Aalto University
School of Engineering

COE-C2004 - Materials Science and Engineering

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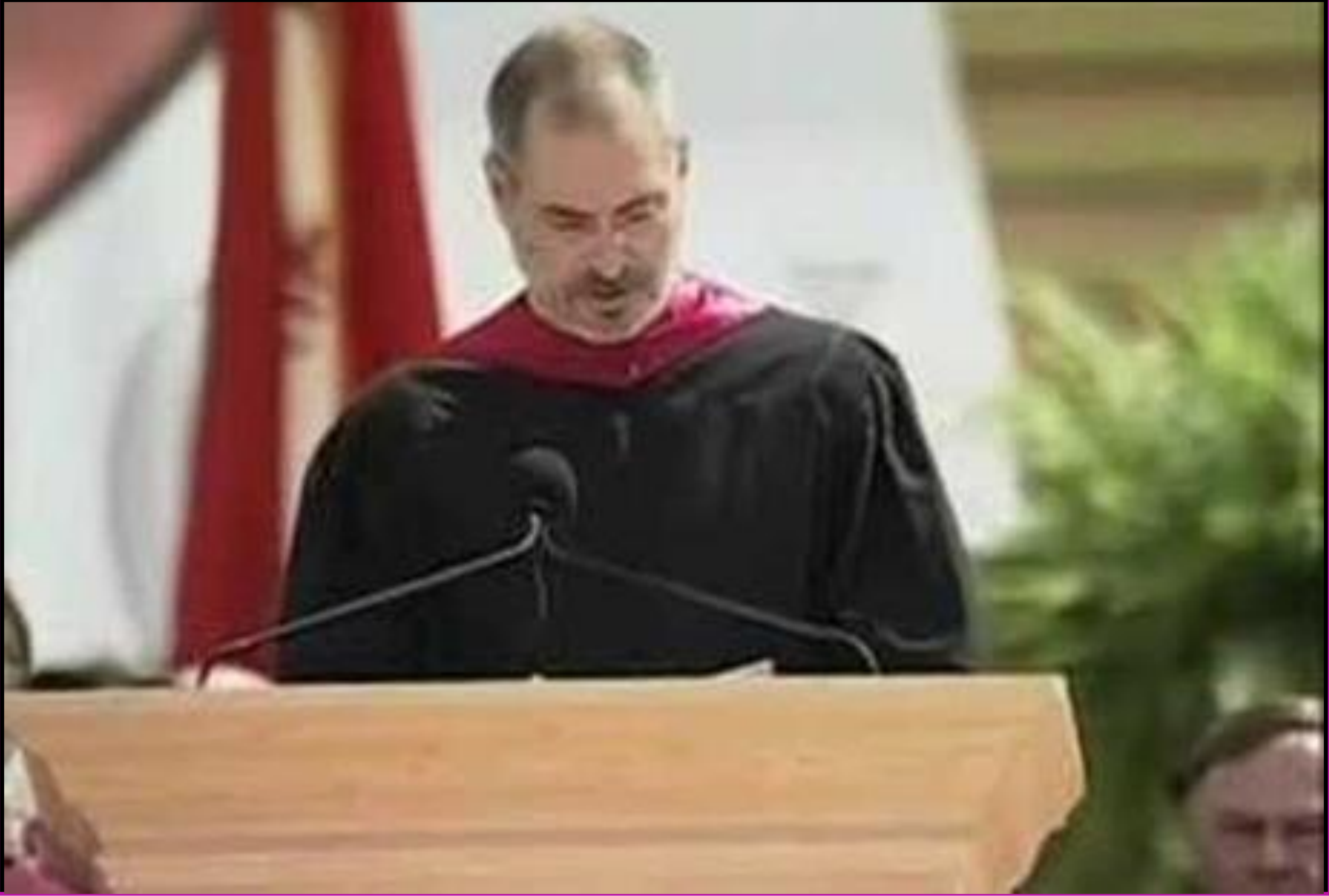
Connecting the Dots - Steve Jobs' 2005 Stanford Commencement Address (https://www.youtube.com/embed/UF8uR6Z6KLc)

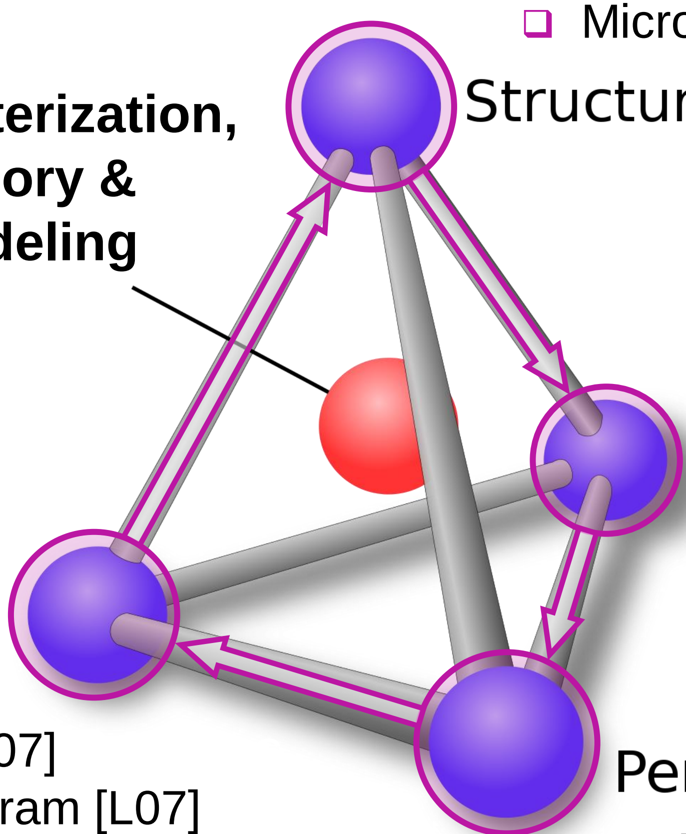


Lecture flow

- Atomic structure [L01 & L10]
- Crystal structure [L02 & L10]
- Microstructure (phases) [L07-09 & L10]

Structure

Characterization, Theory & Modeling



- Elasticity [L03]
- Plasticity [L03 & L04]
- Hardness [L03]
- Failure [L05 & 06]
- **Physical properties [L11]**

Properties

Process

- Diffusion [L07]
- Phase Diagram [L07]
- Phase Transformation [L08]
- Processes [L09]

Performance

- Elasticity and plasticity [L03 & L04]
- Failure [L05 & 06]

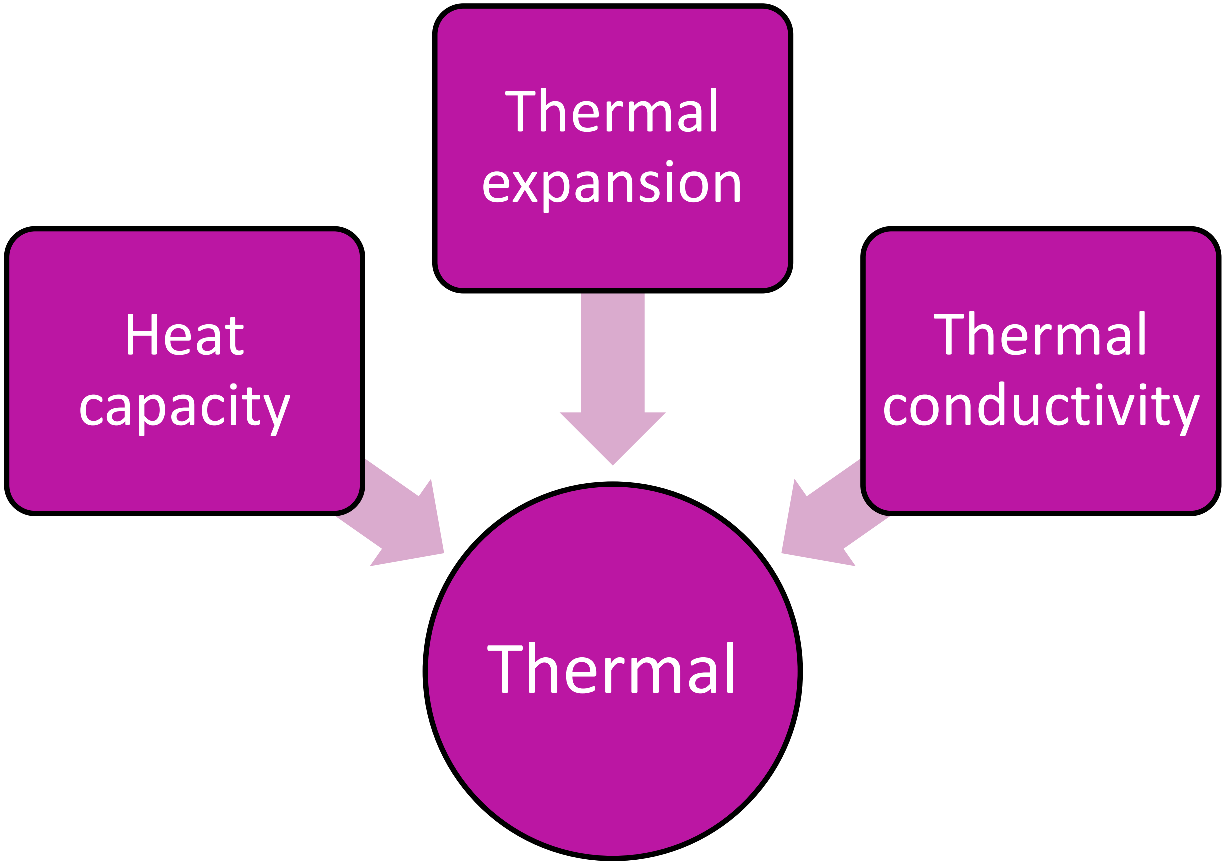
Thermal properties

Learning Objectives

After studying this chapter you should be able to do the following:

- Define heat capacity and specific heat capacity.
- Note the primary mechanism by which thermal energy is assimilated in solid materials.
- Determine the linear coefficient of thermal expansion given the length alteration that accompanies a specified temperature change.
- Briefly explain the phenomenon of thermal expansion from an atomic perspective using a potential-energy-versus-interatomic-separation plot.
- Define thermal conductivity.
- Note the two principal mechanisms of heat conduction in solids and compare the relative magnitudes of these contributions for each of metals, ceramics, and polymeric materials.

Thermal Properties



Heat Capacity

The ability of a material to absorb heat

- Quantitatively: The energy required to produce a unit rise in temperature for one mole of a material.

heat capacity (J/mol-K) → $C = \frac{dQ}{dT}$ ← energy input (J/mol); ← temperature change (K)

- Two ways to measure heat capacity:
  - C_p : Heat capacity at constant pressure.
  - C_v : Heat capacity at constant volume.

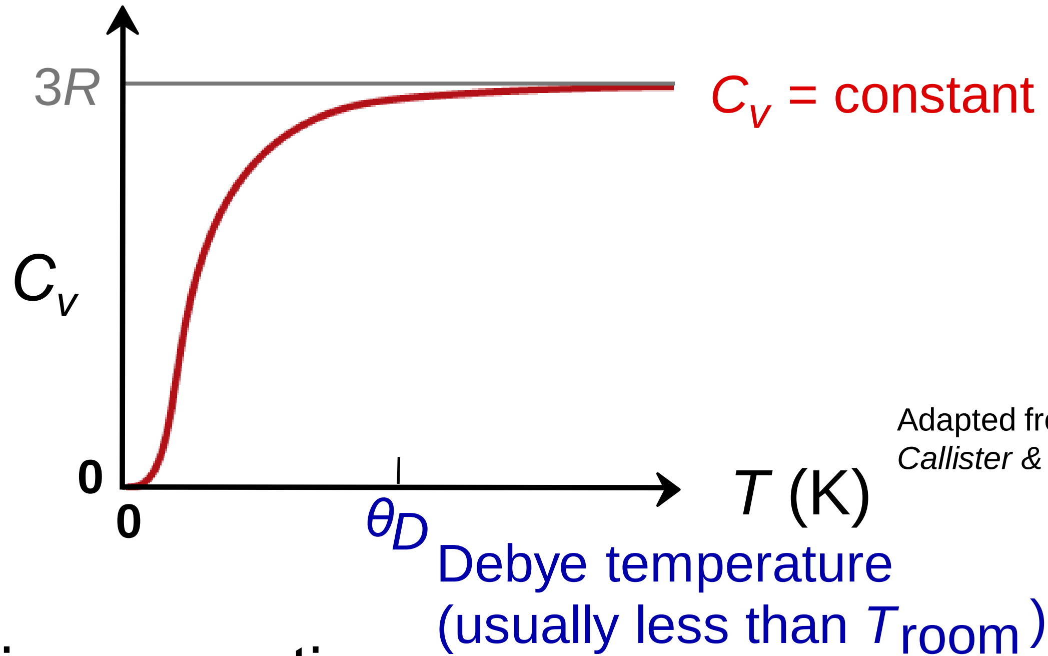
$$C_p \text{ usually} > C_v$$

- Heat capacity has units of $\frac{\mathrm{J}}{\mathrm{mol} \cdot \mathrm{K}} \left(\frac{\mathrm{Btu}}{\mathrm{lb\text{-}mol} \cdot {}^\circ\mathrm{F}} \right)$

Dependence of Heat Capacity on Temperature

- Heat capacity...
  -- increases with temperature
  -- for solids it reaches a limiting value of 3*R*

R = gas constant
= 8.31 J/mol-K



Adapted from Fig. 19.2, *Callister & Rethwisch 10e*.

- From atomic perspective:
  -- Energy is stored as atomic vibrations.
  -- As temperature increases, the average energy of atomic vibrations increases.

Atomic Vibrations

Atomic vibrations are in the form of lattice waves or phonons

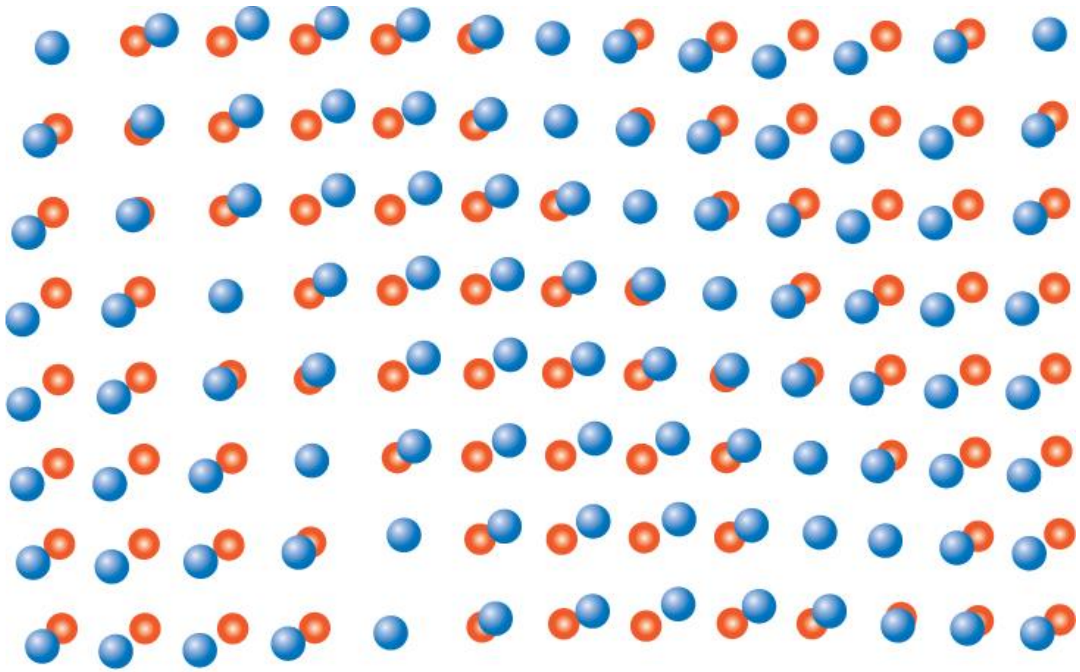
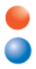
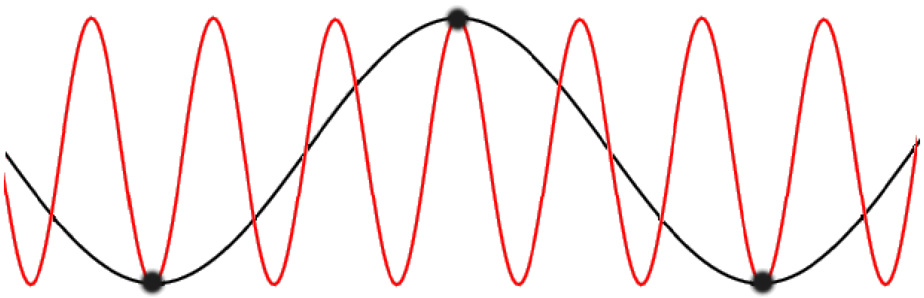


Fig. 19.1, *Callister & Rethwisch 10e*. (Adapted from "The Thermal Properties of Materials" by J. Ziman. Copyright © 1967 by Scientific American, Inc. All rights reserved.)





https://en.wikipedia.org/wiki/Phonon#:~:text=A%20phonon%20is%20the%20quantum,a%20normal%20mode%20of%20vibration.

Specific Heat: Comparison

Material	c_p (J/kg-K) at room T
• **Polymers**	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
• **Ceramics**	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
• **Metals**	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

increasing c_p

c_p (specific heat): (J/kg-K)

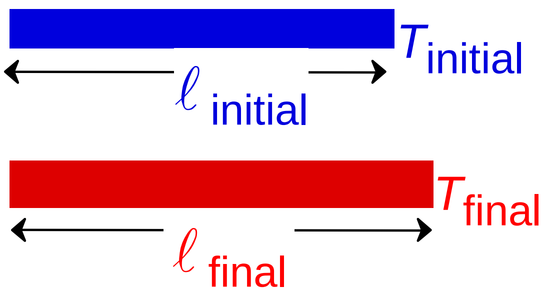
C_p (heat capacity): (J/mol-K)

- Why is c_p significantly larger for polymers?

Selected values from Table 19.1, *Callister & Rethwisch 10e*.

Thermal Expansion

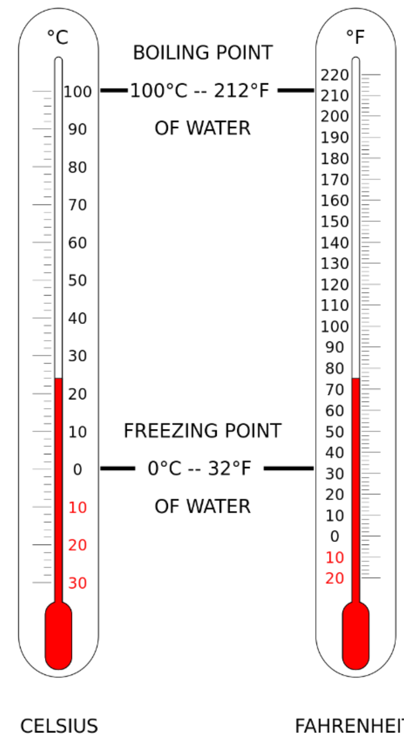
Materials change size when temperature is changed



$T_{final} > T_{initial}$

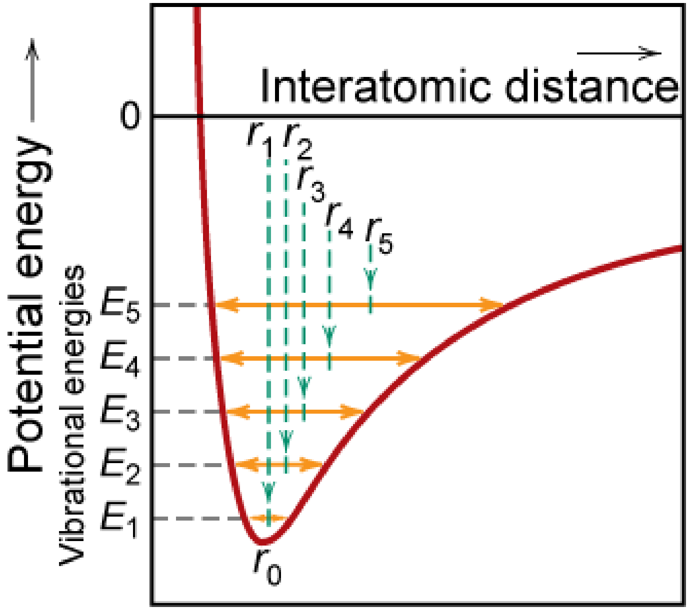
$$\frac{\ell_{final} - \ell_{initial}}{\ell_{initial}} = \alpha_\ell (T_{final} - T_{initial})$$

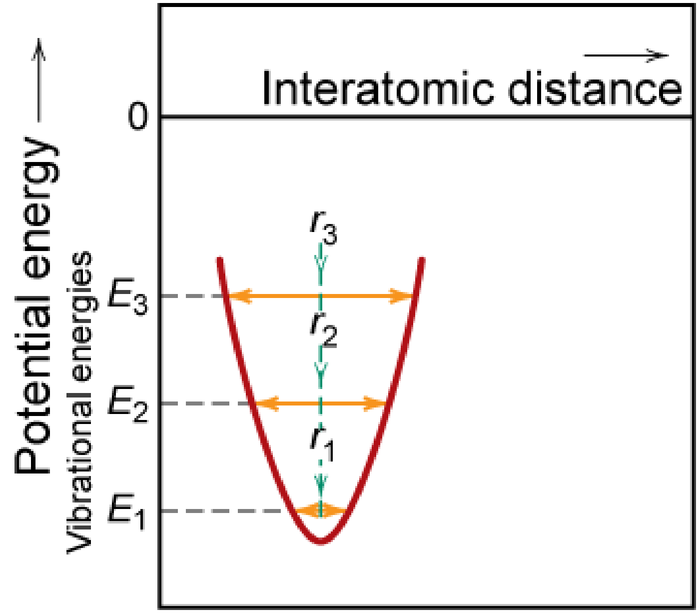
linear coefficient of thermal expansion (1/K or 1/°C)



https://en.wikipedia.org/wiki/Temperature

Atomic Perspective: Thermal Expansion





Asymmetric curve:
- -- increase temperature,
- -- increase in interatomic separation
- -- thermal expansion

Symmetric curve:
- -- increase temperature,
- -- no increase in interatomic separation
- -- no thermal expansion

Fig. 19.3, *Callister & Rethwisch 10e*. (Adapted from R. M. Rose, L. A. Shepard, and J. Wulff, The Structure and Properties of Materials, Vol. IV, Electronic Properties, John Wiley & Sons, 1966. Reproduced with permission of Robert M. Rose.)

Coefficient of Thermal Expansion: Comparison

increasing α_ℓ

Material	α_ℓ (10^{-6}/° C) at room *T*
• **Polymers**	
Polypropylene	145-180
Polyethylene	106-198
Polystyrene	90-150
Teflon	126-216
• **Metals**	
Aluminum	23.6
Steel	12
Tungsten	4.5
Gold	14.2
• **Ceramics**	
Magnesia (MgO)	13.5
Alumina (Al_2O_3)	7.6
Soda-lime glass	9
Silica (cryst. SiO_2)	0.4

Polymers have larger α_ℓ values because of weak secondary bonds

- **Q: Why does α_ℓ generally decrease with increasing bond energy?**

Selected values from Table 19.1, *Callister & Rethwisch 10e*.

Thermal Expansion: Example

Ex: A copper wire 15 m long is cooled from 40 to -9° C. How much change in length will it experience?

- Answer: For Cu $\alpha_\ell = 16.5 \times 10^{-6}\ (°C)^{-1}$

rearranging Equation

$$\Delta\ell = \alpha_\ell \ell_0 \Delta T = [16.5 \times 10^{-6} (1/°C)](15\ m)\ [40°C - (-9°C)]$$

$$\boxed{\Delta\ell = 0.012\ m = 12\ mm}$$

Thermal Stresses

- Occur due to:

  -- restrained thermal expansion/contraction

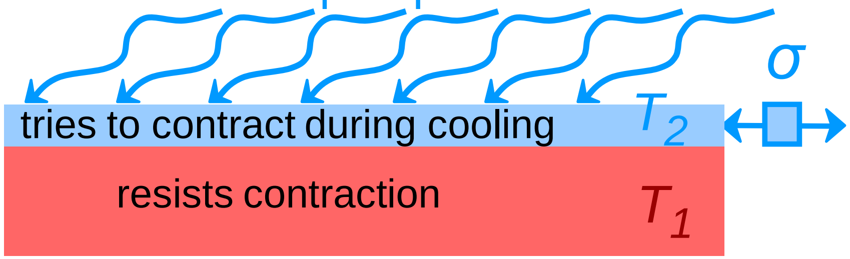
  -- temperature gradients that lead to differential dimensional changes

$$\text{Thermal stress} = s$$

$$= Ea_{\ell}(T_0 - T_f) = Ea_{\ell}\mathrm{D}T$$

Thermal Shock Resistance

- Occurs due to: nonuniform heating/cooling
- Ex: Assume top thin layer is rapidly cooled from T_1 to T_2



Tension develops at surface

$$s = -Ea_\ell(T_1 - T_2)$$

Temperature difference that can be produced by cooling:

$$(T_1 - T_2) = \frac{\text{quench rate}}{k}$$

Critical temperature difference for fracture (set $\sigma = \sigma_f$)

$$(T_1 - T_2)_{\text{fracture}} = \frac{s_f}{Ea_\ell}$$

set equal

- $(\text{quench rate})_{\text{for fracture}} = \text{Thermal Shock Resistance } (TSR) \mu \dfrac{s_f k}{Ea_\ell}$
- Large TSR when $\dfrac{s_f k}{Ea_\ell}$ is large

Thermal Conductivity

The ability of a material to transport heat.

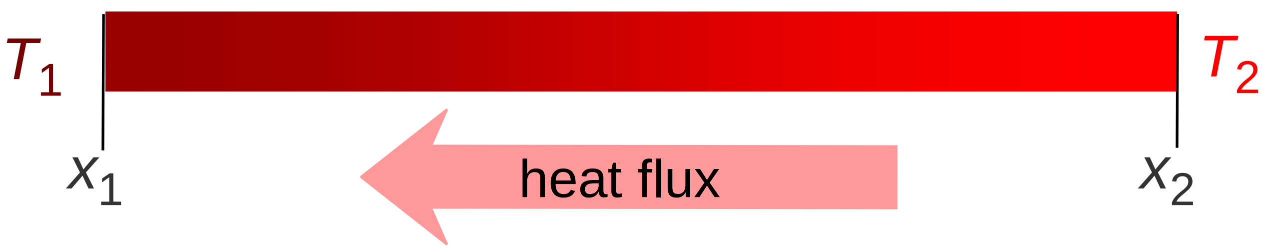
Fourier's Law

$$q = -k \frac{dT}{dx}$$

heat flux (J/m^2•s)

thermal conductivity (J/m•K•s)

temperature gradient



$T_2 > T_1$

- Atomic perspective: Atomic vibrations and free electrons in hotter regions transport energy to cooler regions.

Thermal Conductivity: Comparison

increasing k

Material	k (W/m-K)	Energy Transfer Mechanism
• Metals		
Aluminum	247	atomic vibrations and motion of free electrons
Steel	52	
Tungsten	178	
Gold	315	
• Ceramics		
Magnesia (MgO)	38	atomic vibrations
Alumina (Al_2O_3)	39	
Soda-lime glass	1.7	
Silica (cryst. SiO_2)	1.4	
• Polymers		
Polypropylene	0.12	vibration/rotation of chain molecules
Polyethylene	0.46-0.50	
Polystyrene	0.13	
Teflon	0.25	

Selected values from Table 19.1, *Callister & Rethwisch 10e*.

Summary

The thermal properties of materials include:

- **Heat capacity:**
  -- energy required to increase a mole of material by a unit *T*
  -- energy is stored as atomic vibrations
- **Thermal expansion:**
  -- the size of a material changes with a change in temperature
  -- polymers have the largest values
- **Thermal conductivity:**
  -- the ability of a material to transport heat
  -- metals have the largest values
- **Thermal shock resistance:**
  -- the ability of a material to be rapidly cooled and not fracture

  -- is proportional to $\dfrac{s_f k}{E a_\ell}$

Electrical properties

Learning Objectives

After studying this chapter you should be able to do the following:

- Describe the Ohm's Law.
- Define electrical Resistivity and Conductivity.
- Calculate the sample resistance based on the material property and geometrical properties.
- Compare the electrical conductivities of various materials, such as metals, ceramics, polymers.

Electrical Conduction

- Ohm's Law: $V = I\,R$

voltage drop (volts = J/C)
C = Coulomb

current (amps = C/s)

resistance (Ohms)

- Resistivity, ρ:
  -- a material property that is independent of sample size and geometry

$$\rho = \frac{RA}{\ell}$$

cross-sectional area of current flow

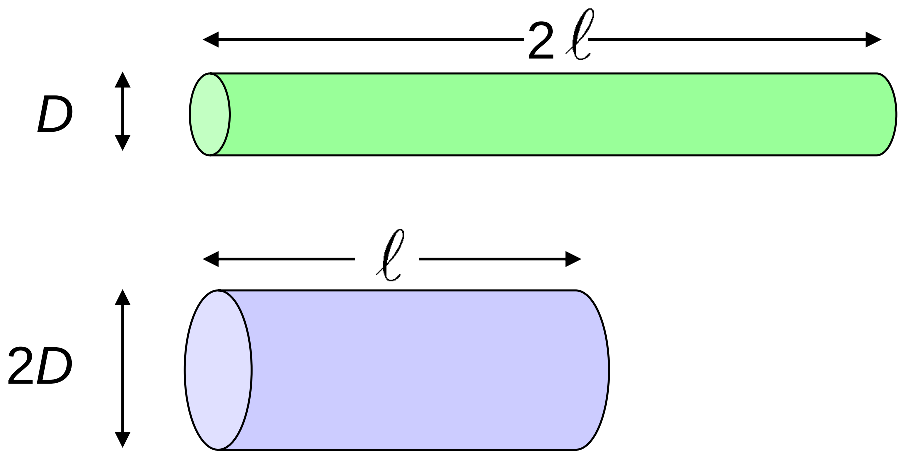
current flow path length

- Conductivity, σ

$$\sigma = \frac{1}{\rho}$$

Electrical Properties

- Which will have the greater resistance?



$$R_1 = \frac{2r\ell}{p\left(\frac{D}{2}\right)^2} = \boxed{\frac{8r\ell}{pD^2}}$$

$$R_2 = \frac{\rho\ell}{\pi\left(\frac{2D}{2}\right)^2} = \boxed{\frac{\rho\ell}{\pi D^2}} = \frac{R_1}{8}$$

- Analogous to flow of water in a pipe
- Resistance depends on sample geometry and size.

Definitions

Further definitions

$\boxed{J = \sigma \mathcal{E}}$ <= another way to state Ohm's law

$J \equiv$ current density $= \dfrac{\text{current}}{\text{surface area}} = \dfrac{I}{A}$ like a flux

$\mathcal{E} \equiv$ electric field potential $= V/\ell$

$$J = \sigma (V/\ell)$$

Electron flux conductivity voltage gradient

Conductivity: Comparison

- Room temperature values $(\text{Ohm-m})^{-1} = (\Omega - \text{m})^{-1}$

METALS	conductors	CERAMICS	
Silver	6.8×10^{7}	Soda-lime glass	10^{-10}-10^{-11}
Copper	6.0×10^{7}	Concrete	10^{-9}
Iron	1.0×10^{7}	Aluminum oxide	$<10^{-13}$

SEMICONDUCTORS		POLYMERS	
Silicon	4×10^{-4}	Polystyrene	$<10^{-14}$
Germanium	2×10^{0}	Polyethylene	10^{-15}-10^{-17}
GaAs	10^{-6}		
	semiconductors		insulators

Selected values from Tables 18.1, 18.3, and 18.4, *Callister & Rethwisch 10e.*

Summary

- Electrical *conductivity* and *resistivity* are:

  -- material parameters

  -- geometry independent

- Conductors, semiconductors, and insulators...

  -- differ in range of conductivity values

  -- differ in availability of electron excitation states

Overall Picture

Total Materials Cycle

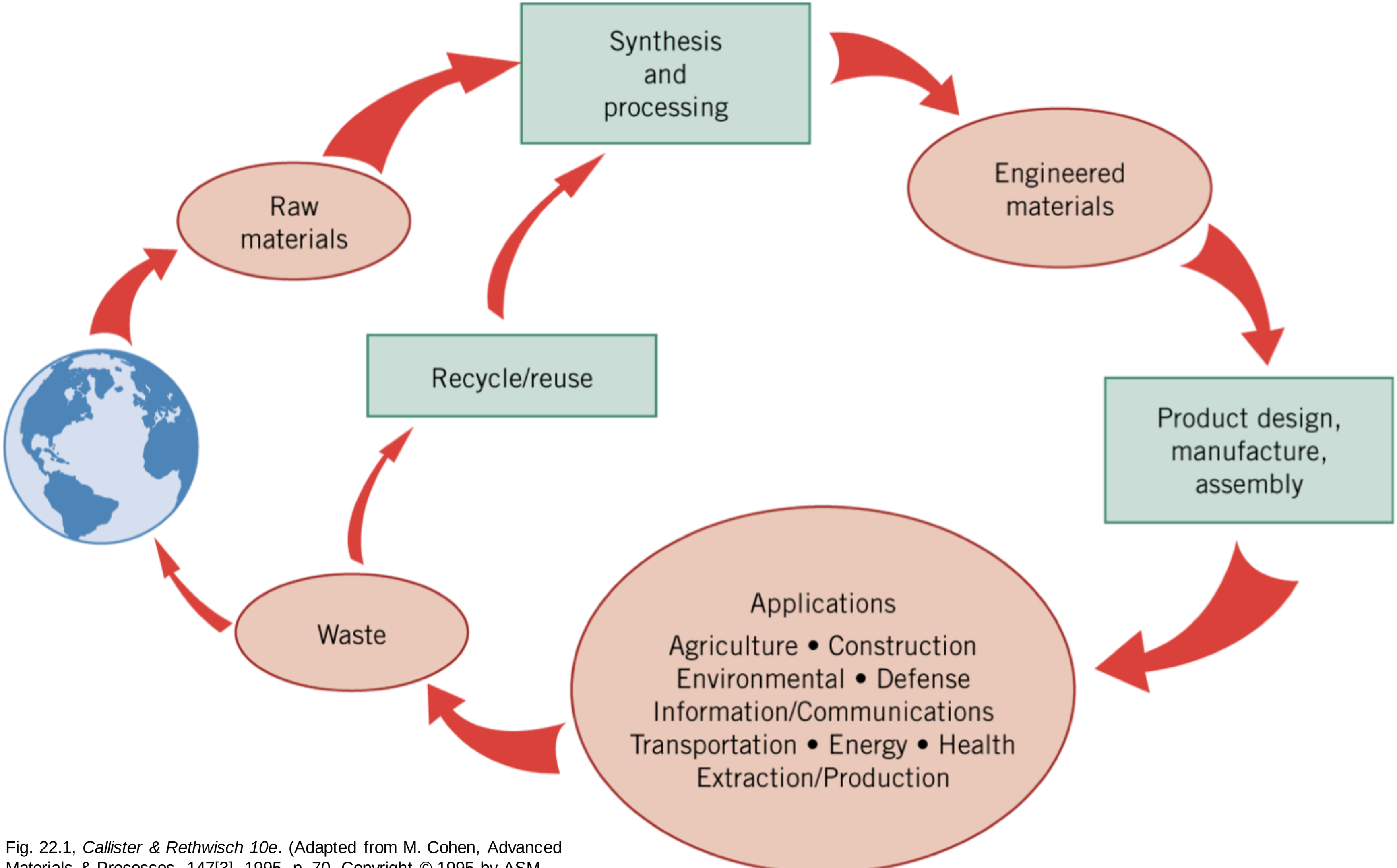


Fig. 22.1, *Callister & Rethwisch 10e*. (Adapted from M. Cohen, Advanced Materials & Processes, 147[3], 1995, p. 70. Copyright © 1995 by ASM International. Reprinted by permission of ASM International, Materials Park, OH.)

Components Of "Green Design"

Christopher Steer/iStockphoto

- **Reduce** – redesign the product to use less material
  example: PET bottles with thinner walls

- **Reuse** – fabricate the product of a material that can reused
  example: refillable bottles and shipping containers

- **Recycle** – reprocess the material into a new product
  example: convert PET bottles to carpet fibers

Recycling Materials

- Proper product design facilitates recycling

- Advantages to recycling
  - reduced pollution emissions
  - reduced landfill deposits

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- Recycling Issues
  - Product must be disassembled or shredded to recover materials
  - Collection and transportation costs are significant factors in recycling economics

Recycling of Metals

- Aluminum is the most commonly recycled metal
- Compared to refining raw ore, reprocessing metals
  - is more energy efficient
  - produces less waste (pollution)
- Difficult to recycle metals that are susceptible to Corrosion
- Toxic metals (e.g., Cd and Hg):
  - must be handled as hazardous waste
  - are difficult to reprocess
  - should not be added to landfills

Lya Cattel/iStockphoto

Recycling of Glass

- Glasses are the most common commercial ceramics
- Little economic incentive to recycle glass
  - – raw materials inexpensive
  - – relatively dense - expensive to transport
  - – must be sorted by
    - color – clear, amber, green, brown
    - type – plate vs. container
    - composition – soda-lime, leaded, borosilicate

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Announcements

In-depth reading (**Ch. 19**) and further reading (Ch. 18, 20, 21)

Assignment: Open; DL: **18:00 Sunday, 12.12.2021 (No late submission)**

Solution to Assignment: Open on **Sunday, 12.12.2021**

Case studies: Open; DL: **18:00 Sunday, 19.12.2021**

Final exercise: **10:15 – 12:00 Thursday**

Exam: **09:00 – 13:00 Tuesday, 14.12.2021**
Online MyCourses
Two parts: written (70%) and oral (30%) exam
More details will be given on Thursday's exercise

Questions?