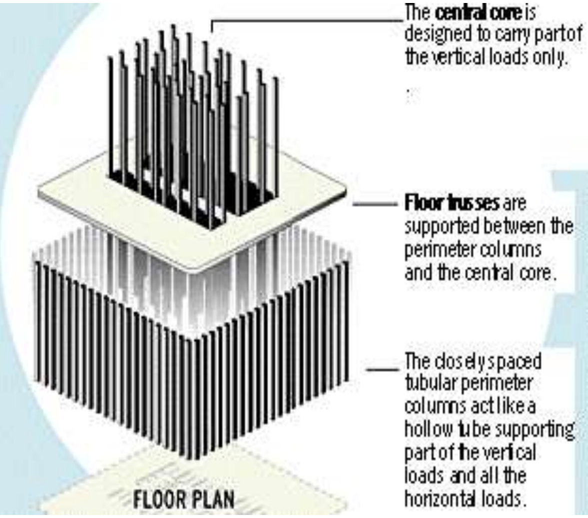
Without the right material, a good engineering design is wasted. Need the right material for the right job!

- Materials properties then are responsible for helping achieve engineering advances.
- Failures advance understanding and material's design.
- Some examples to introduce topics we will learn.

Example-World Trade Center Collapse

- *Tubular* constructed building.
- Well designed and *strong*.
- Strong but not from *buckling*.
- Supports lost at crash site, and the floor supported inner and outer tubular structures.
- Heat from burning fuel adds to loss of structural support from softening of steel (strength vs. T, stress-strain behavior).
- Building "pancakes" due to enormous buckling loads.





Future of materials science

Design of materials having specific desired characteristics directly from our knowledge of atomic structure.

- **Miniaturization:** "Nanostructured" materials, with microstructure that has length scales between 1 and 100 nanometers with unusual properties. Electronic components, materials for quantum computing.
- **Smart materials:** airplane wings that deice themselves, buildings that stabilize themselves in earthquakes…
- **Environment-friendly materials:** biodegradable or photodegradable plastics, advances in nuclear waste processing, etc.
- **Learning from Nature:** shells and biological hard tissue can be as strong as the most advanced laboratory-produced ceramics, mollusces produce biocompatible adhesives that we do not know how to reproduce…
- Materials for lightweight batteries with high storage densities, for turbine blades that can operate at 2500 C, room-temperature superconductors? chemical sensors (artificial nose) of extremely high sensitivity, cotton shirts that never require ironing…