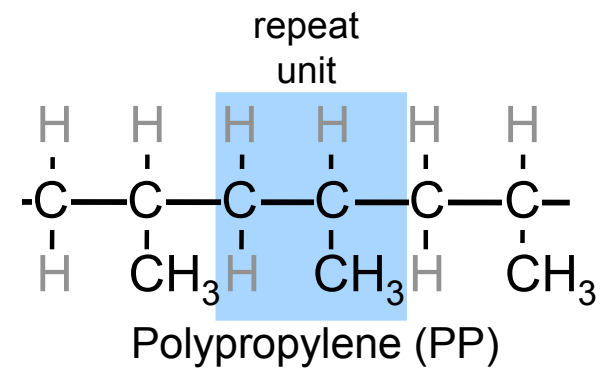
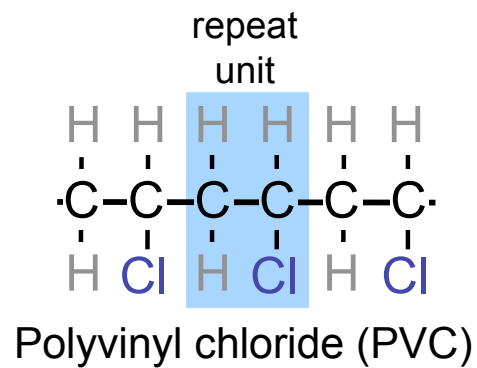
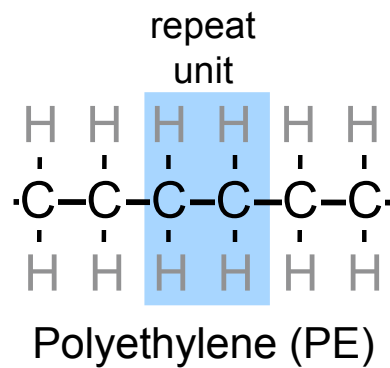


Polymers



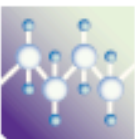
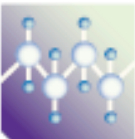
Poly **mer**
many repeat unit



Adapted from Fig. 14.2, *Callister 7e*.

Bulk or commodity polymers

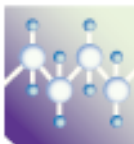
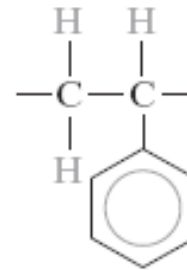
Table 14.3 A Listing of Repeat Units for 10 of the More Common Polymeric Materials

<i>Polymer</i>	<i>Repeat Unit</i>
 Polyethylene (PE)	$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{H} \end{array}$
 Poly(vinyl chloride) (PVC)	$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{Cl} \end{array}$
 Polytetrafluoroethylene (PTFE)	$\begin{array}{c} \text{F} \quad \text{F} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{F} \quad \text{F} \end{array}$
 Polypropylene (PP)	$\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ -\text{C}-\text{C}- \\ \quad \\ \text{H} \quad \text{CH}_3 \end{array}$

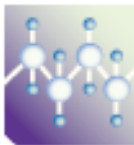
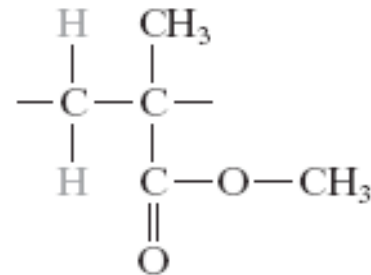
Bulk or commodity polymers



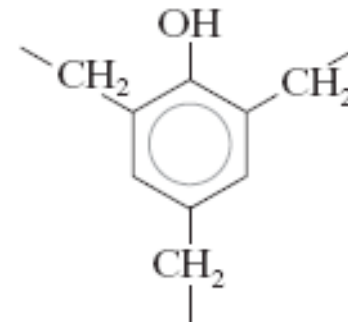
Polystyrene (PS)



Poly(methyl methacrylate) (PMMA)

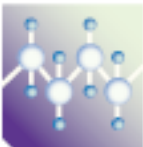
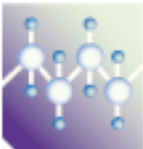
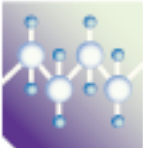


Phenol-formaldehyde (Bakelite)



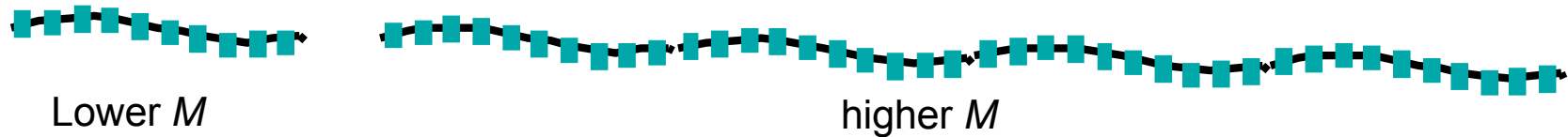
Bulk or commodity polymers

Table 14.3 A Listing of Repeat Units for 10 of the More Common Polymeric Materials

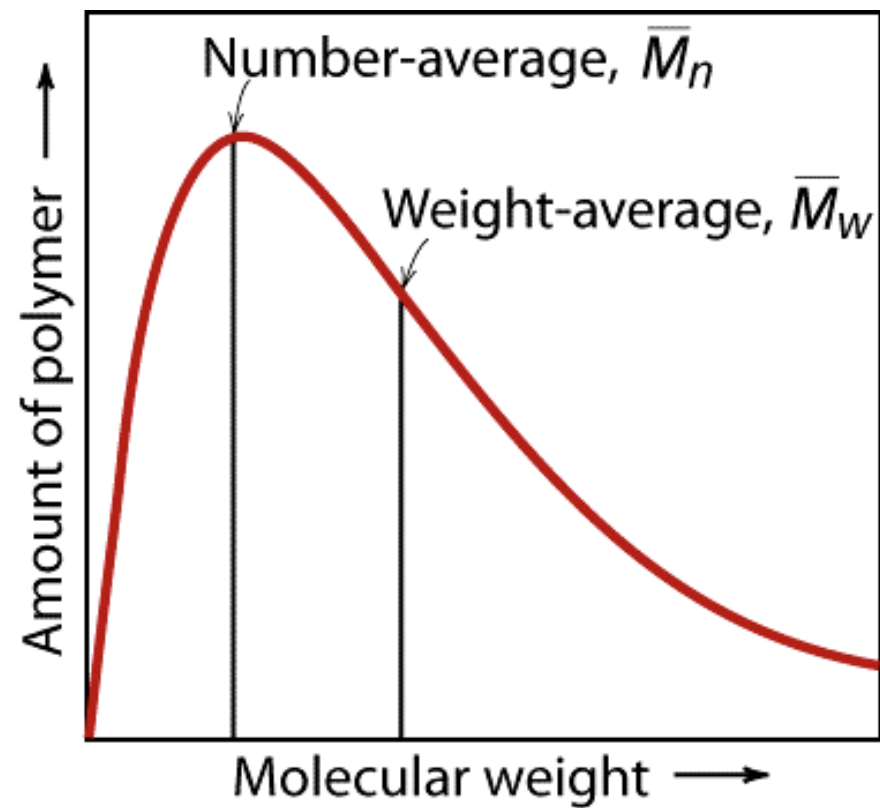
<i>Polymer</i>	<i>Repeat Unit</i>
 Poly(hexamethylene adipamide) (nylon 6,6)	$\text{---N---}\left[\begin{array}{c} \text{H} \\ \\ \text{---C---} \\ \\ \text{H} \end{array}\right]_6\text{---N---}\overset{\text{O}}{\parallel}\text{C---}\left[\begin{array}{c} \text{H} \\ \\ \text{---C---} \\ \\ \text{H} \end{array}\right]_4\text{---}\overset{\text{O}}{\parallel}\text{C---}$
 Poly(ethylene terephthalate) (PET, a polyester)	$\text{---}\overset{\text{O}}{\parallel}\text{C---}\overset{b}{\text{C}_6\text{H}_4}\text{---}\overset{\text{O}}{\parallel}\text{C---O---}\begin{array}{cc} \text{H} & \text{H} \\ & \\ \text{---C} & \text{---C---} \\ & \\ \text{H} & \text{H} \end{array}\text{---O---}$
 Polycarbonate (PC)	$\text{---O---}\overset{b}{\text{C}_6\text{H}_4}\text{---}\overset{\text{CH}_3}{\underset{\text{CH}_3}{\text{C}}}\text{---}\text{C}_6\text{H}_4\text{---O---}\overset{\text{O}}{\parallel}\text{C---}$

Molecular weight

- **Molecular weight**, M_i : Mass of a mole of chains.



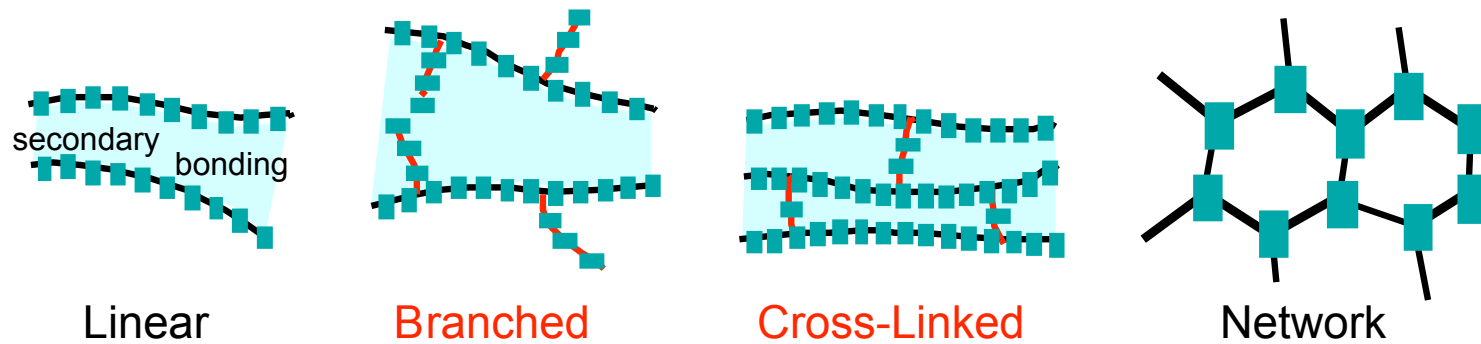
\bar{M}_w is more sensitive to higher molecular weights



Adapted from Fig. 14.4, *Callister 7e*.

Molecular structures

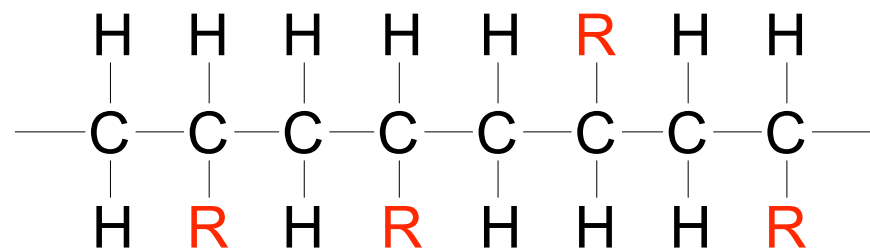
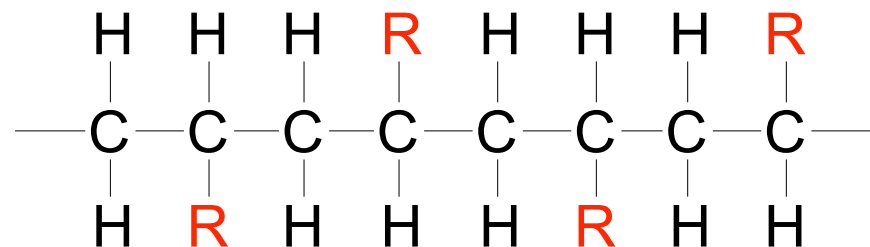
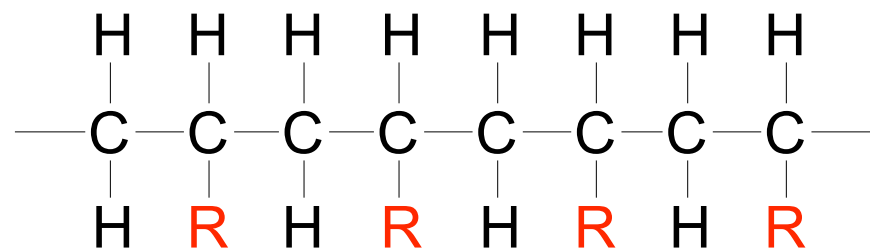
- Covalent **chain** configurations and strength:



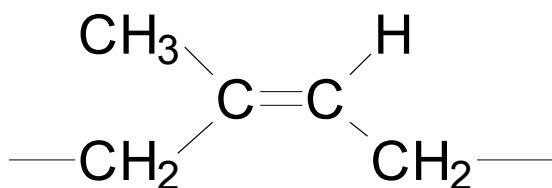
Adapted from Fig. 14.7, *Callister 7e*.

Tacticity

Tacticity – stereoregularity of chain



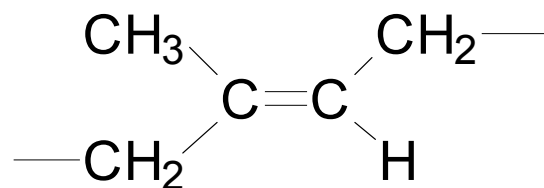
Cis and trans isomerism



cis

cis-isoprene
(natural rubber)

bulky groups on same side of
chain



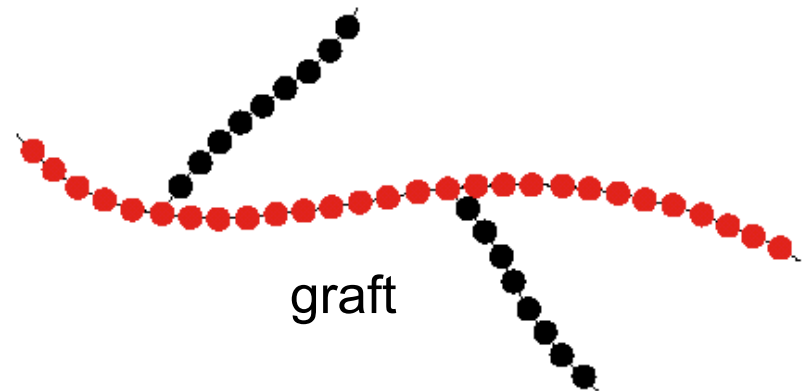
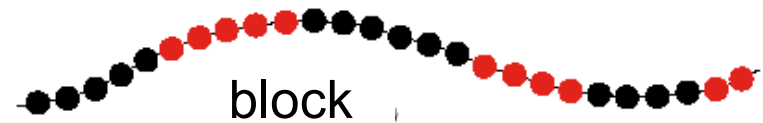
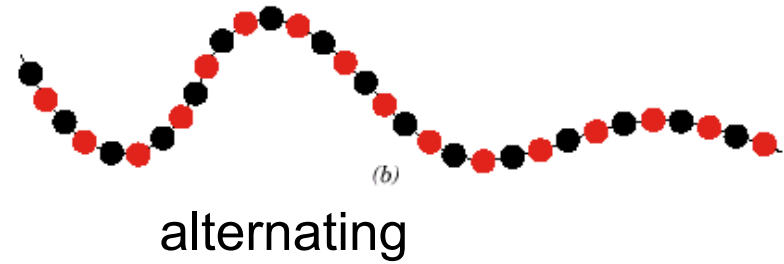
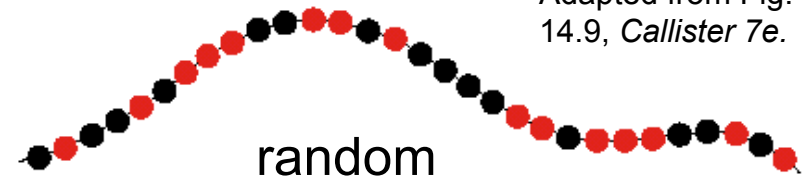
trans

trans-isoprene
(gutta percha)

bulky groups on opposite sides
of chain

Copolymers

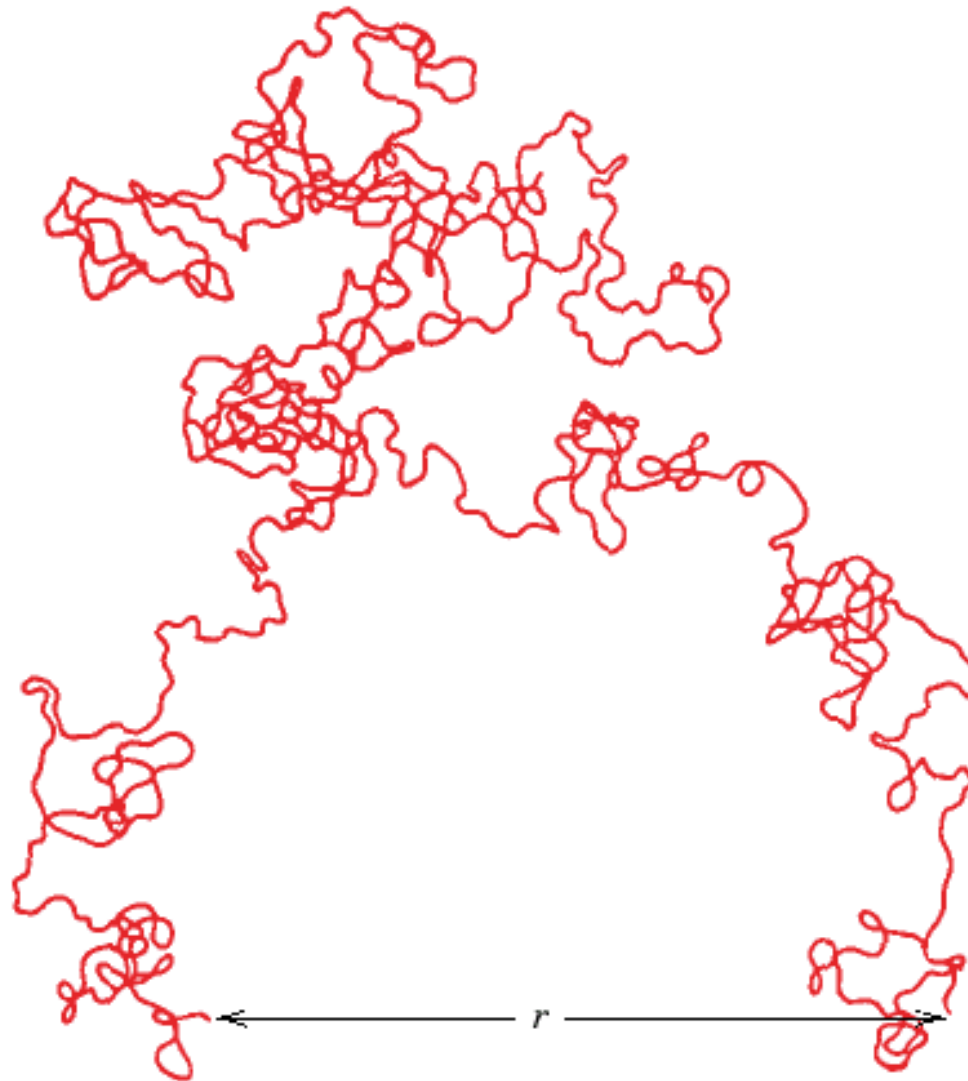
Adapted from Fig.
14.9, *Callister 7e*.



A – ●

B – ●

End to end distance



Adapted from Fig.
14.6, *Callister 7e*.

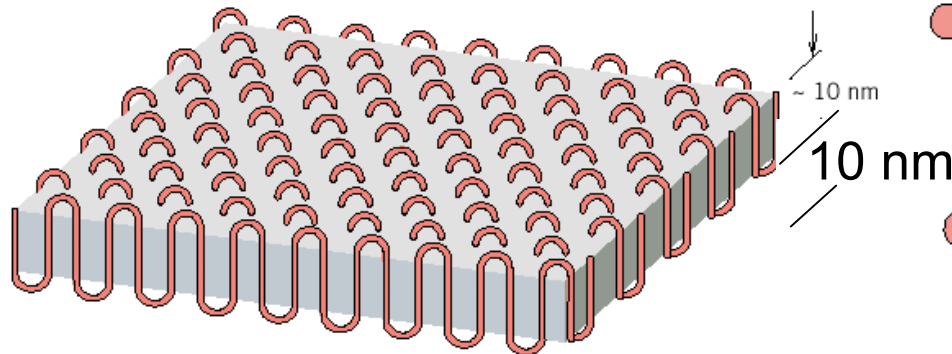
Polymer crystalline structure

Ex: polyethylene unit cell

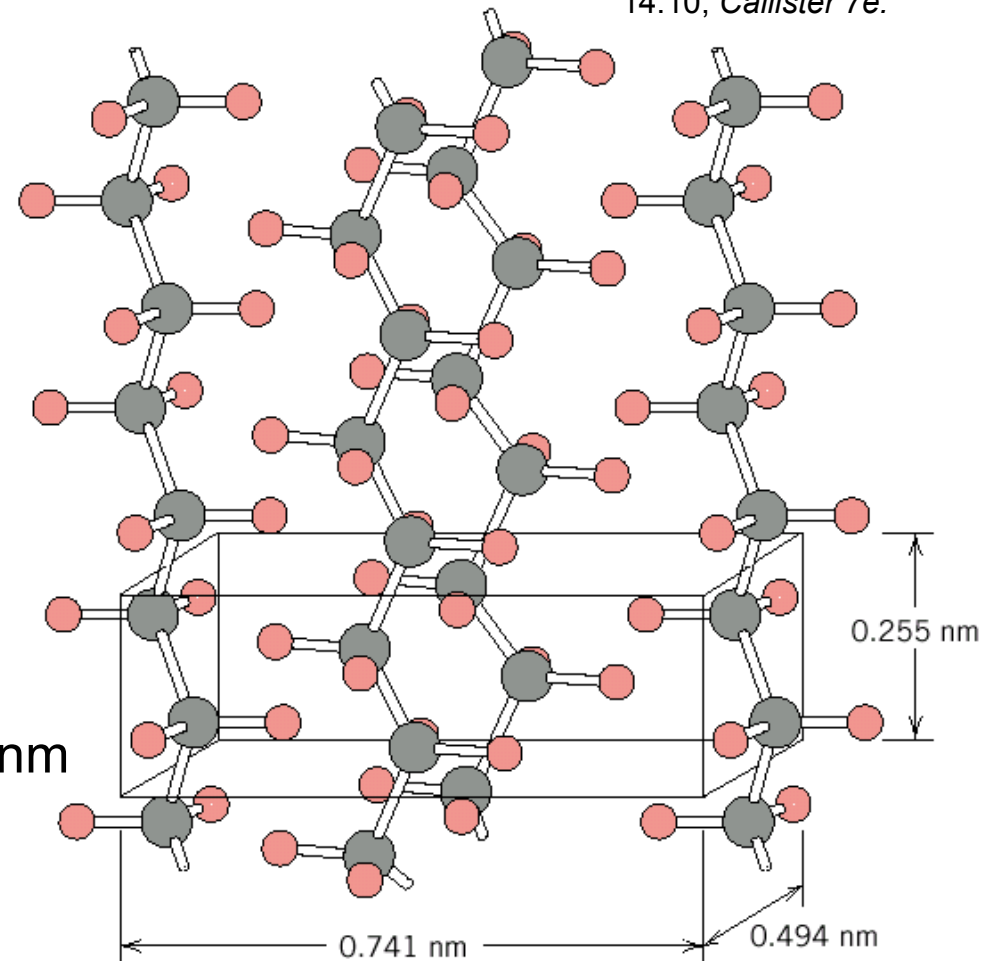
Crystals must contain the polymer chains in some way

Chain folded structure

Adapted from Fig. 14.12, Callister 7e.



Adapted from Fig. 14.10, Callister 7e.

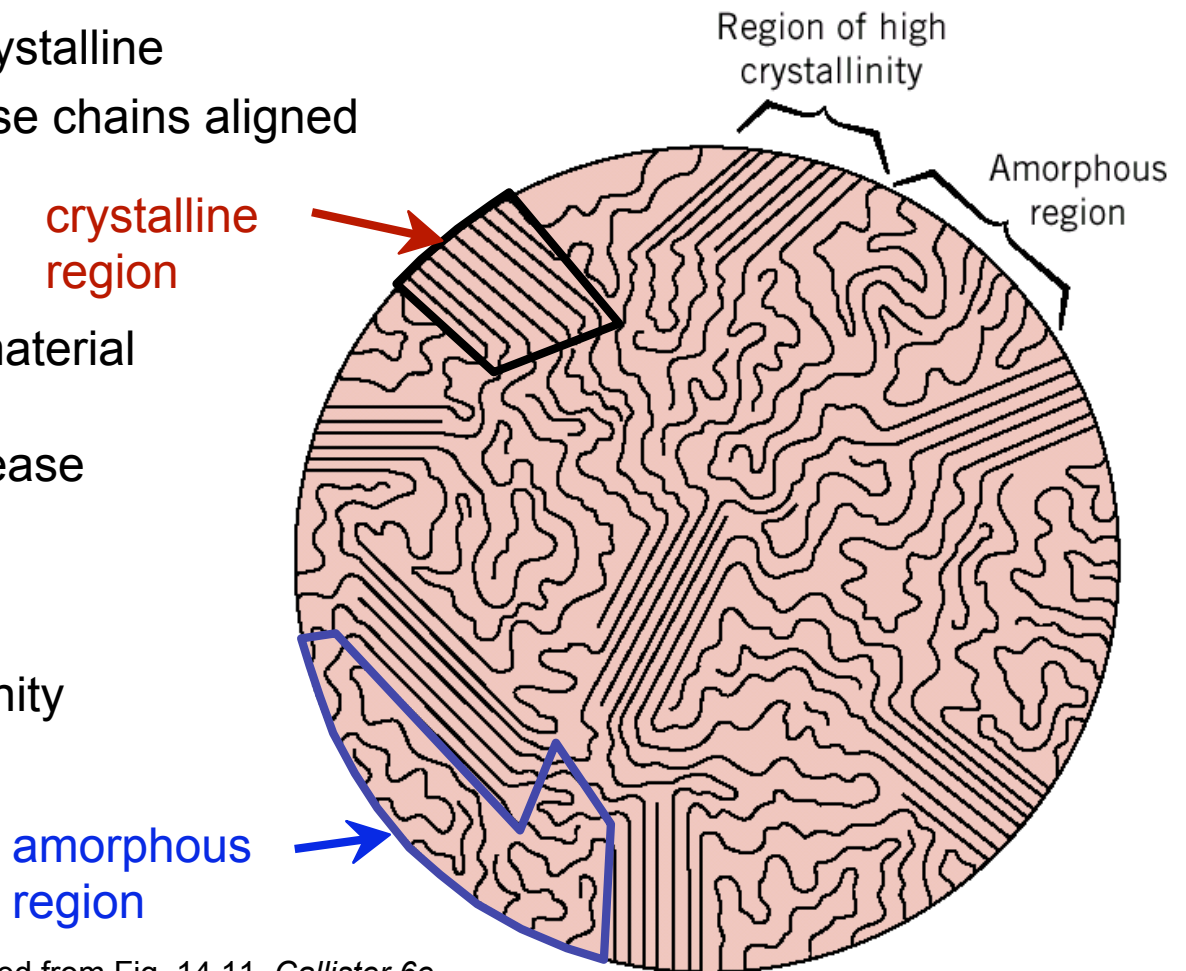


Polymer crystalline structure

Polymers rarely 100% crystalline

Too difficult to get all those chains aligned

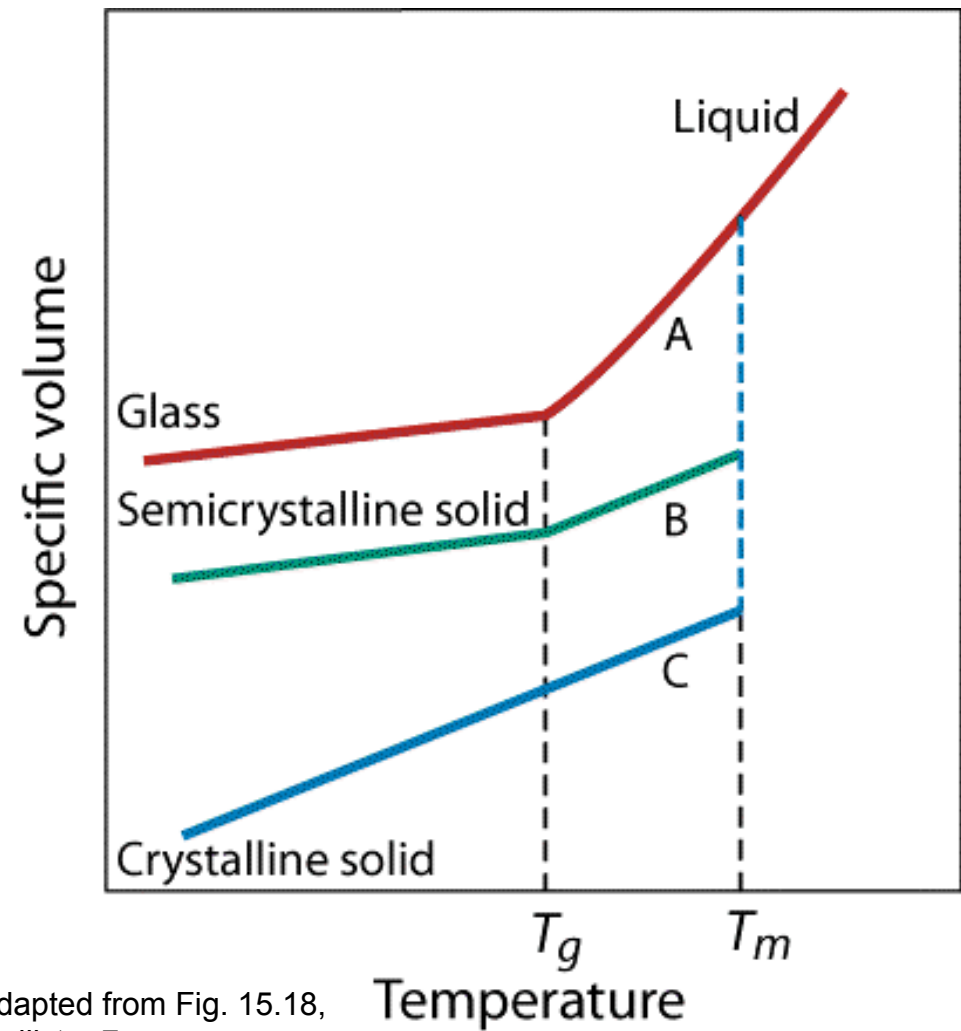
- **% Crystallinity**: % of material that is crystalline.
 - TS and E often increase with % crystallinity.
 - Annealing causes crystalline regions to grow. % crystallinity increases.



Adapted from Fig. 14.11, *Callister 6e*.
(Fig. 14.11 is from H.W. Hayden, W.G. Moffatt,
and J. Wulff, *The Structure and Properties of
Materials*, Vol. III, *Mechanical Behavior*, John Wiley
and Sons, Inc., 1965.)

T_m and T_g

What factors affect T_m and T_g ?

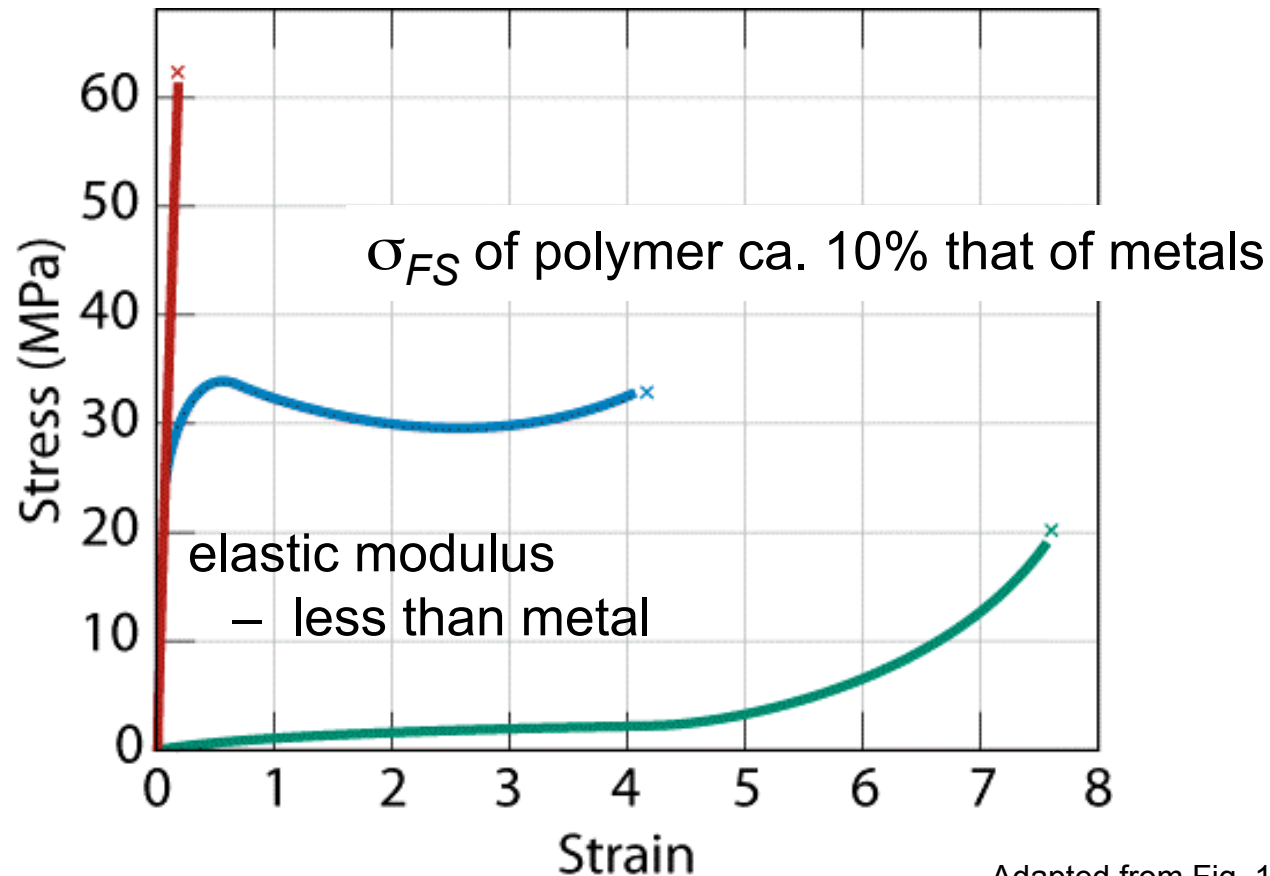


Adapted from Fig. 15.18,
Callister 7e.

Temperature

Mechanical properties

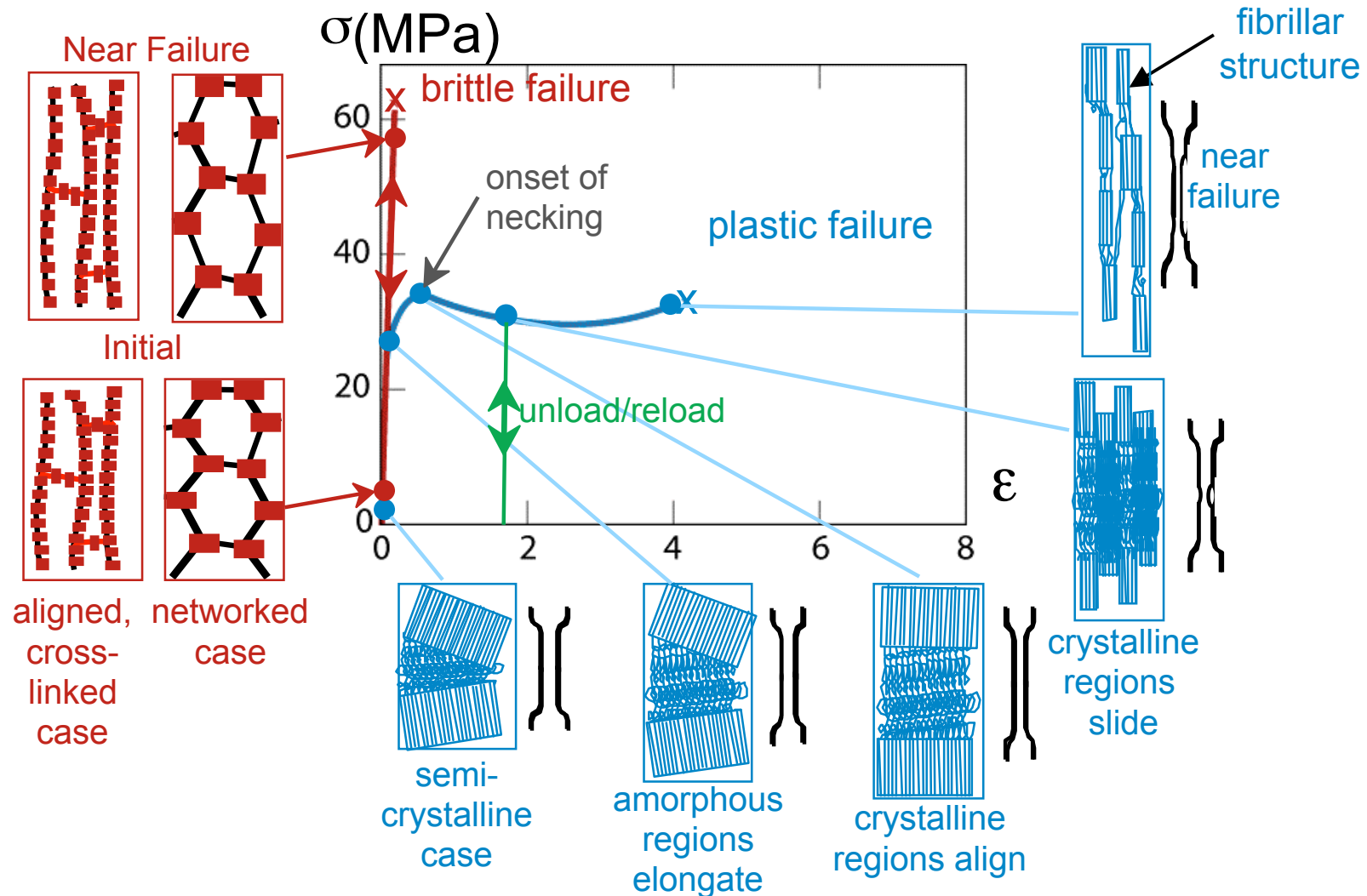
i.e. stress-strain behavior of polymers



Strains – deformations > 1000% possible
(for metals, maximum strain ca. 10% or less)

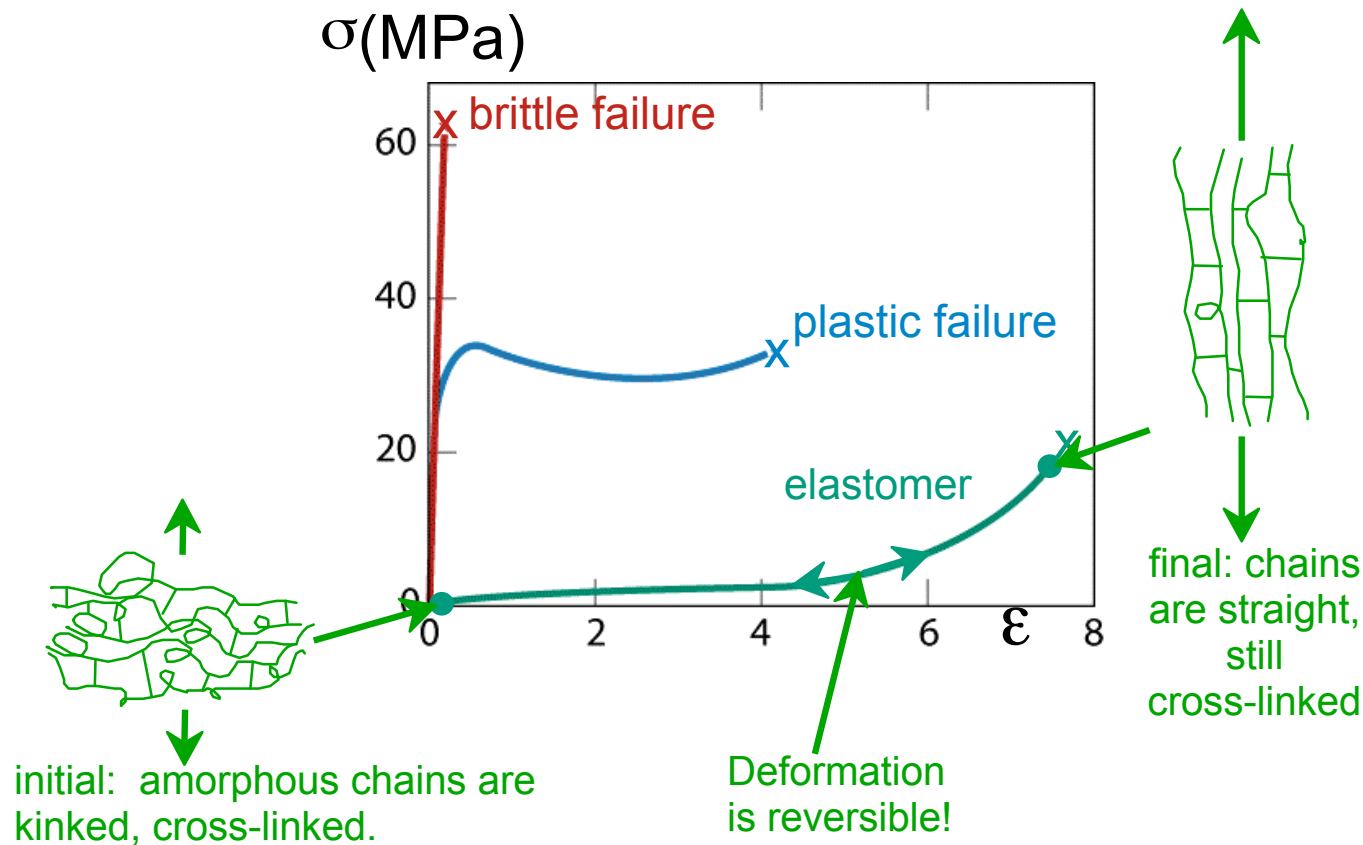
Adapted from Fig. 15.1,
Callister 7e.

Brittle and plastic behavior



Stress-strain curves adapted from Fig. 15.1, *Callister 7e*. Inset figures along plastic response curve adapted from Figs. 15.12 & 15.13, *Callister 7e*. (Figs. 15.12 & 15.13 are from J.M. Schultz, *Polymer Materials Science*, Prentice-Hall, Inc., 1974, pp. 500-501.)

Tensile response: elastomers



Stress-strain curves adapted from Fig. 15.1, *Callister 7e*. Inset figures along elastomer curve (green) adapted from Fig. 15.15, *Callister 7e*. (Fig. 15.15 is from Z.D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd ed., John Wiley and Sons, 1987.)

- Compare to responses of other polymers:
 - brittle response (aligned, crosslinked & networked polymer)
 - plastic response (semi-crystalline polymers)

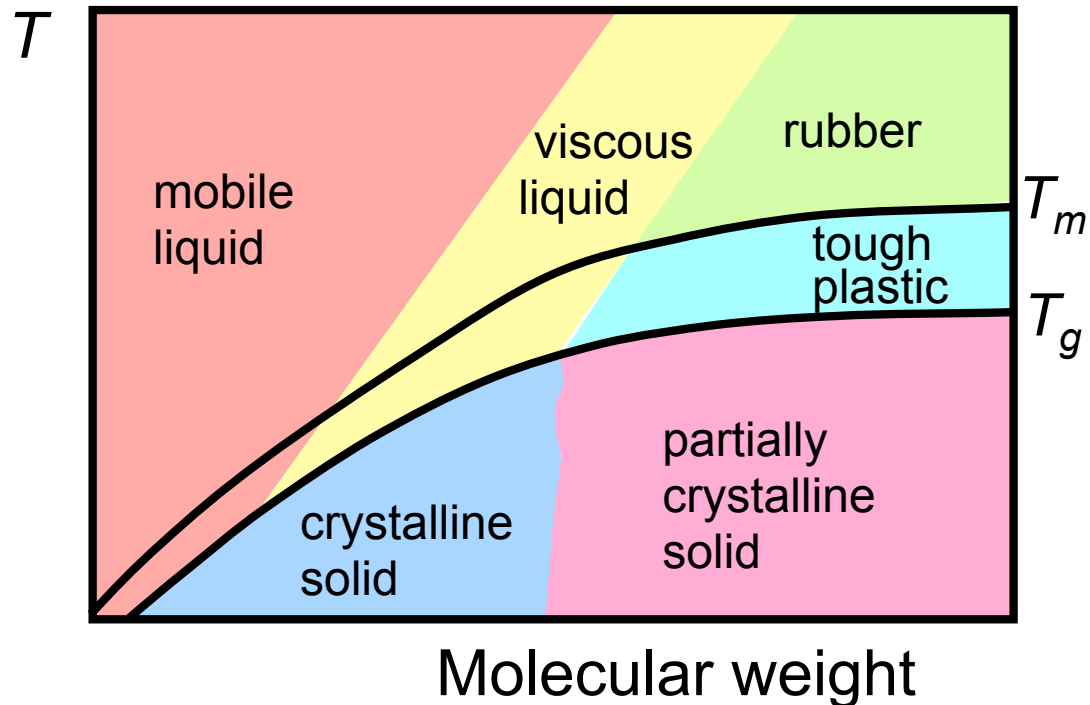
Thermoplastic vs. thermosets

- **Thermoplastics:**

- little crosslinking
- ductile
- soften w/heating
- polyethylene
- polypropylene
- polycarbonate
- polystyrene

- **Thermosets:**

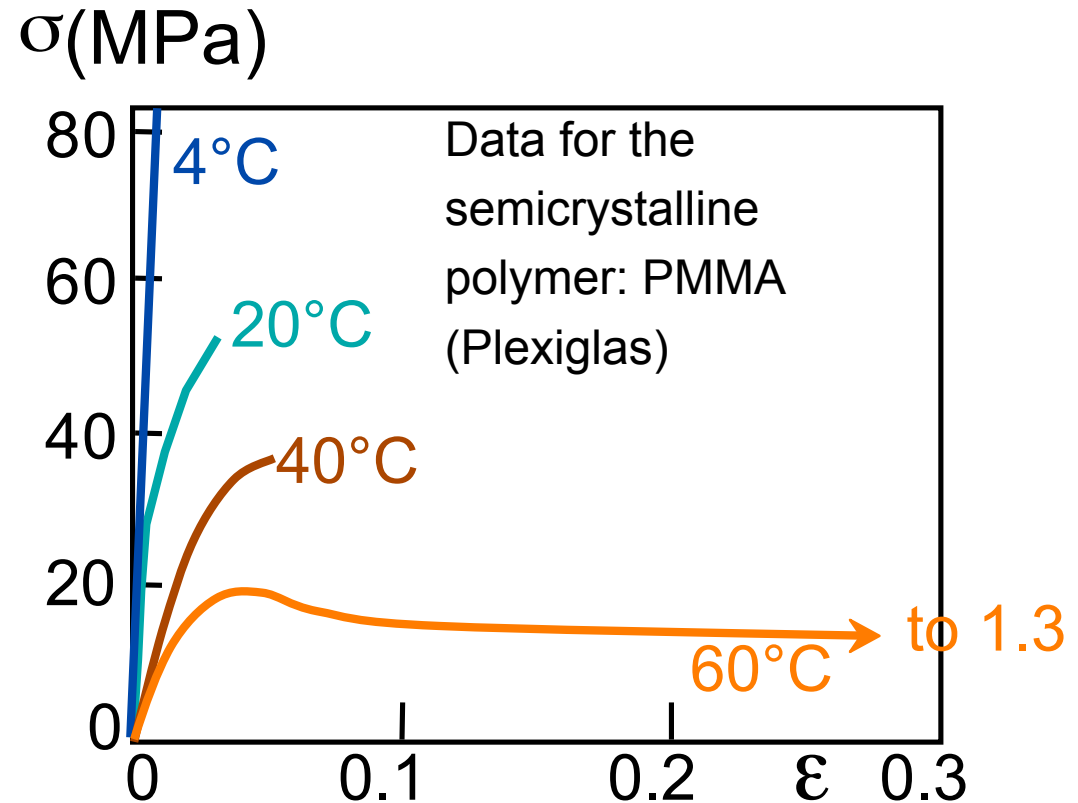
- large crosslinking
(10 to 50% of mers)
- hard and brittle
- do NOT soften w/heating
- vulcanized rubber, epoxies,
polyester resin, phenolic resin



Adapted from Fig. 15.19, *Callister 7e*. (Fig. 15.19 is from F.W. Billmeyer, Jr., *Textbook of Polymer Science*, 3rd ed., John Wiley and Sons, Inc., 1984.)

Strain rates and T

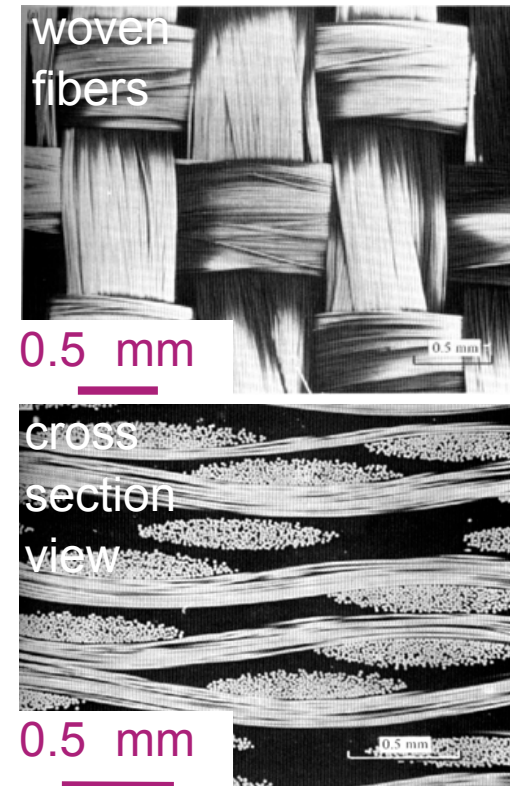
- Decreasing T ...
 - increases E
 - increases TS
 - decreases $\%EL$
- Increasing strain rate...
 - same effects as decreasing T .



Adapted from Fig. 15.3, *Callister 7e*. (Fig. 15.3 is from T.S. Carswell and J.K. Nason, 'Effect of Environmental Conditions on the Mechanical Properties of Organic Plastics', *Symposium on Plastics*, American Society for Testing and Materials, Philadelphia, PA, 1944.)

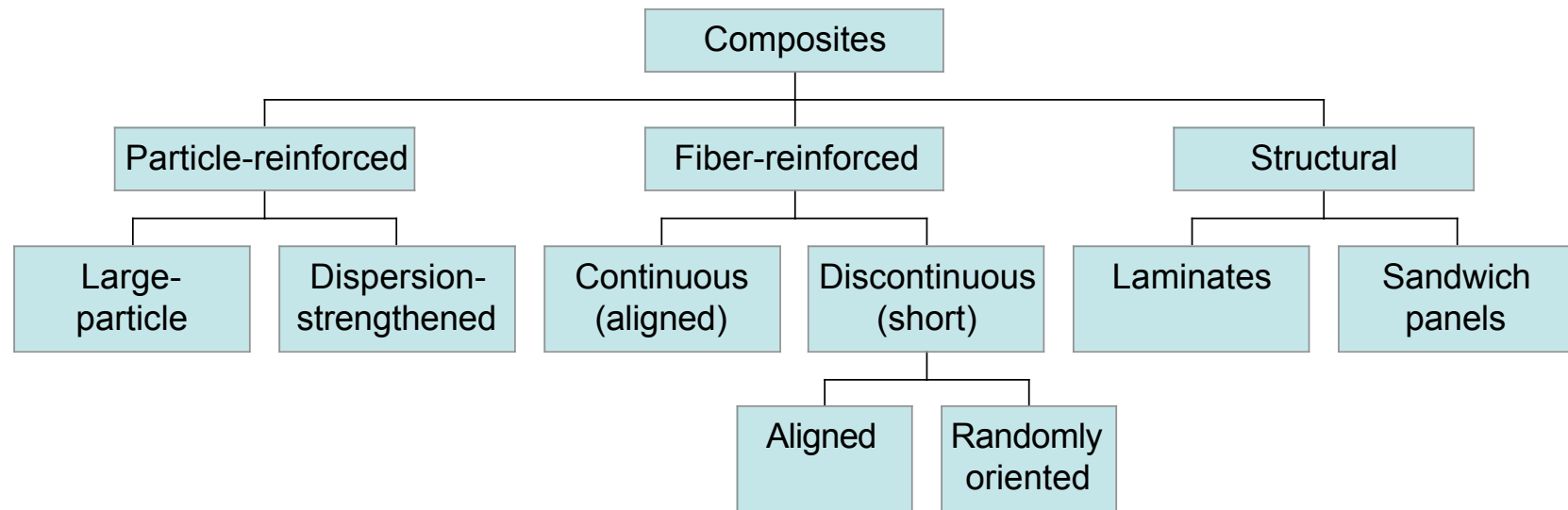
Composites

- **Composites:**
 - Multiphase material w/significant proportions of each phase.
- **Matrix:**
 - The continuous phase
 - Purpose is to:
 - transfer stress to other phases
 - protect phases from environment
 - Classification: MMC, CMC, PMC
 - metal → ceramic → polymer
- **Dispersed phase:**
 - Purpose: enhance matrix properties.
 - MMC:** increase σ_y , TS , creep resist.
 - CMC:** increase Kc
 - PMC:** increase E , σ_y , TS , creep resist.
 - Classification: Particle, fiber, structural



Reprinted with permission from
D. Hull and T.W. Clyne, *An
Introduction to Composite Materials*,
2nd ed., Cambridge University Press,
New York, 1996, Fig. 3.6, p. 47.

Composite classifications



Adapted from Fig.
16.2, *Callister 7e*.

Composite classifications

Particle-reinforced

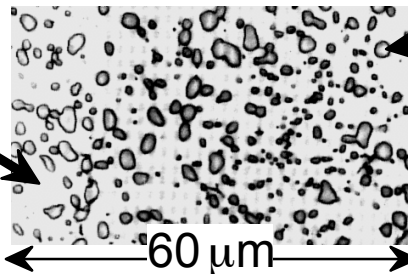
Fiber-reinforced

Structural

- Examples:

- Spheroidite steel

matrix:
ferrite (α)
(ductile)

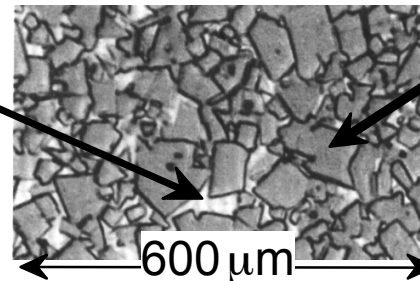


particles:
cementite
(Fe_3C)
(brittle)

Adapted from Fig. 10.19, *Callister 7e*.
(Fig. 10.19 is copyright United States Steel Corporation, 1971.)

- WC/Co cemented carbide

matrix:
cobalt
(ductile)
 V_m :
10-15 vol%!

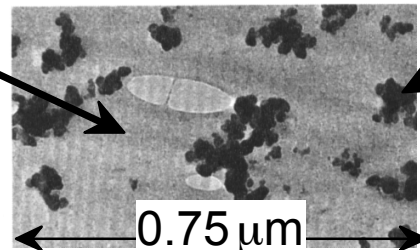


particles:
WC
(brittle,
hard)

Adapted from Fig. 16.4, *Callister 7e*.
(Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)

- Automobile tires

matrix:
rubber
(compliant)



particles:
C
(stiffer)

Adapted from Fig. 16.5, *Callister 7e*.
(Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)

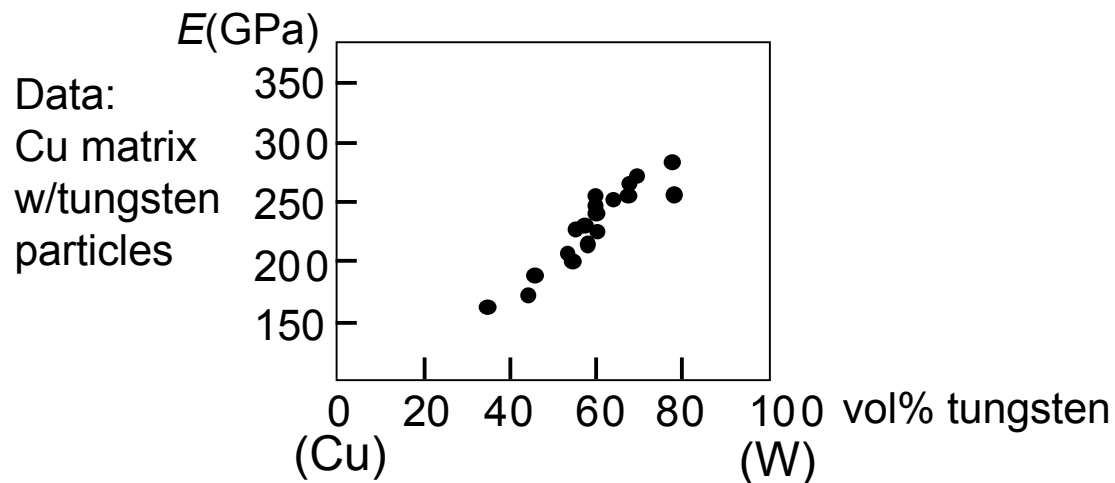
Composite classifications

Particle-reinforced

Fiber-reinforced

Structural

- **Elastic modulus**, E_c , of composites:
-- two approaches.



Adapted from Fig. 16.3,
Callister 7e. (Fig. 16.3 is
from R.H. Krock, *ASTM
Proc*, Vol. 63, 1963.)

- Application to other properties:
 - **Electrical conductivity**, σ_e : Replace E in equations with σ_e .
 - **Thermal conductivity**, k : Replace E in equations with k .

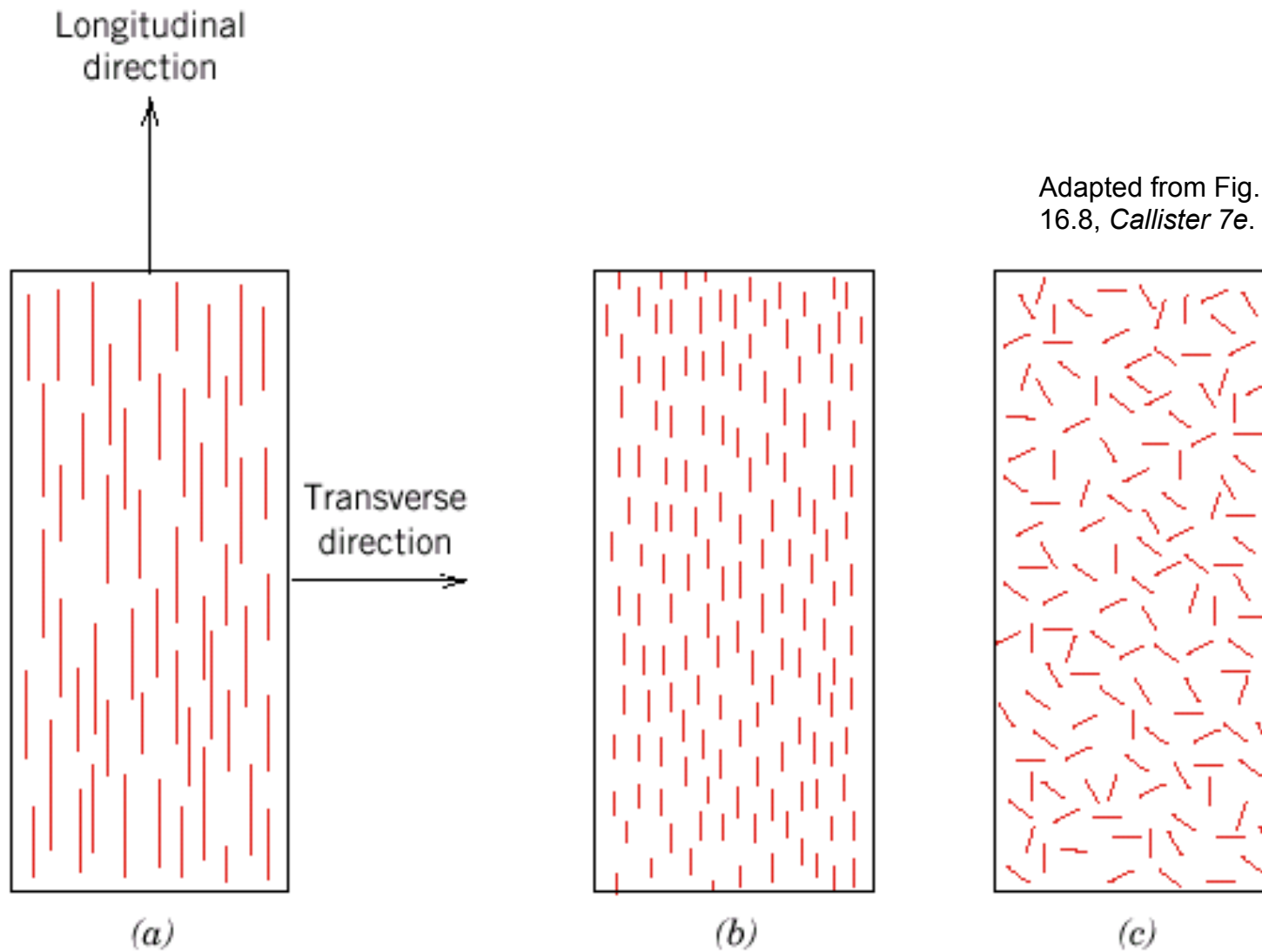
Composite classifications



Fiber Materials

- **Whiskers** - Thin single crystals - large length to diameter ratio
graphite, SiN, SiC
high crystal perfection – extremely strong, strongest known
very expensive
- **Fibers**
 - polycrystalline or amorphous
 - generally polymers or ceramics
 - Ex: Al_2O_3 , Aramid, E-glass, Boron, UHMWPE
- **Wires**
 - Metal – steel, Mo, W

Fiber alignment



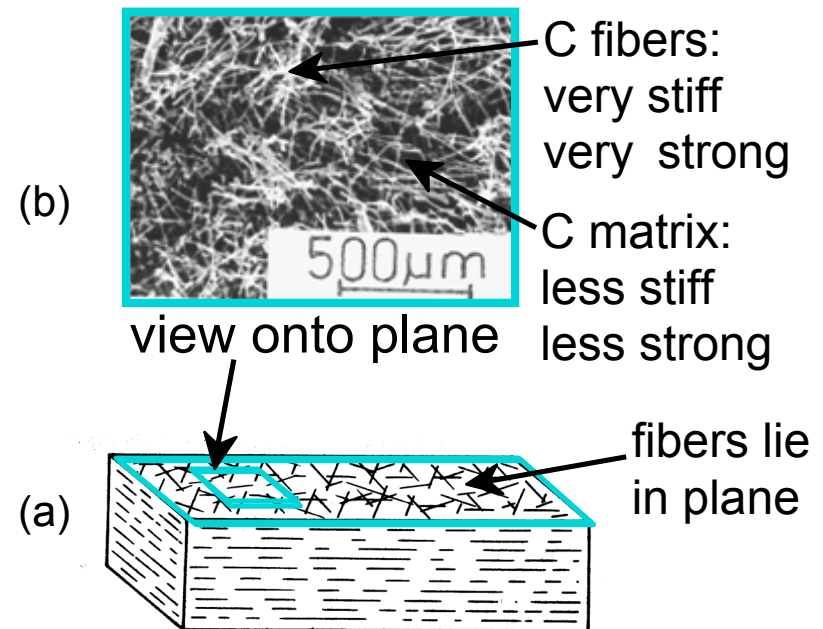
Fiber alignment

Particle-reinforced

Fiber-reinforced

Structural

- Discontinuous, random 2D fibers
- Example: Carbon-Carbon
 - process: fiber/pitch, then burn out at up to 2500°C.
 - uses: disk brakes, gas turbine exhaust flaps, nose cones.



- Other variations:
 - Discontinuous, random 3D
 - Discontinuous, 1D

Adapted from F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.24(a), p. 151; (b) Fig. 4.24(b) p. 151. (Courtesy I.J. Davies) Reproduced with permission of CRC Press, Boca Raton, FL.

Fiber alignment

Particle-reinforced

Fiber-reinforced

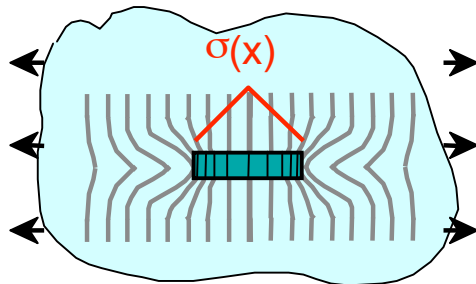
Structural

- **Critical** fiber length for effective stiffening & strengthening:

- Ex: For fiberglass, fiber length > 15 mm needed

Shorter, thicker fiber:

$$\text{fiber length} < 15 \frac{\sigma_f d}{\tau_c}$$

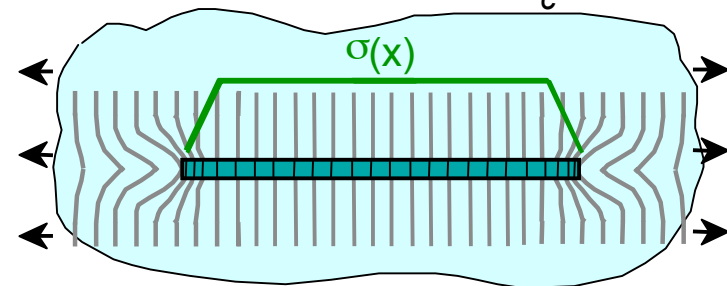


Poorer fiber efficiency

Adapted from Fig.
16.7, Callister 7e.

Longer, thinner fiber:

$$\text{fiber length} > 15 \frac{\sigma_f d}{\tau_c}$$



Better fiber efficiency

Fiber reinforcement

Particle-reinforced

Fiber-reinforced

Structural

- Estimate of E_c and TS for discontinuous fibers:

-- valid when fiber length $> 15 \frac{\sigma_f d}{\tau_c}$

-- Elastic modulus in fiber direction:

Values from Table 16.3, *Callister 7e*.
(Source for Table 16.3 is H. Krenchel,
Fibre Reinforcement, Copenhagen:
Akademisk Forlag, 1964.)

-- TS in fiber direction:

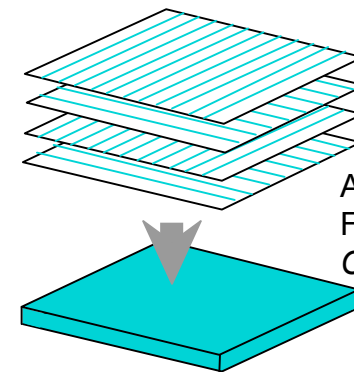
Structural composites

Particle-reinforced

Fiber-reinforced

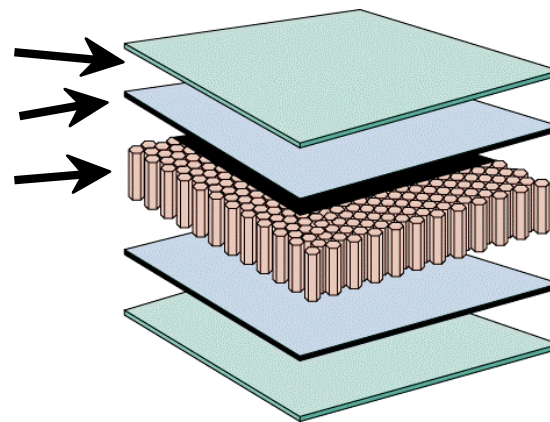
Structural

- Stacked and bonded fiber-reinforced sheets
 - stacking sequence: e.g., $0^\circ/90^\circ$
 - benefit: balanced, in-plane stiffness
- Sandwich panels
 - low density, honeycomb core
 - benefit: small weight, large bending stiffness

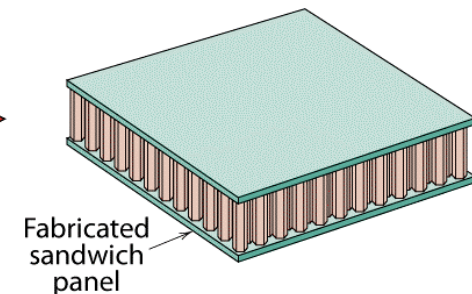


Adapted from
Fig. 16.16,
Callister 7e.

face sheet
adhesive layer
honeycomb

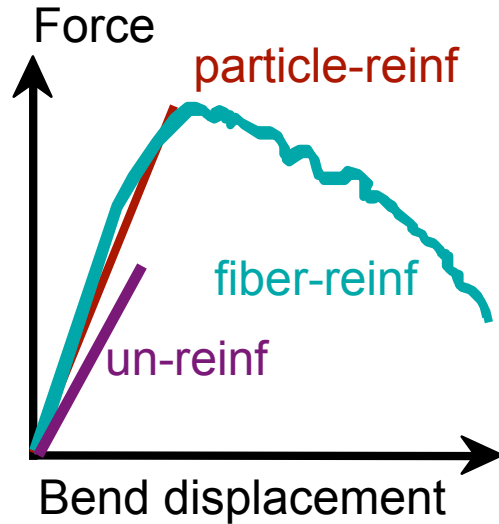


Adapted from Fig. 16.18,
Callister 7e. (Fig. 16.18 is
from *Engineered Materials
Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.)

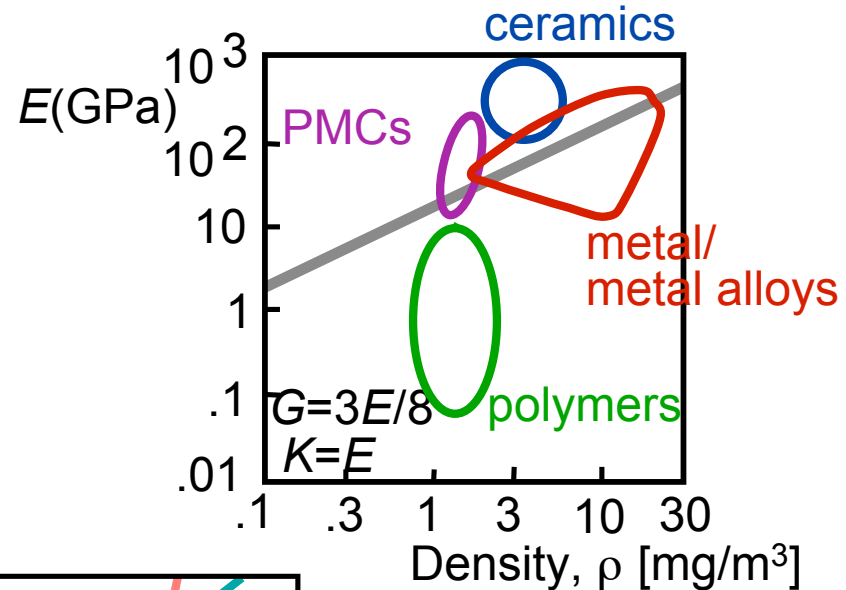


Composite benefits

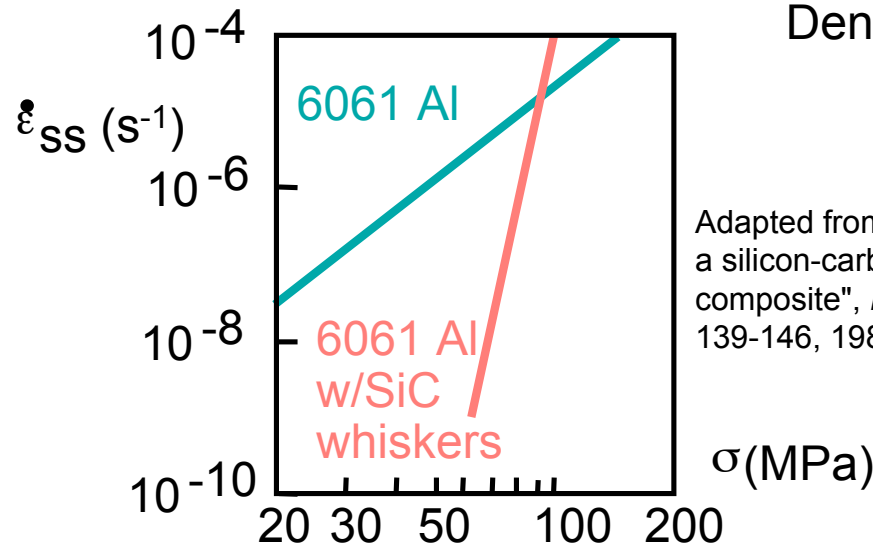
- CMCs: Increased toughness



- PMCs: Increased E/ρ



- MMCs: Increased creep resistance



Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.