

# Material Science



By

Dr. Amar Patnaik

Mechanical Engineering Department

Malaviya National Institute of Technology,

Jaipur

# Chapter Outline

- **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.

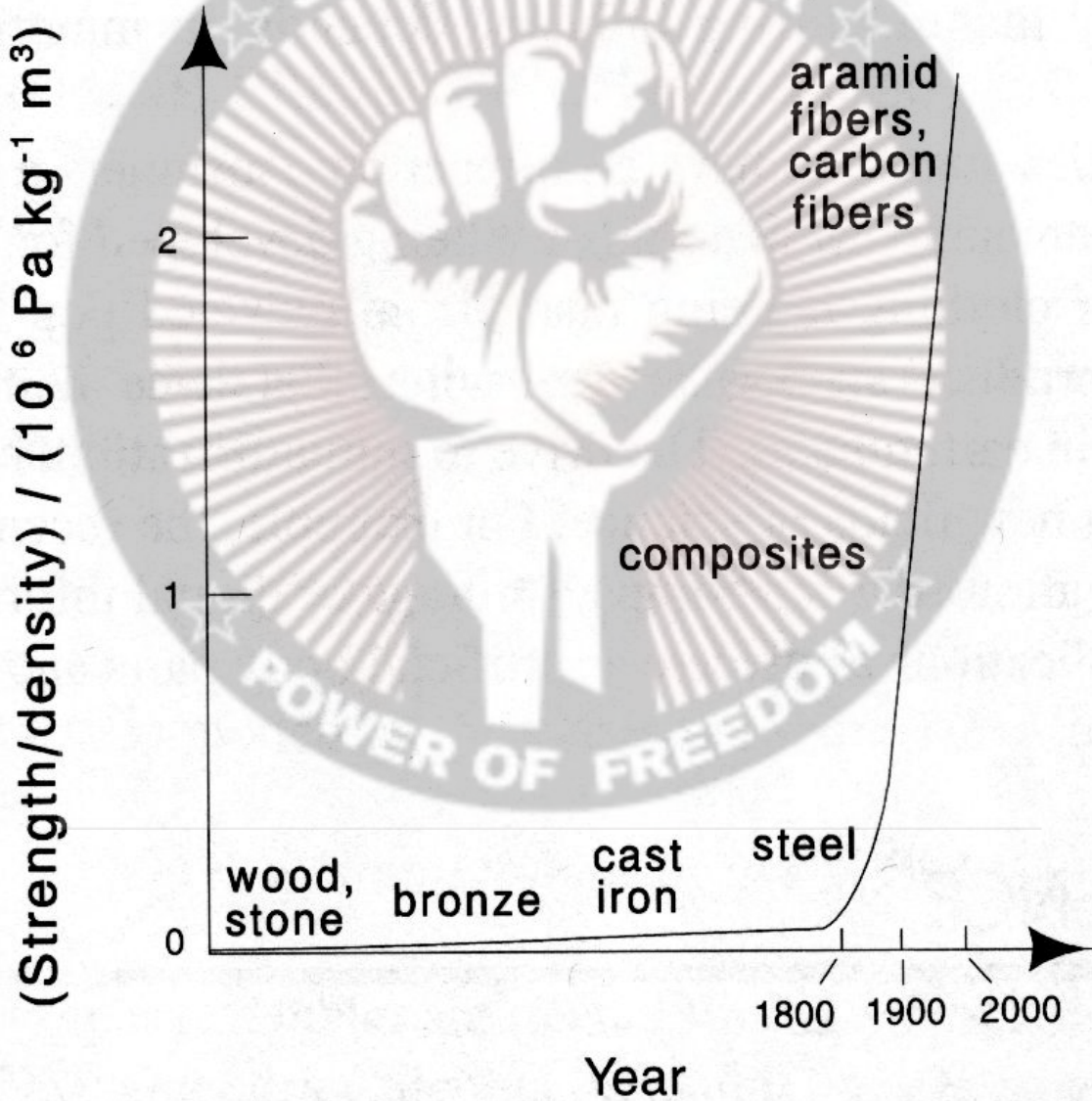
- The Stone Age ended about 5000 years ago with introduction of Bronze in the Far East. Bronze is an **alloy** (a metal made up of more than one element), copper + < 25% of tin + other elements.

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.

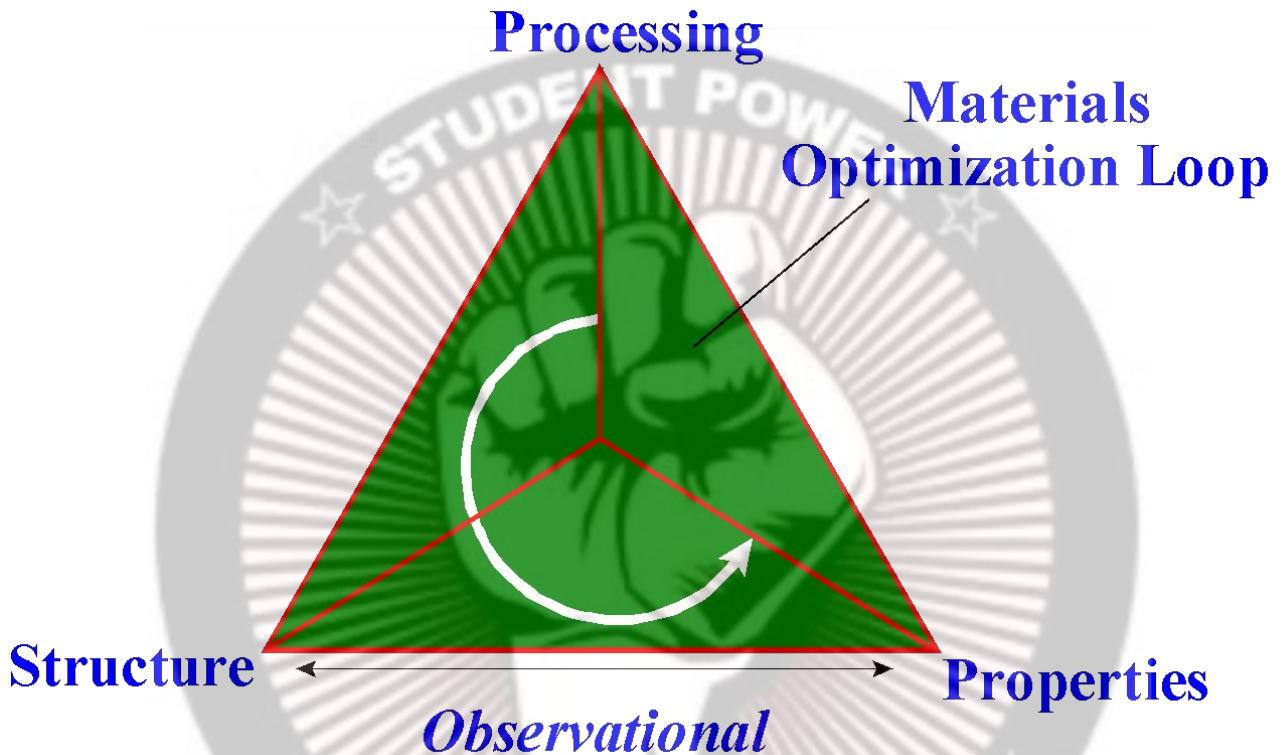
- The Iron Age began about 3000 years ago and continues today. Use of iron and steel, a stronger and cheaper material changed drastically daily life of a common person.

- 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 led 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.



# What is Materials Science and Engineering ?

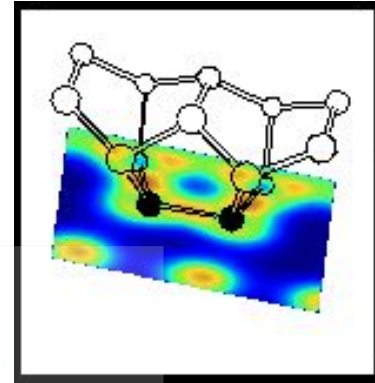


Material science is the investigation of the relationship among processing, structure, properties, and performance of materials.

# Structure

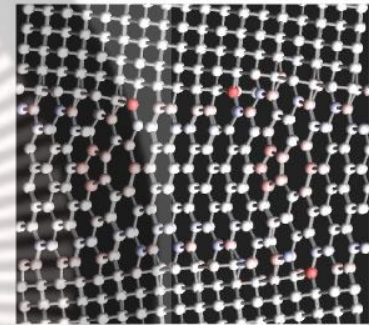
- **Subatomic level (Chapter 2)**

Electronic structure of individual atoms that defines interaction among atoms (interatomic bonding).



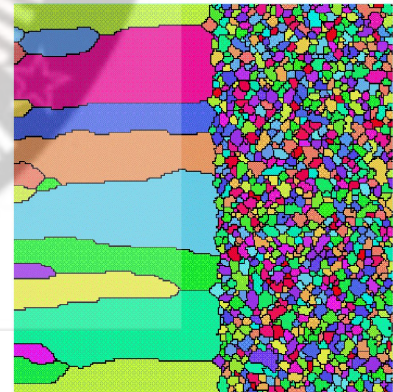
- **Atomic level (Chapters 2 & 3)**

Arrangement of atoms in materials (for the same atoms can have different properties, e.g. two forms of carbon: graphite and diamond)



- **Microscopic structure (Ch. 4)**

Arrangement of small grains of material that can be identified by microscopy.



- **Macroscopic structure**

Structural elements that may be viewed with the naked eye.



## Length-scales

**Angstrom** =  $1\text{\AA} = 1/10,000,000,000$  meter =  $10^{-10}$  m

**Nanometer** =  $10\text{ nm} = 1/1,000,000,000$  meter =  $10^{-9}$  m

**Micrometer** =  $1\mu\text{m} = 1/1,000,000$  meter =  $10^{-6}$  m

**Millimeter** =  $1\text{mm} = 1/1,000$  meter =  $10^{-3}$  m

Interatomic distance  $\sim$  a few  $\text{\AA}$

A human hair is  $\sim 50\ \mu\text{m}$

Elongated bumps that make up the data track on CD are  
 $\sim 0.5\ \mu\text{m}$  wide, minimum  $0.83\ \mu\text{m}$  long, and  $125\ \text{nm}$  high

---

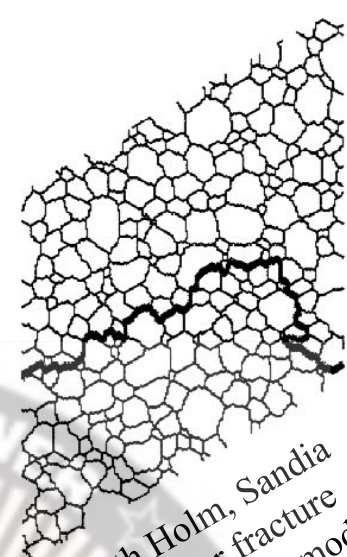
# Length and Time Scales from the point of view of Materials Modeling

$10^{-9}$   $10^3$   
 $10^{-8}$   $10^6$   
 $10^{-7}$   $10^9$   
 Length Scale, number of atoms  
 $10^{-7}$   $10^9$   
 Length Scale, meters  
 $0.1$   $10^{27}$

Mesoscopic

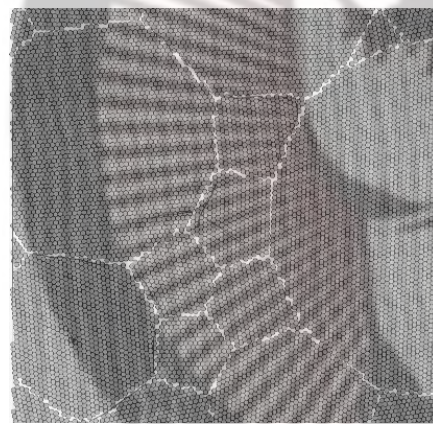


Dislocation Dynamics  
Nature, 12 February, 1998

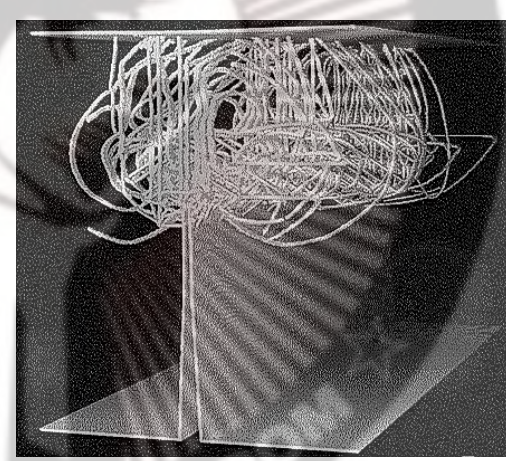


Elizabeth Holm, Sandia  
Intergranular fracture  
Monte Carlo Potts model

Microscopic

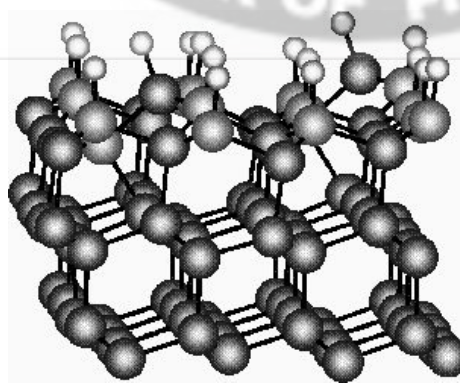


Mo Li, JHU, Atomistic model of a nanocrystalline



Farid Abraham, IBM  
MD of crack propagation

Nanosopic



Leonid Zhigilei, UVA  
Phase transformation on diamond surfaces

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

# THE SCALE OF THINGS

## Things Natural

## Things Manmade



**Cat**  
~ 0.3 m



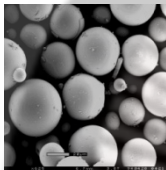
**Monarch butterfly**  
~ 0.1 m



**Bee**  
~ 15 mm



**Dust mite**  
300  $\mu$ m



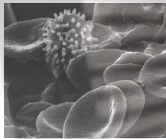
**Fly ash**  
~ 10-20  $\mu$ m



**Human hair**  
~ 50  $\mu$ m wide

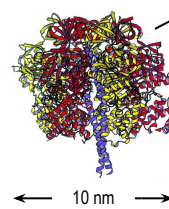


**Magnetic domains garnet film**  
11  $\mu$ m wide stripes

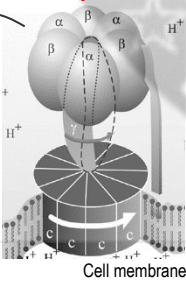


**Red blood cells with white cell**  
~ 2-5  $\mu$ m

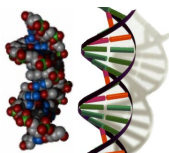
Schematic, central core



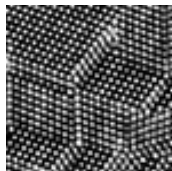
**ATP synthase**



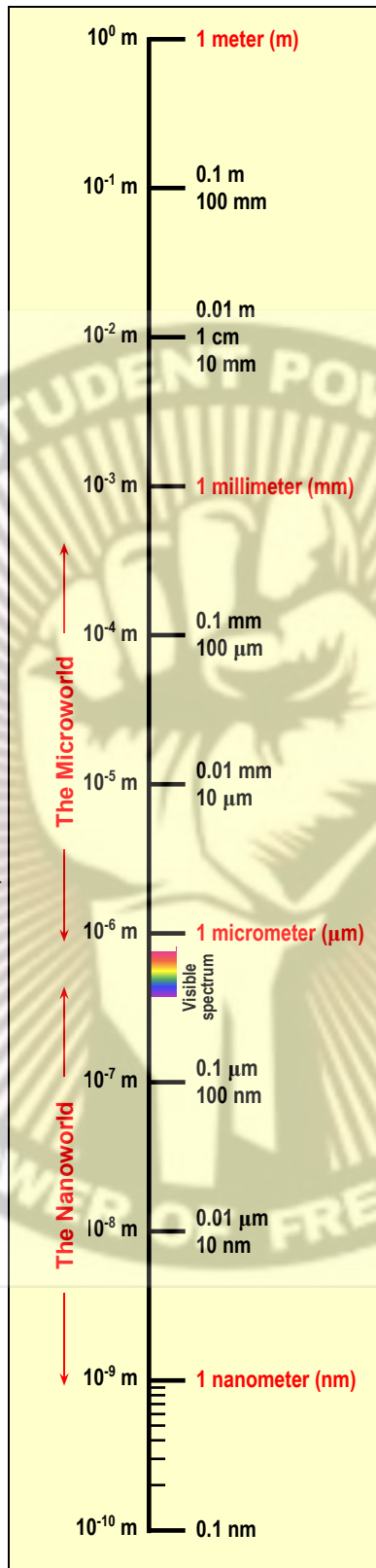
Cell membrane



**DNA**  
~2 nm wide



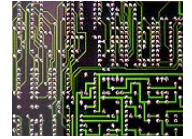
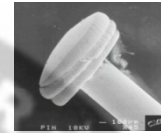
**Atoms of silicon**  
spacing ~tenths of nm



Objects fashioned from metals, ceramics, glasses, polymers ...

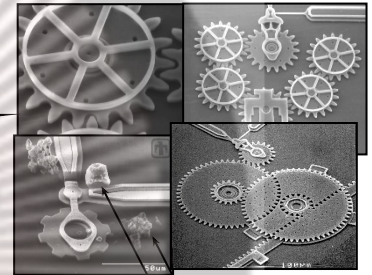


**Head of a pin**  
1-2 mm

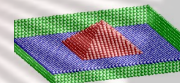


**Microelectronics**

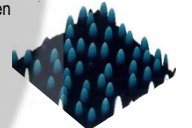
**MEMS (MicroElectroMechanical Systems) Devices**  
10 -100  $\mu$ m wide



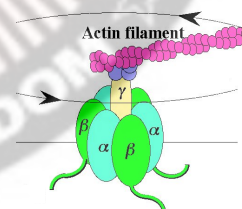
Red blood cells  
Pollen



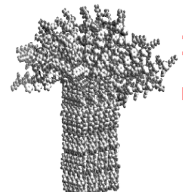
**Indium arsenide quantum dot**



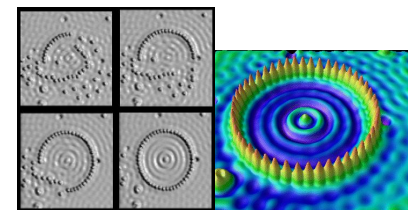
**Quantum dot array -- germanium dots on silicon**



**Biomotor using ATP**



**Self-assembled "mushroom"**



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

The 21st century challenge -- Fashion materials at the nanoscale with desired properties and functionality

meter	m	10 <sup>0</sup>	1 m
centimeter	cm	10 <sup>-2</sup>	0.01 m
millimeter	mm	10 <sup>-3</sup>	0.001 m
micrometer	$\mu$ m	10 <sup>-6</sup>	0.000001 m

Chart from [http://www.sc.doe.gov/production/bes/scale\\_of\\_things.html](http://www.sc.doe.gov/production/bes/scale_of_things.html)

# 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.

# Types of Materials

Let us classify materials according to the way the atoms are bound together (Chapter 2).

**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.

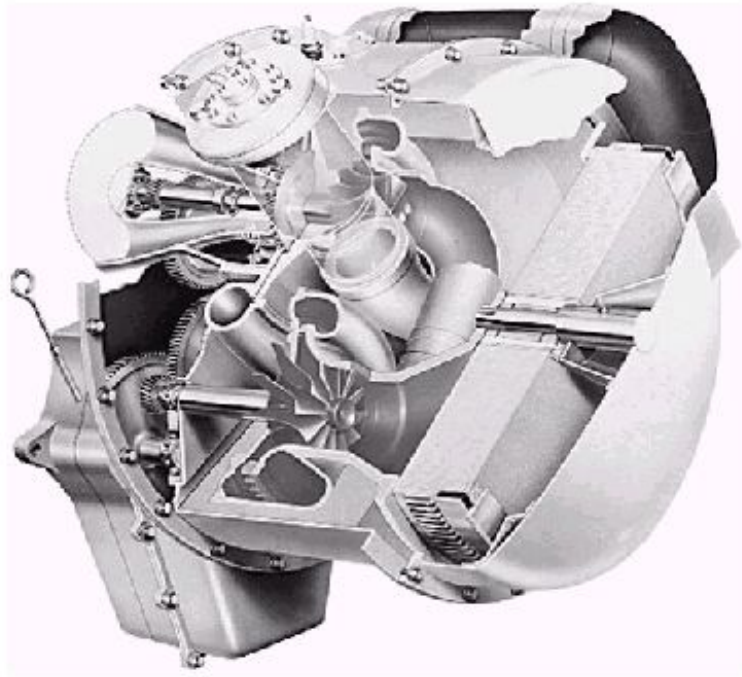
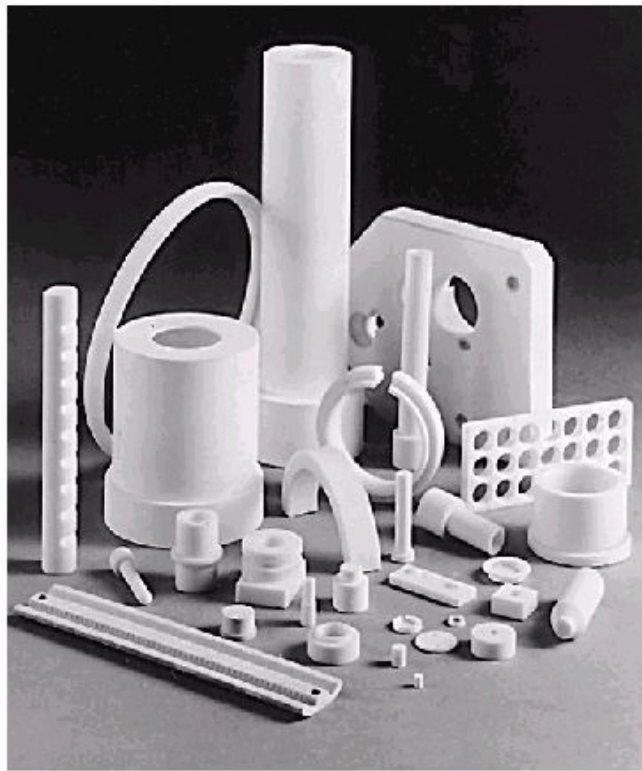
# Metals



Several uses of steel and pressed aluminum.



# Ceramics



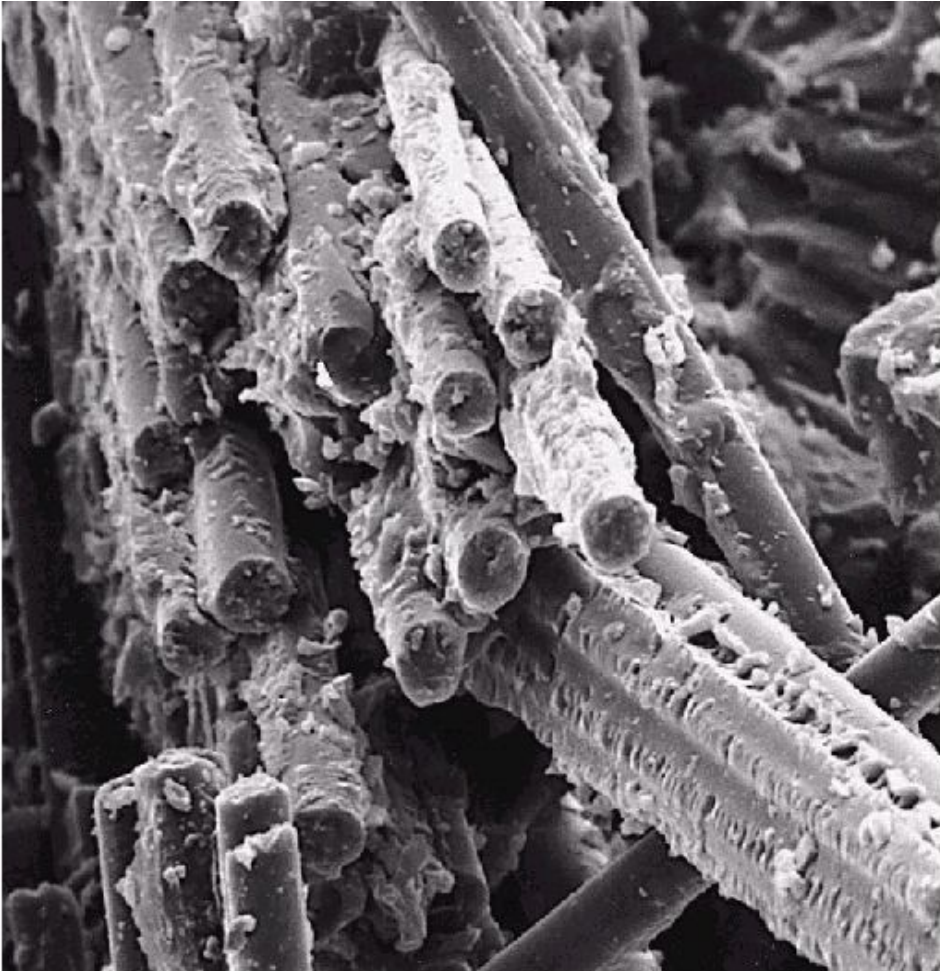
Examples of ceramic materials ranging from household to high performance combustion engines which utilize both metals and ceramics.

# Polymers



Polymers include “Plastics” and rubber materials

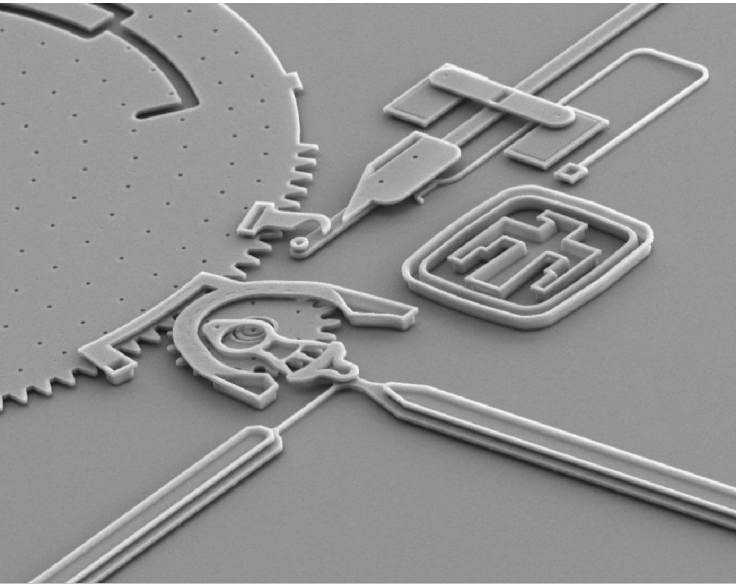
# Composites



Polymer composite materials:  
reinforcing glass fibers in a  
polymer matrix.

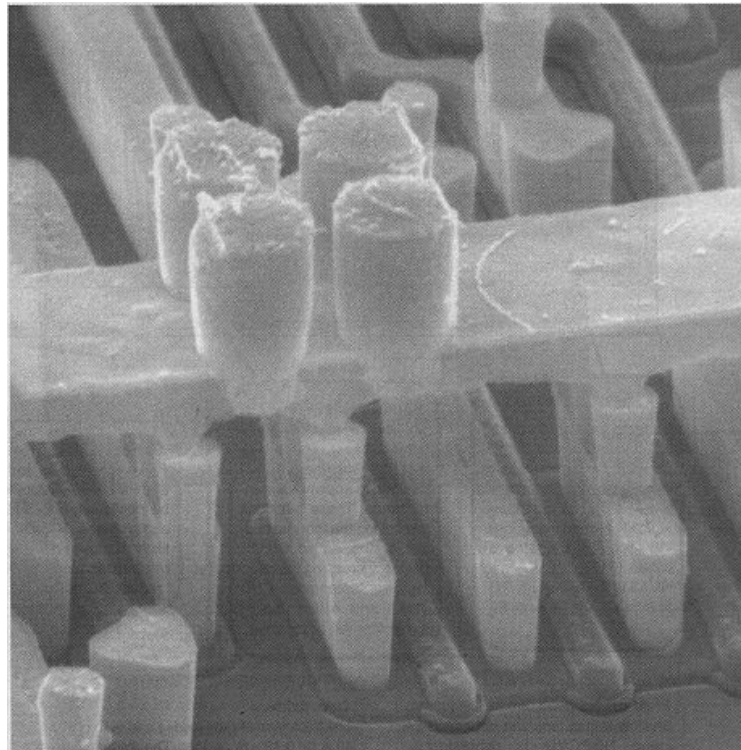
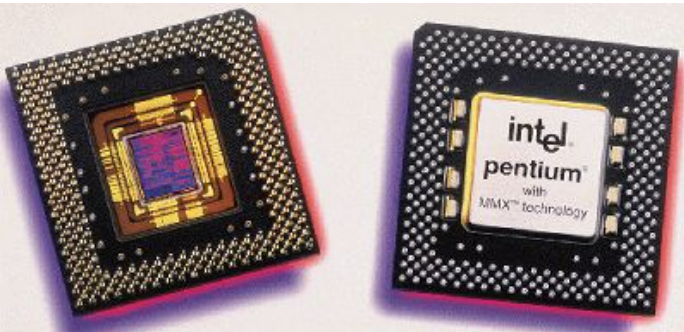


# Semiconductors



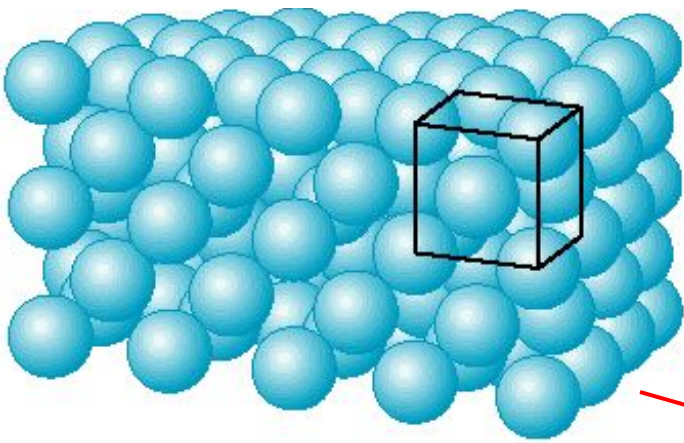
Micro-Electrical-Me  
chanical Systems  
(MEMS)

Si wafer for computer  
chip devices.

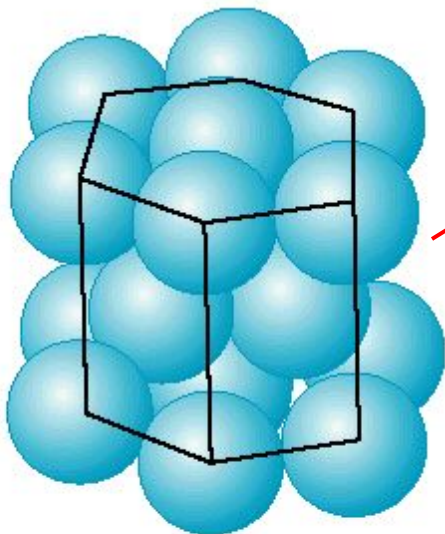


# Material Selection

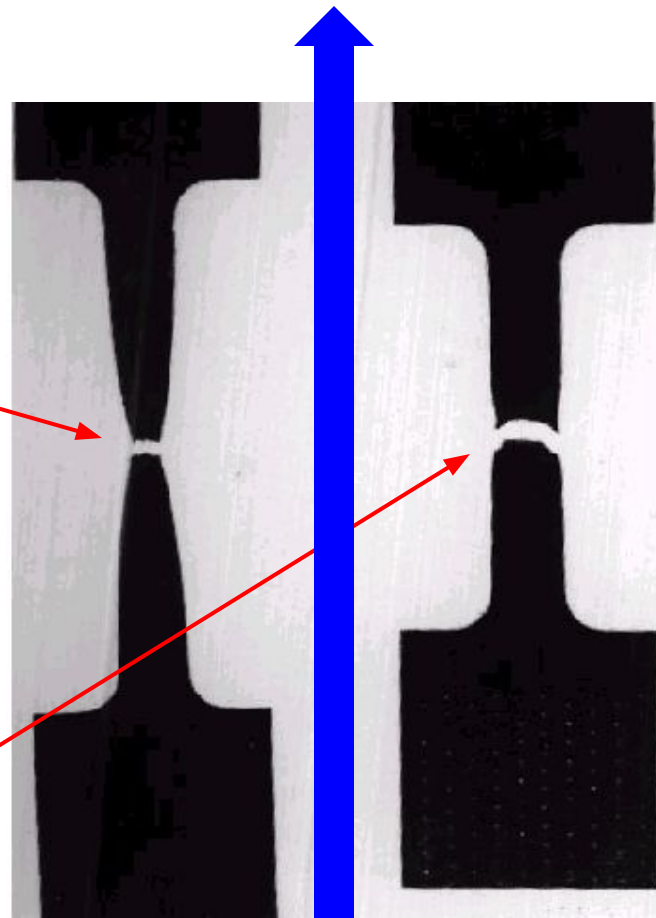
Different materials exhibit different **crystal structures** (Chapter 3) and resultant Properties



(a) Aluminum



(b) Magnesium



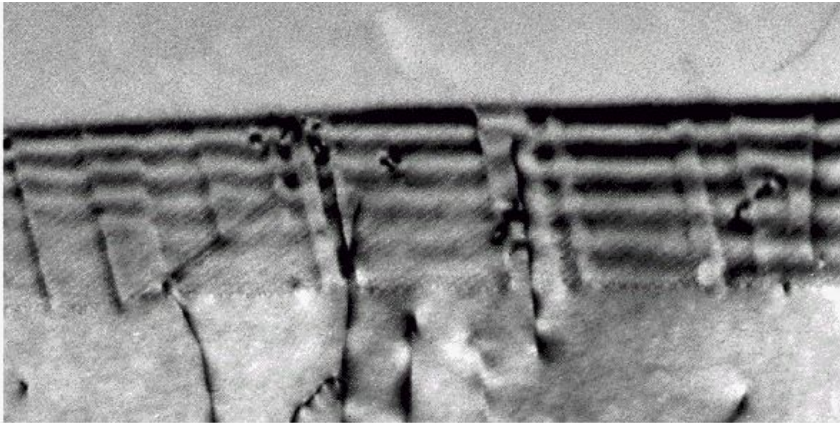
(a)

(b)

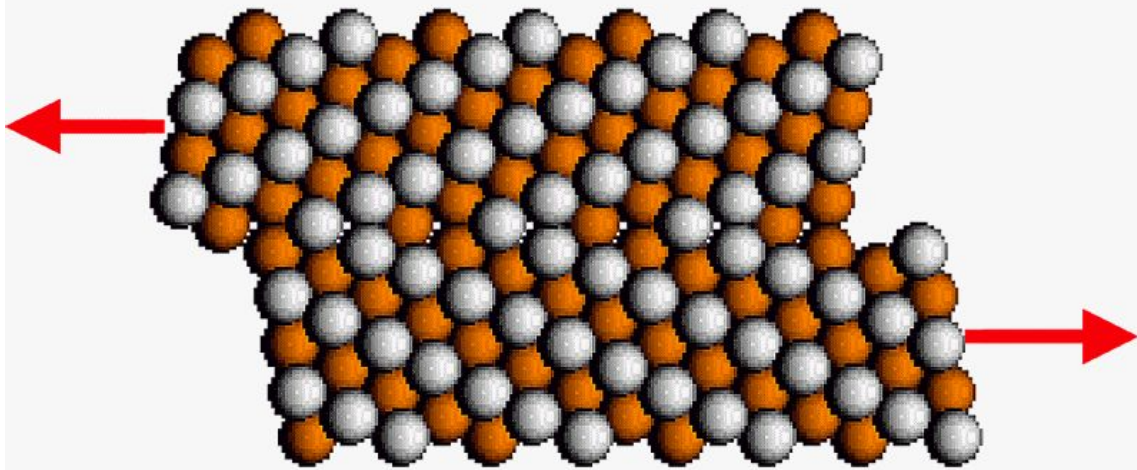
force

# Material Selection

Different materials exhibit different **microstructures** (Chapter 4) and resultant Properties



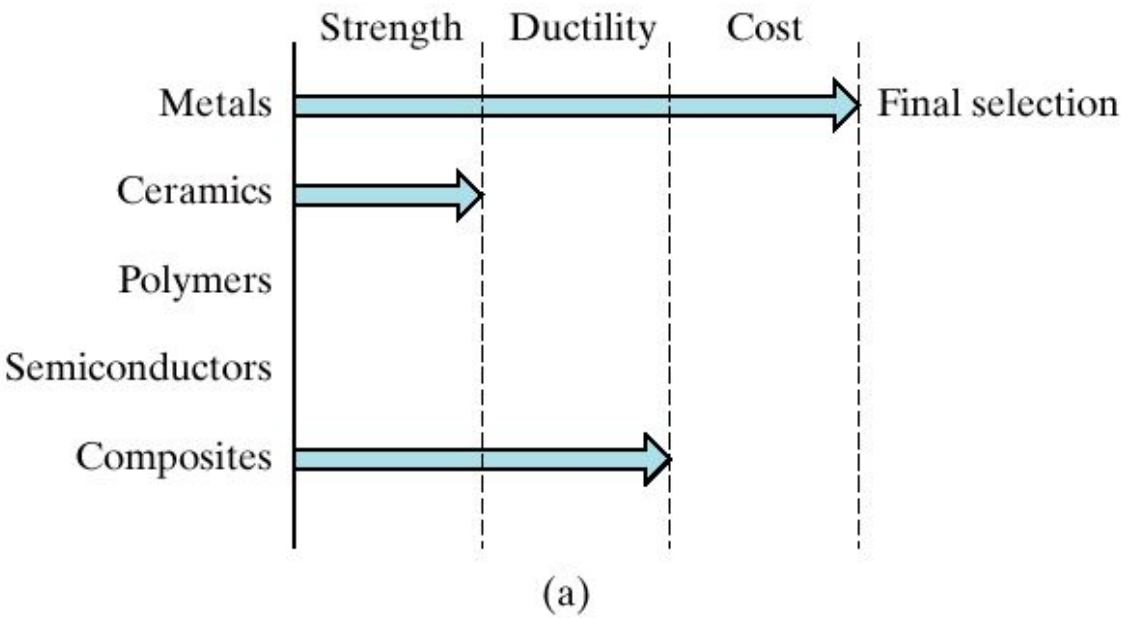
**Extrinsic grain boundary dislocations in Al**



**Sliding of defect free  $\Sigma 11$  {131} grain boundary**

Superplastic deformation involves low-stress sliding along grain boundaries, a complex process of which material scientists have limited knowledge and that is a subject of current investigations.

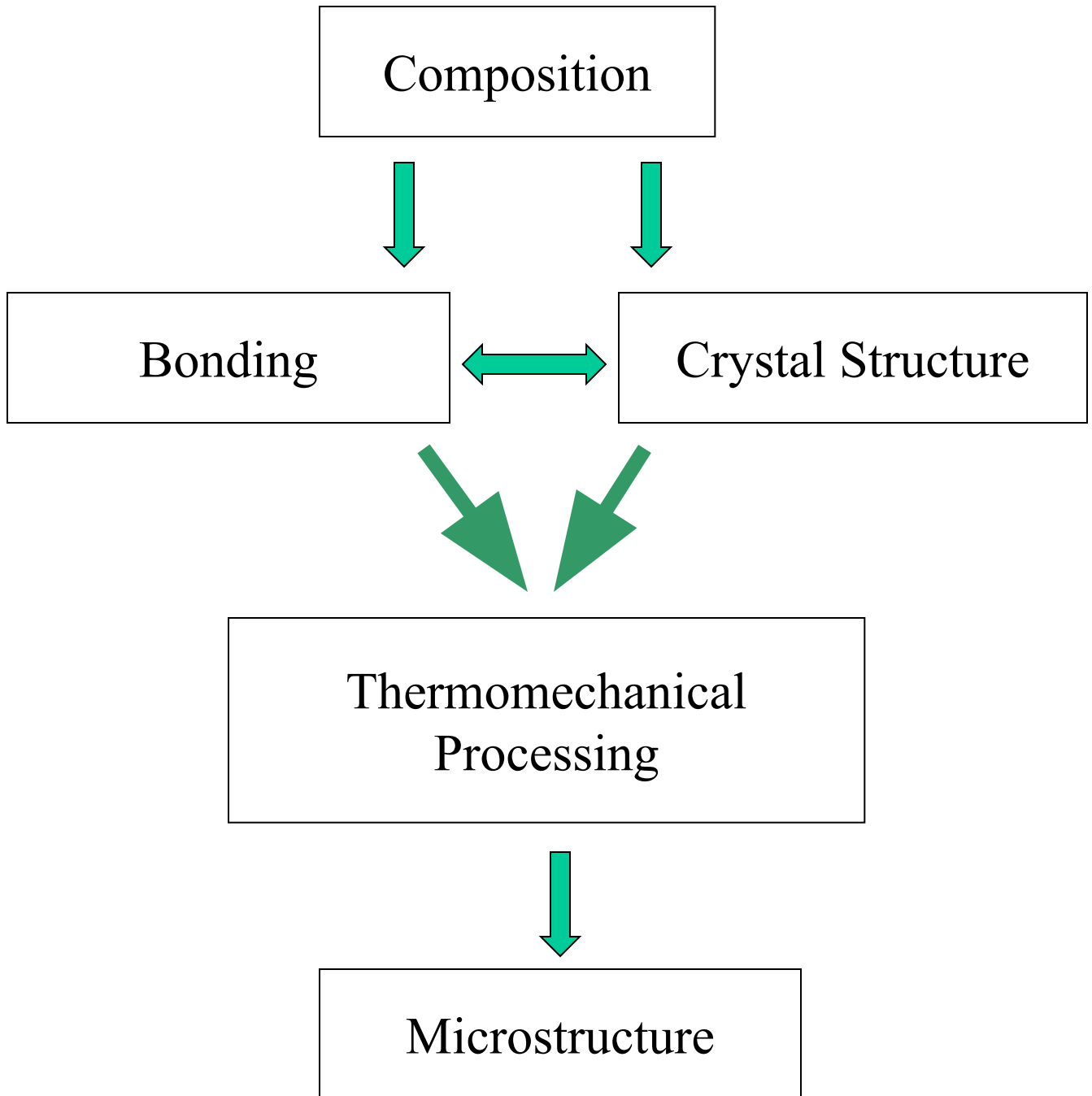
# Material Selection



(b)

How do you decide on a specific material for your application ?

# Composition, Bonding, Crystal Structure and Microstructure DEFINE Materials Properties



## 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, molluscs 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...