Models and Materials Program: A Brief Introduction to Materials Science and Engineering

Elaine D. Haberer

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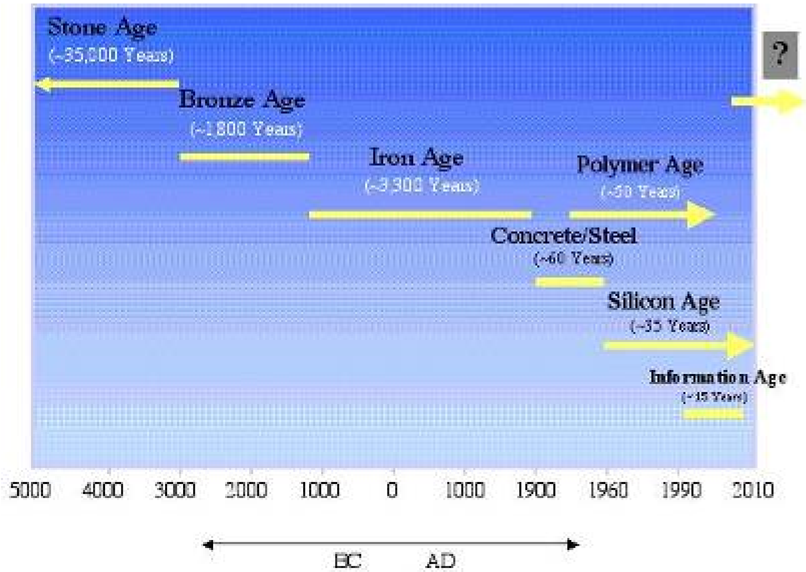
History of Materials Science & Engineering

- materials closely connected our culture
- the development and advancement of societies are dependent on the available materials and their use
- early civilizations designated by level of materials development



- initially natural materials
- develop techniques to produce materials with superior qualities (heat treatments and addition of other substances)

MATERIALS SELECTION!

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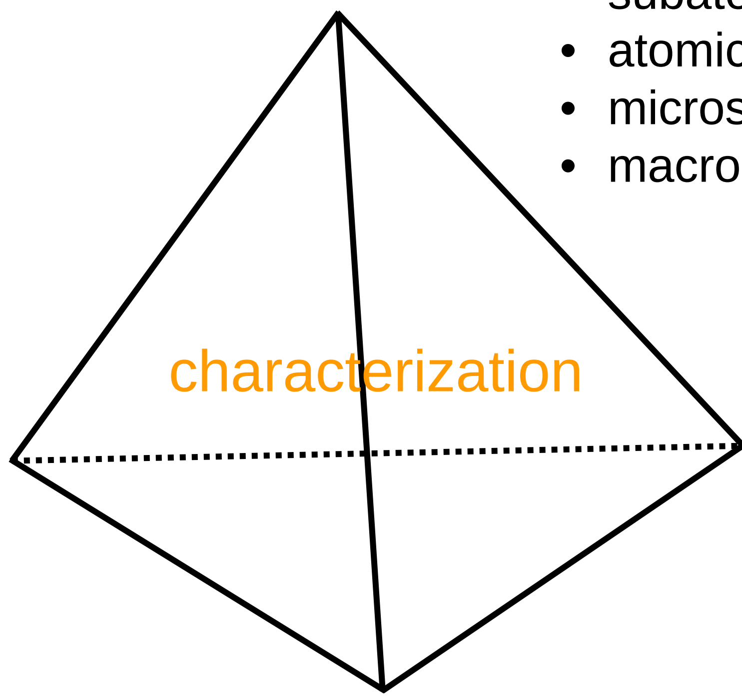
Materials Science and Engineering

structure

- arrangement of internal components
- subatomic
- atomic
- microscopic
- macroscopic (bulk)



processing

- method of preparing material

properties

- material characteristic
- response to external stimulus
- mechanical, electrical, thermal, magnetic, optical, deteriorative

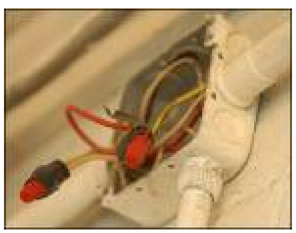
performance

- behavior in a particular application

Classification of Materials

Metals

- good conductors of electricity and heat
- lustrous appearance
- susceptible to corrosion
- strong, but deformable



Ceramics & Glasses

- thermally and electrically insulating
- resistant to high temperatures and harsh environments
- hard, but brittle

Polymers

- very large molecules
- low density, low weight
- maybe extremely flexible

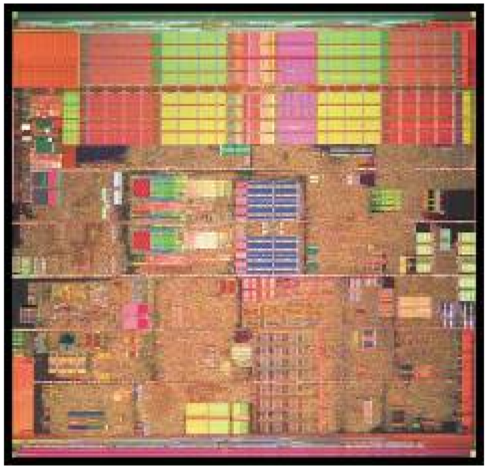
Classification of Materials: A Few Additional Catagories

Biomaterials
- implanted in human body
- compatible with body tissues

Semiconductors
- electrical properties between conductors and insulators
- electrical properties can be precisely controlled

Composites
- consist of more than one material type
- designed to display a combination of properties of each component


hip replacement


Intel Pentium 4


fiberglass surfboards

Why study materials?

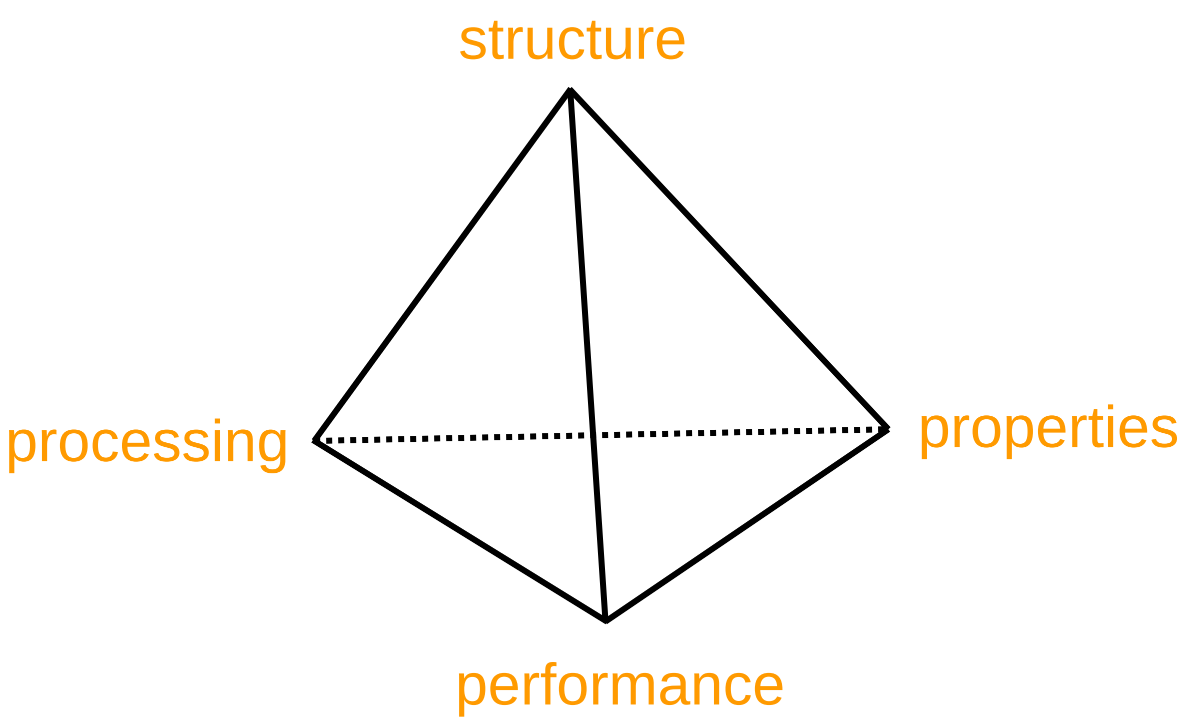
- applied scientists or engineers must make material choices
- materials selection
  - in-service performance
  - deterioration
  - economics

BUT…really, everyone makes material choices!

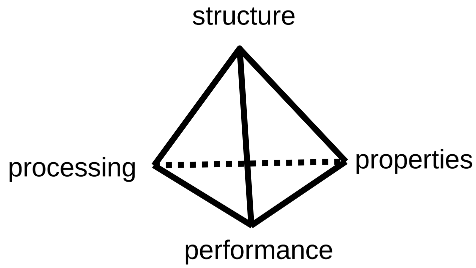
aluminum

glass

plastic


structure
processing
properties
performance

Levels of Structure



STRUCTURE (length scale)

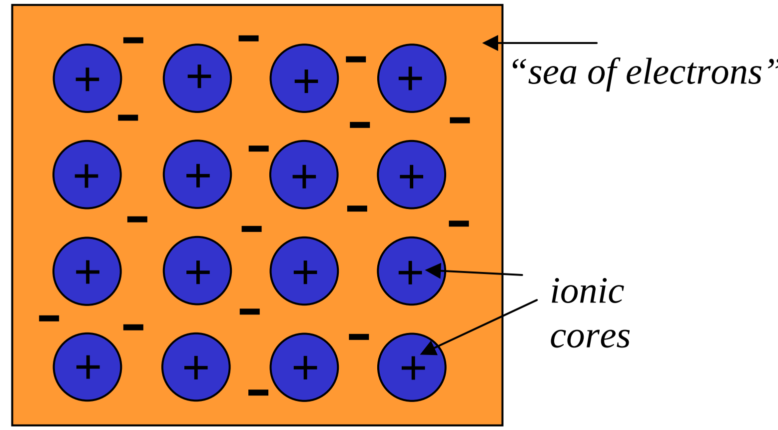
Sub-atomic

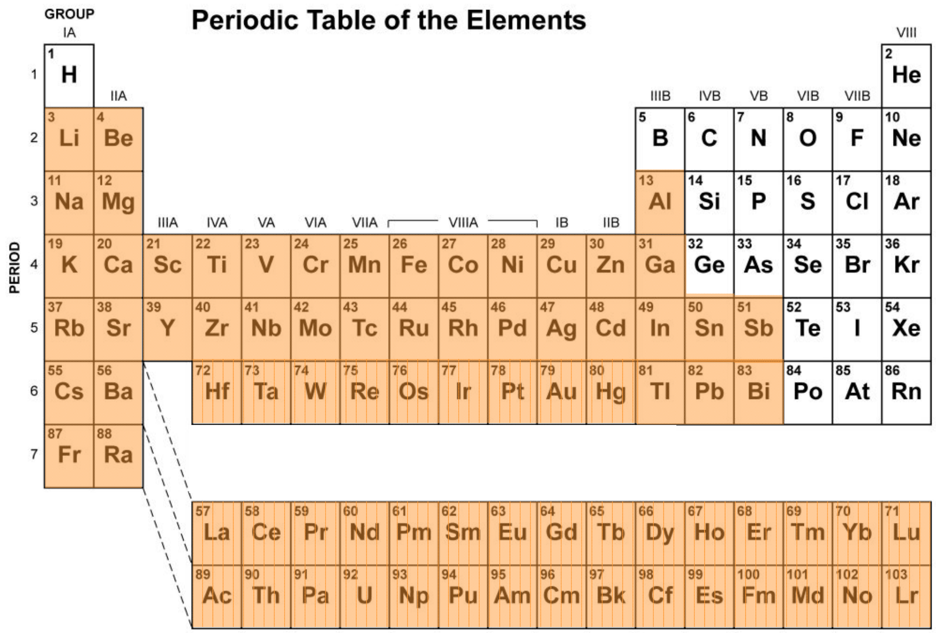
< 0.2 nm

Metals

Metallic Bond

- one, two, or three valence electrons
- valence electrons free to drift through the entire material forming a *"sea of electrons"* surrounding net positive *ionic cores*
- non-directional bond





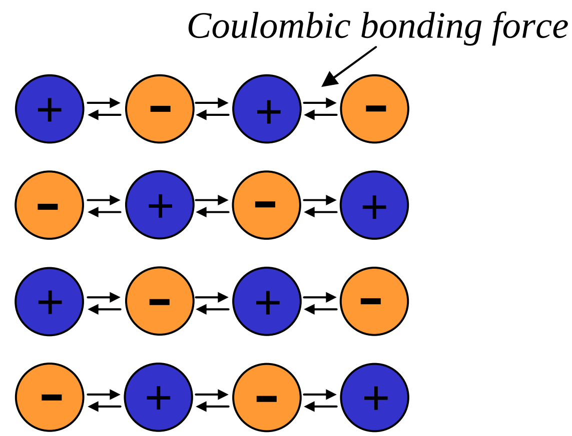
Properties

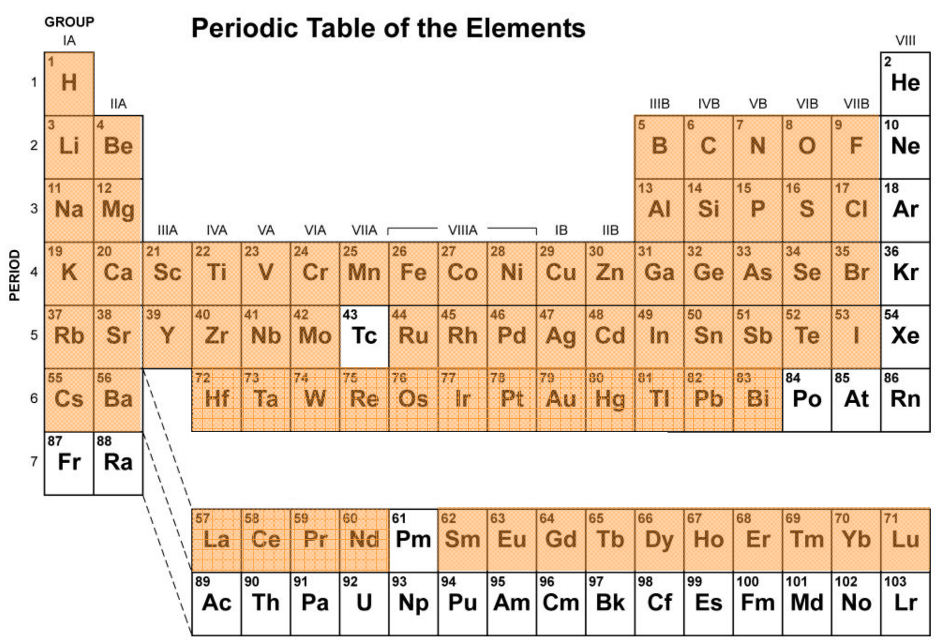
- good conductors of electricity and heat
- lustrous appearance
- susceptible to corrosion
- strong, but deformable

Ceramics and Glasses

Ionic Bond

- composed of metallic and non-metallic elements
- metallic elements give up valence electrons to non-metallic elements
- all atoms have filled “inert gas” configuration
- ionic solid
- non-directional bond





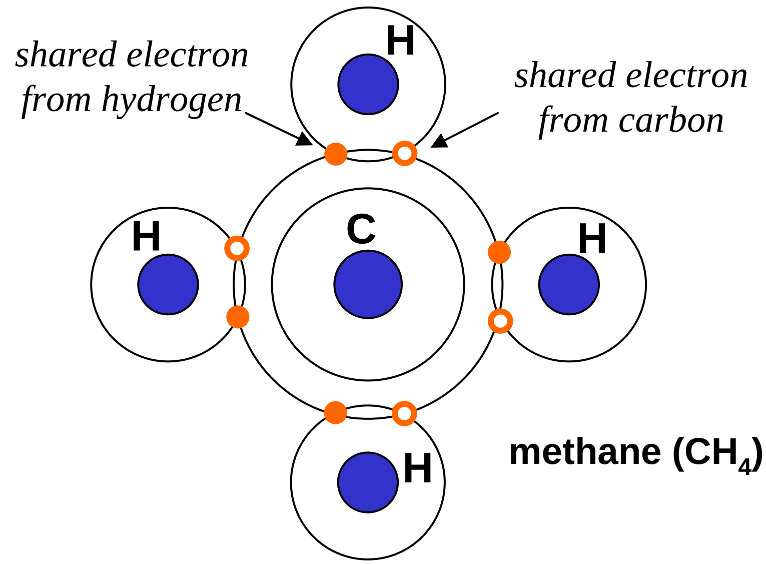
Ceramics & Glasses

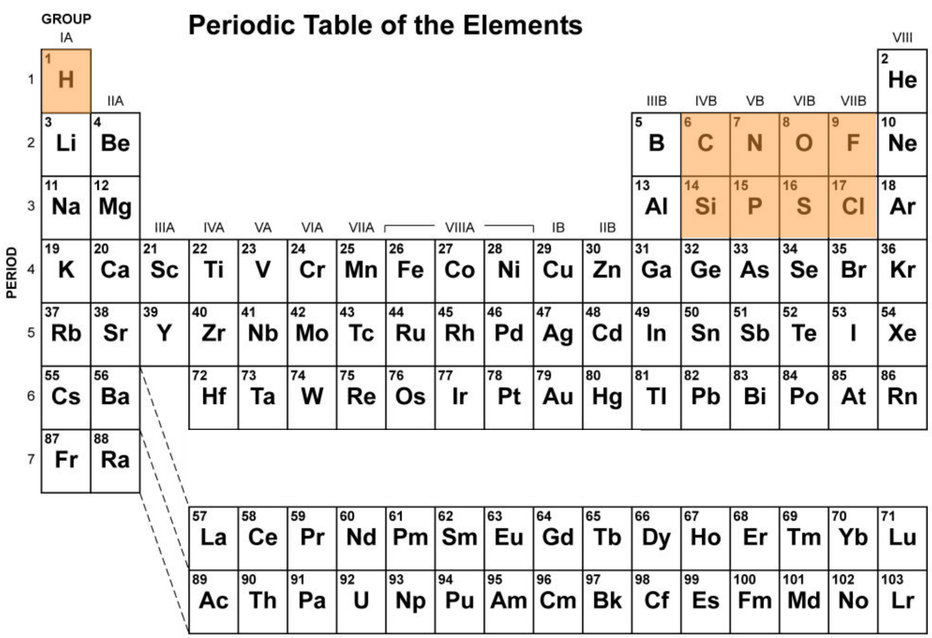
- thermally and electrically insulating
- resistant to high temperatures and harsh environments
- hard, but brittle

Polymers

Covalent Bond

- electrons are shared between adjacent atoms, each contributing at least one electron
- shared electrons belong to both atoms
- directional bond

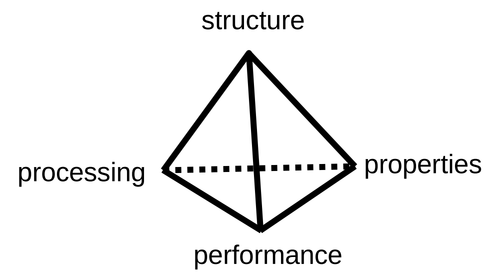




Polymers

- very large molecules
- low density, light weight materials
- maybe extremely flexible

Levels of Structure



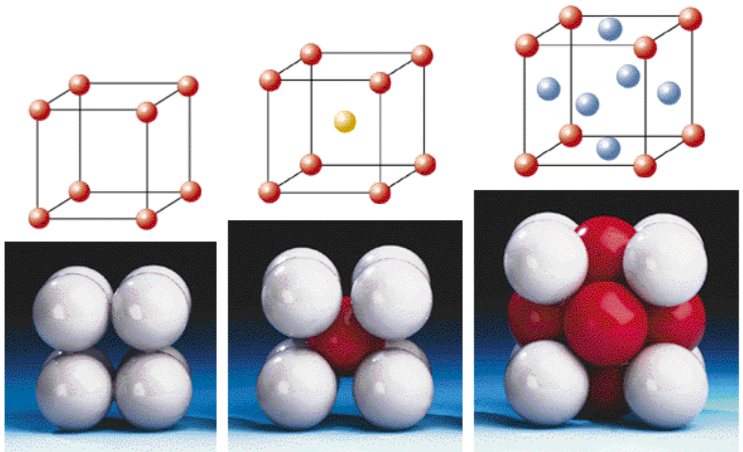
STRUCTURE (length scale)

Sub-atomic	Atomic
< 0.2 nm 1 nm = ?	0.2-10 nm

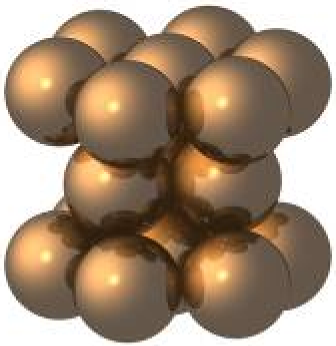
Atomic Arrangement: Ordered vs. Disordered

<u>Crystalline:</u>

atoms are arranged in a 3D, periodic array giving the material "*long range order*"



simple cubic   body-centered cubic   face-centered cubic

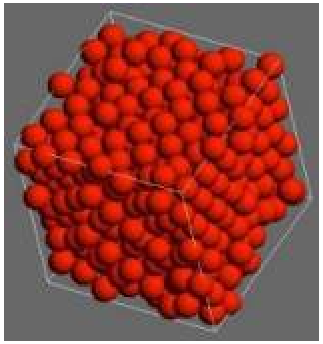


hexagonal close-packed

- stacking can effect properties (i.e. ductility)
- anisotropic materials

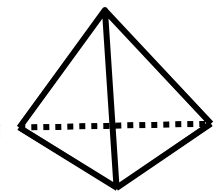
<u>Non-crystalline or amorphous:</u>

atoms only have short-range, *nearest neighbor order*



- viscous materials (generally complex formulas) or rapid cooling
- isotropic materials

Levels of Structure



STRUCTURE (length scale)

Sub-atomic	Atomic	Microscopic
< 0.2 nm 1 nm = ?	0.2-10 nm	1-1000 μm

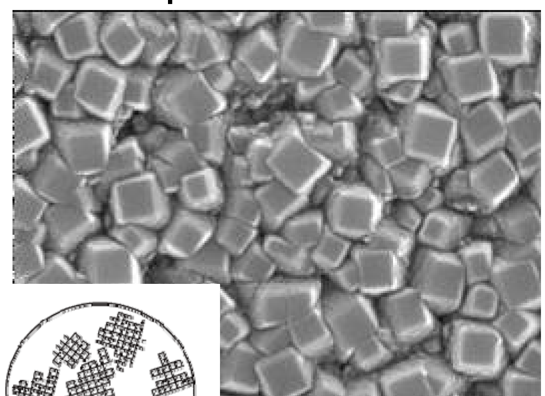
Microstructure

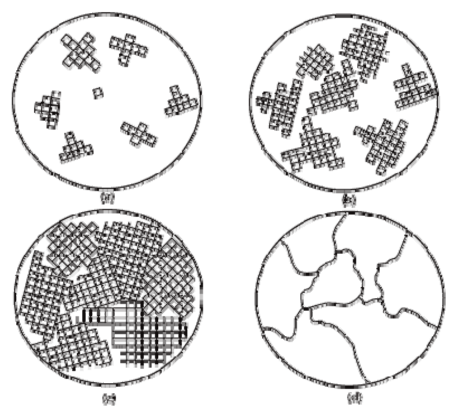
Single Crystal

- the periodic arrangement of atoms extends throughout the entire sample
- difficult to grow, environment must be tightly controlled
- anisotropic materials

Polycrystalline

- many small crystals or grains
- small crystals misoriented with respect to on another
- several crystals are initiated and grow towards each other
- anisotropic or isotropic materials





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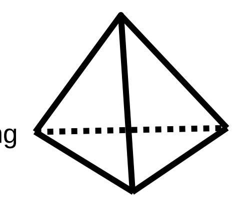
Levels of Structure

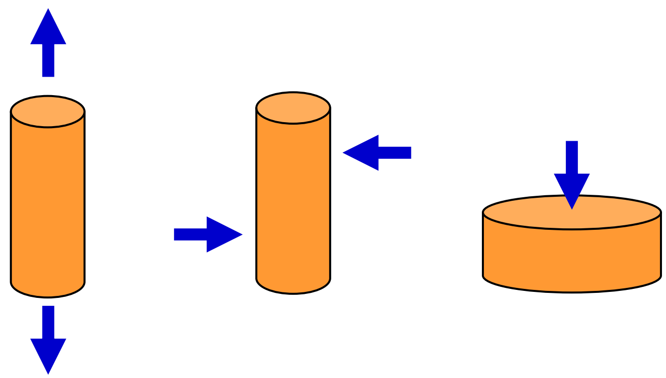


STRUCTURE (length scale)

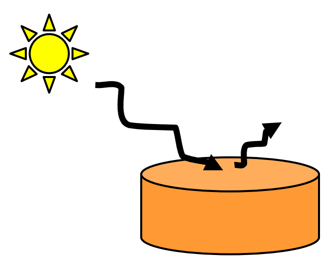
Sub-atomic	Atomic	Microscopic	Bulk
< 0.2 nm 1 nm = ?	0.2-10 nm	1-1000 μm	> 1 mm

Bulk Properties

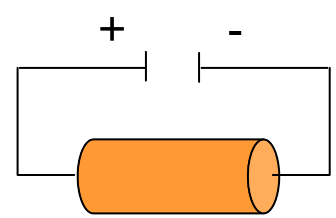
Mechanical:
elastic modulus
shear modulus
hardness



Optical:
reflectivity
absorbance
emission



Electrical:
conductivity
resistivity
capacitance

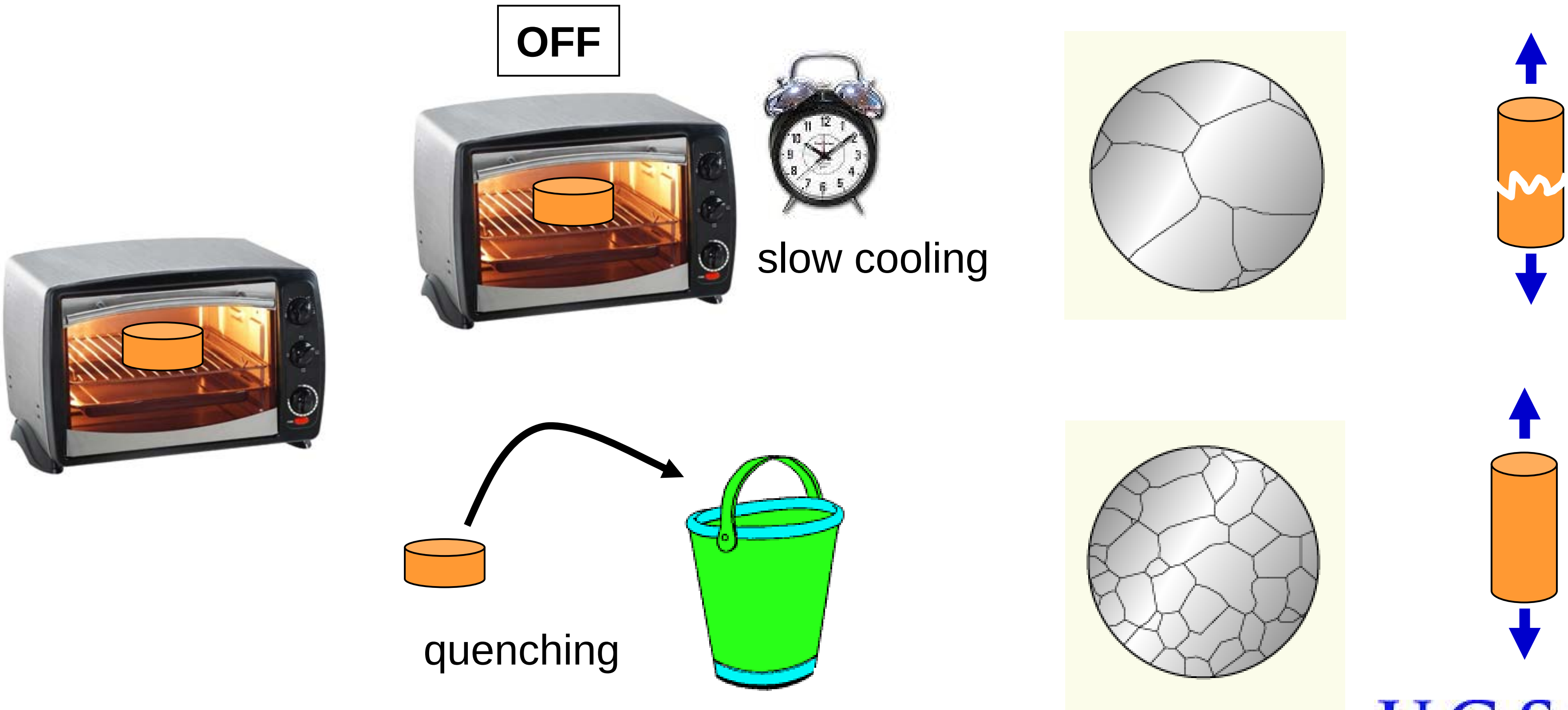


Thermal:
thermal expansion
heat capacity
thermal conductivity

Processing → Structure → Properties → Performance

Performance Goal: increased strength from a metallic material

In actuality, crystals are NOT perfect. There are **defects**!
In metals, **strength** is determined by how easily defects can move!



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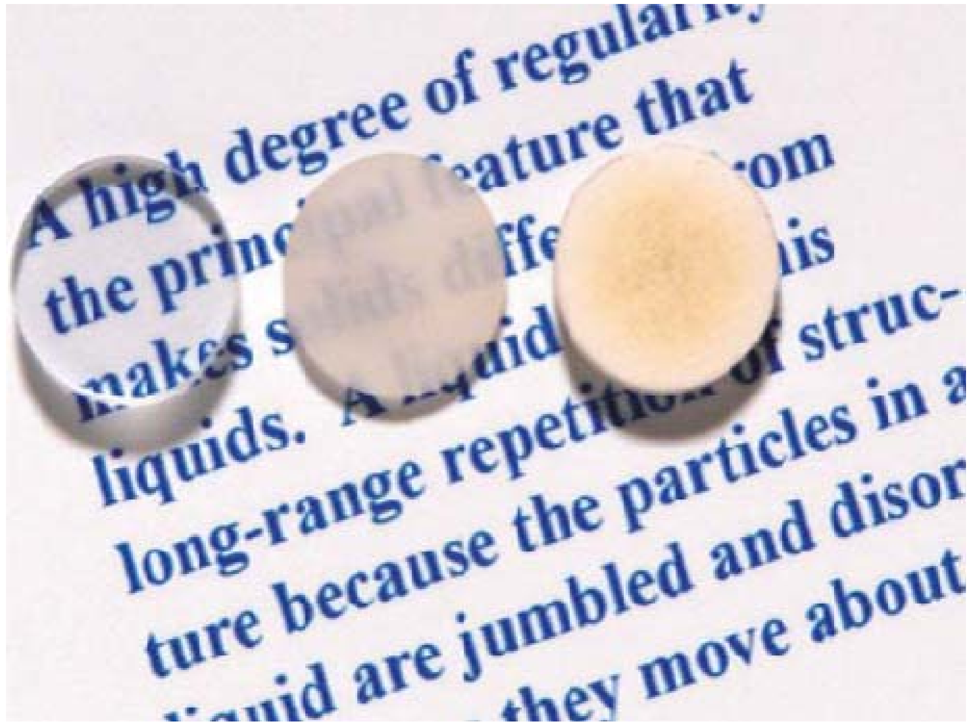
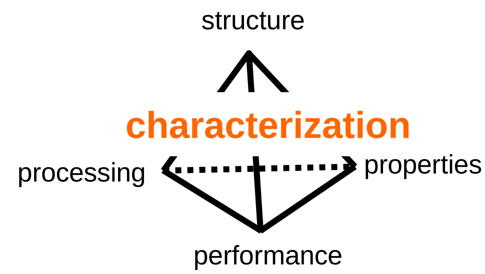
Processing → Structure → Properties → Performance

Aluminum Oxide (Al_2O_3)



single-crystal (transparent)	polycrystalline, fully dense (translucent)	polycrystalline, 5% porosity (opaque)

Characterization Techniques

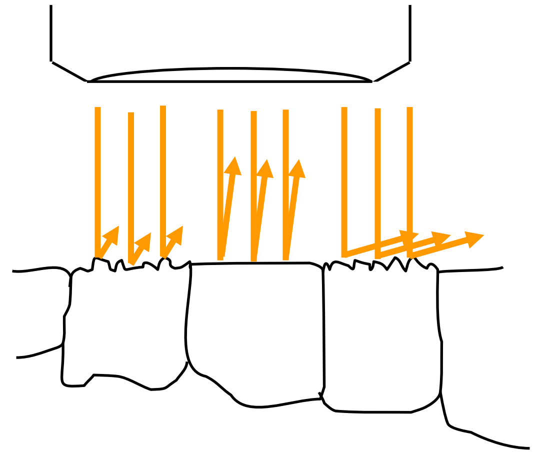


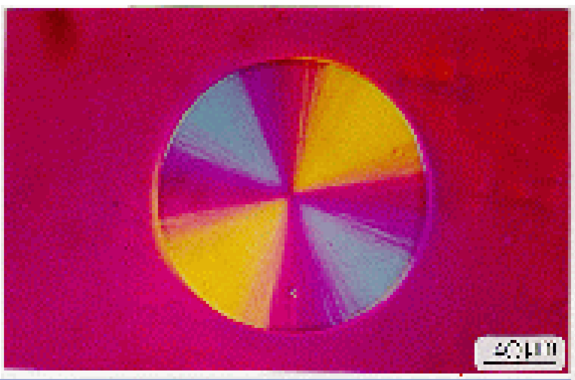
STRUCTURE (length scale)

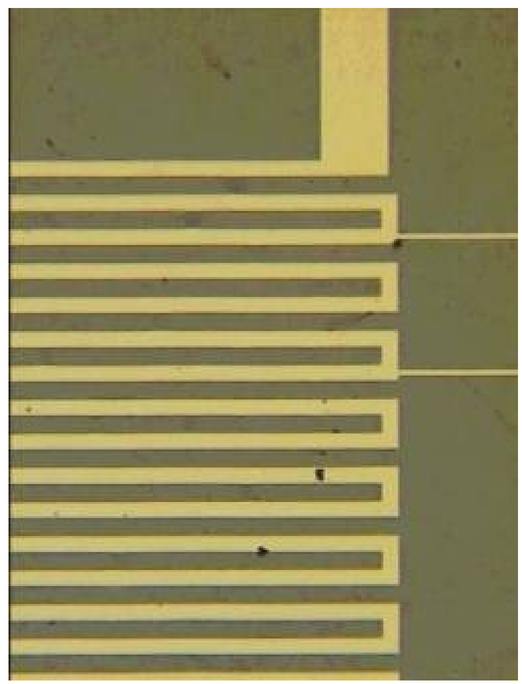
Sub-atomic	Atomic	Microscopic	Bulk
< 0.2 nm 1 nm = ?	0.2-10 nm	1-1000 μm	> 1 mm

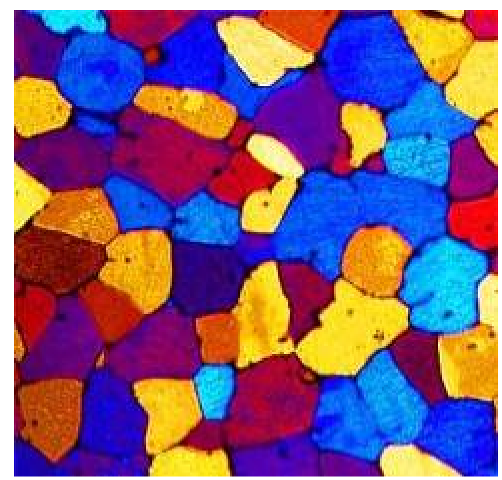
Optical Microscopy

- light is used to study the microstructure
- opaque materials use reflected light, where as transparent materials can use reflected or transmitted light









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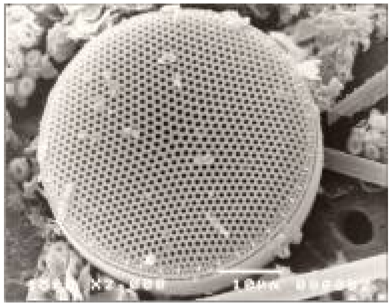
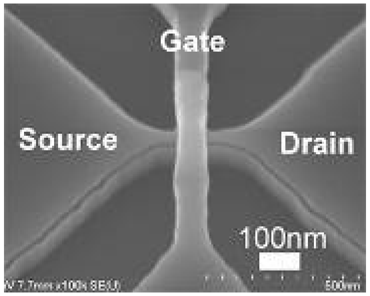
Electron Microscopy

- beams of electrons are used for imaging
- electrons are accelerated across large voltages
- a high velocity electron has a wavelength of about 0.003 nm
- the electron beam is focused and images are formed using magnetic lenses
- reflection and transmission imaging are both possible

<u>*Scanning Electron Microscopy (SEM)*</u>

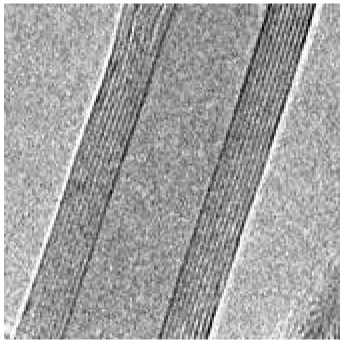
- an electron beam scans the surface and the reflected (backscattered) electrons are collected
- sample must be electrically conductive
- material surface is observed
- 200,000x magnification possible

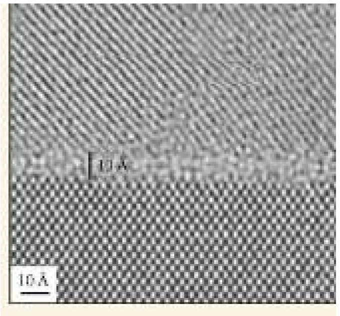




<u>*Transmission Electron Microscopy (TEM)*</u>

- an electron beam passes through the material
- thin samples
- details of internal microstructure observed
- 1,000,000x magnification possible

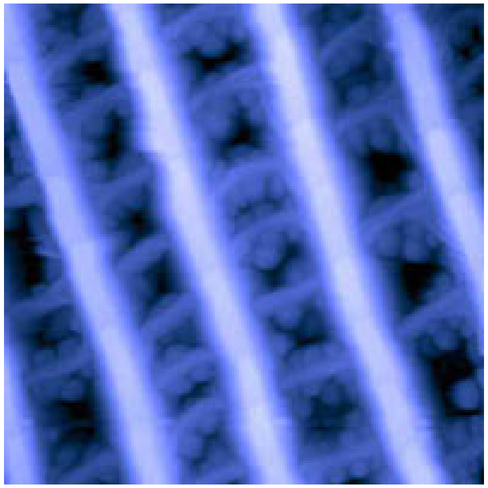




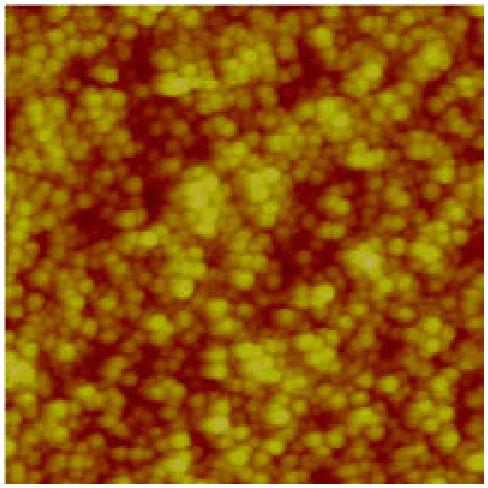
Scanning Probe Microscopy (SPM)

- 3D topographical map of material surface
- probe brought into close proximity of material surface
- probe rastered across the surface experiencing deflection in response to interactions with the material surface
- useful with many different types of materials

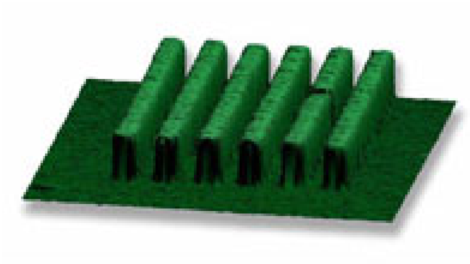
Animation of SPM on epitaxial silicon.



SPM image of a butterfly wing.



SPM image of silica coated gold nanoparticles.



SPM image of 70 nm photoresist lines.

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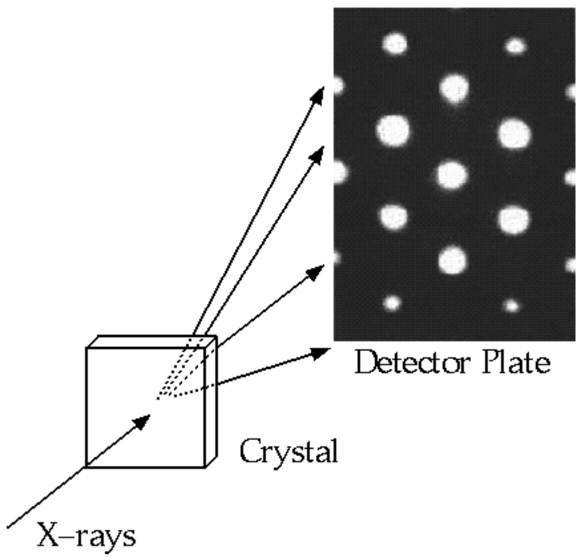
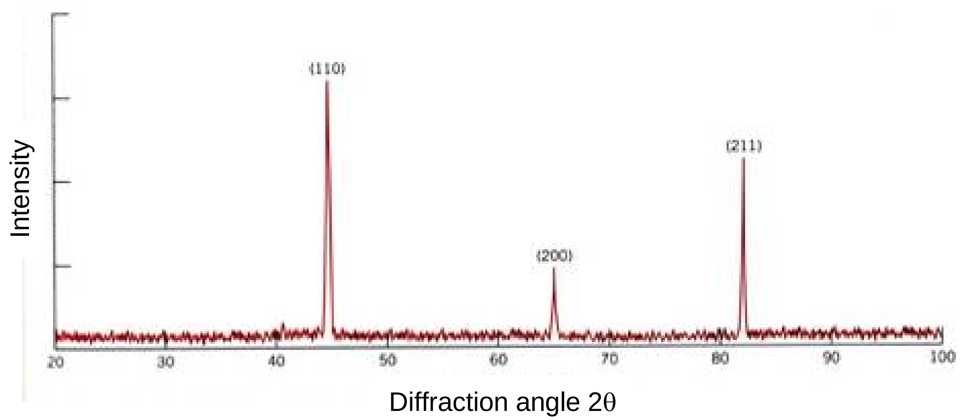
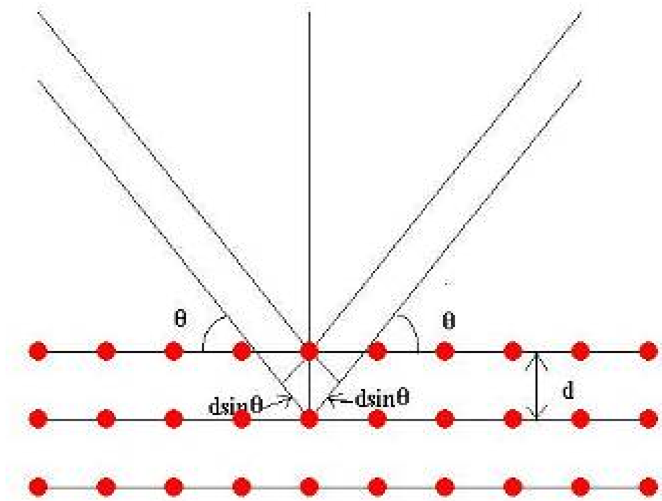
X-ray Diffraction



- x-rays are a form of light that has high energy and short wavelength
- when x-rays strike a material a portion of them are scattered in all directions
- if the atoms in the material is crystalline or well-ordered constructive interference can order



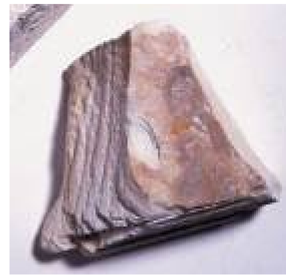
<u>Bragg's</u> Law: $2d \sin \theta = n\lambda$

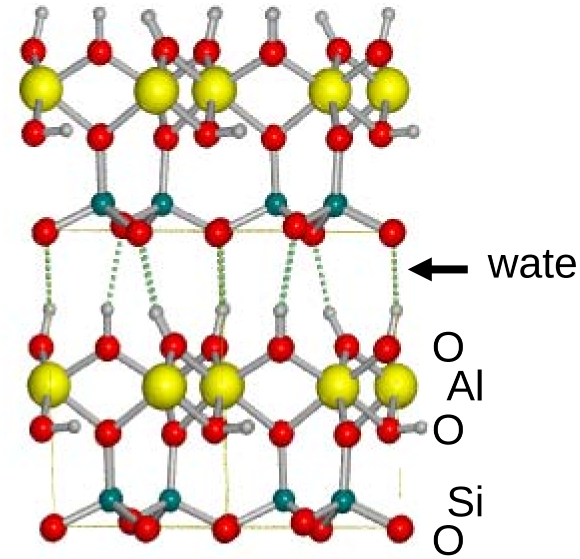


Case Studies

Clay

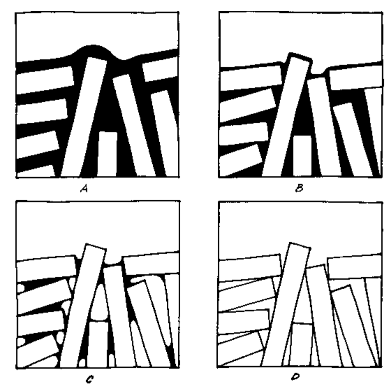
- aluminosilicate: combination of alumina (Al_2O_3) and silica (SiO_2) that bind water
- melting temperature of alumina > silica
- layered crystalline structure: kaolinite ($Al_2Si_2O_5(OH)_4$)
- water fits between layers
- “clay” has three main ingredients:
  (1) clay
  (2) quartz (cheap filler material)
  (3) flux (lowers melting temperature)





Forming:
- hydroplastic forming
- slipcasting

Drying:
- shrinkage
- material becomes brittle



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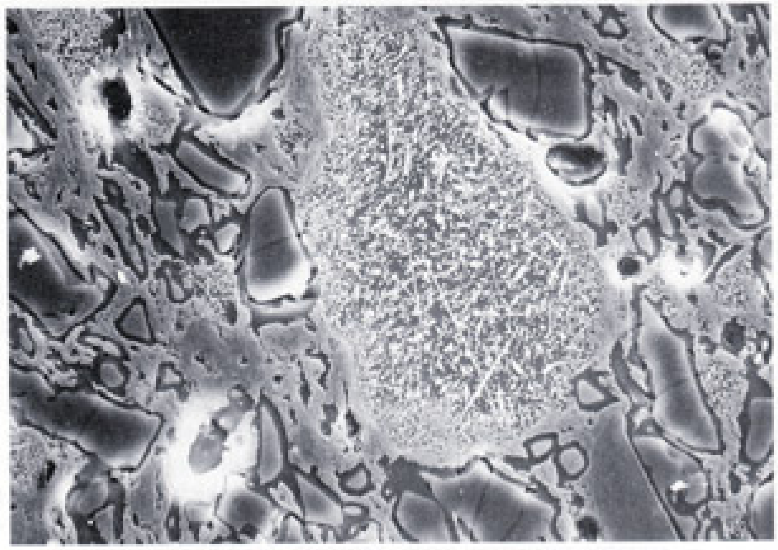
Clay (cont.)

Firing:

- firing temperature, 900-1400°C (1650-2550°F)
- permanent physical and chemical changes
- fuses or melts over large temperature range
- desired shaped is retained
- shrinkage due to removal of bound water

Sintering:

- bonds start to form between particles
- particles are fused into a very porous solid
- melting has not yet occured

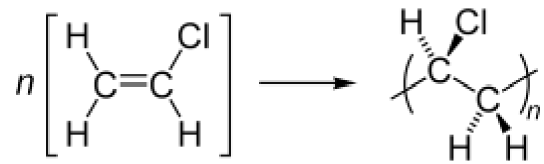


Vitrification:

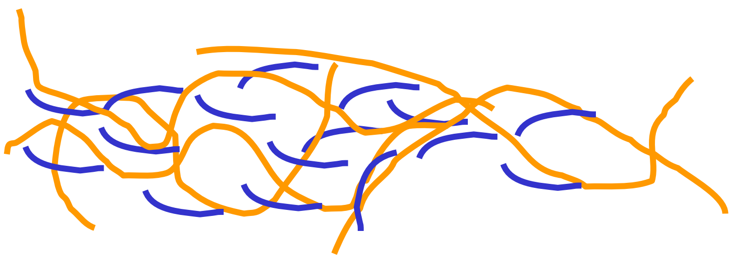
- flux lowers quartz melting temperature
- quartz particles begin to melt and pull silica out of clay matrix
- silicates form increasing the viscosity of the melt
- remaining “alumina rich” clay particles have higher melting temperature
- final structure: alumina rich particles in silicate glass matrix

Polymer Clay (Sculpey, FIMO)

- polyvinyl chloride (PVC)
- long chain or *high molecular weight* polymer
- thermoplastic: polymer that melts to a liquid when heated and freezes to a brittle, glassy state when cooled
- as-purchased a *plasticizer* is added to keep clay malleable
- heating the clay decomposes the plasticizer hardening the clay



without plasticizer: polymer clay is brittle at room temperature



with plasticizer: polymer clay is malleable at room temperature
- the plasticizer acts as a lubricant putting space between chains and allowing them to slide passed each other

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Metal Foil Embossing

- polycrystalline metal sheet
- relatively isotropic in-plane
- ductile material
- embossing process: plastic or non-recoverable, permanent deformation
- during embossing bonds are broken with original neighboring atoms and reformed with new neighbors
- *yield strength*: stress required to produce a very slight deformation
- metals a can generally only support 0.5% elongation before plastic deformation occurs
- materials choice important

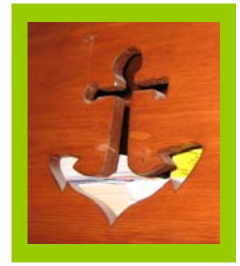
Metal Alloy	Yield Strength (MPa)
Aluminum	35
Copper	69
Iron	130
Steel	180
Titanium	450

Summary

metal

ceramic

polymer



wood

pastels