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VWUXFWXUHV#

By

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Vidyanagar 388 120

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- What are the basic microstructural features of a polymer?
- How are polymer properties affected by molecular weight?
- How do polymeric materials accommodate the polymer chain?
- What are the primary polymer processing methods?

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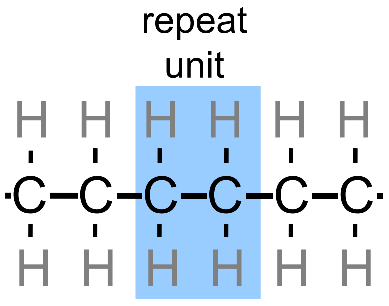
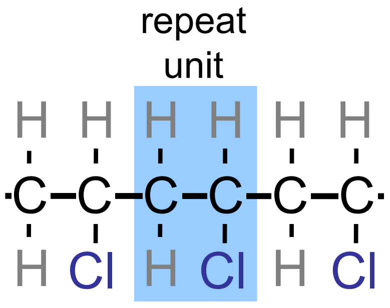
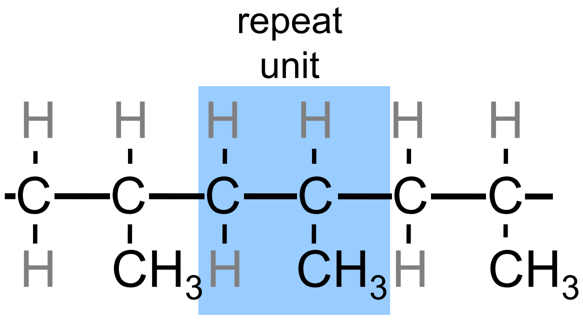


Polyethylene (PE)



Polyvinyl chloride (PVC)



Polypropylene (PP)

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

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- Originally many natural polymers were used
  - Wood
  - Cotton
  - Leather
  - Rubber
  - Wool
  - Silk

- Oldest known uses of "Modern Polymers"
  - Rubber balls used by Incas
  - Noah used pitch (a natural polymer) for the ark – as had all ancient mariners!

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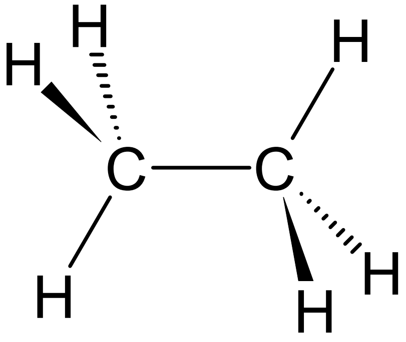
Most polymers are hydrocarbons

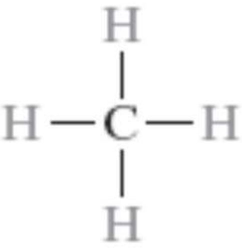
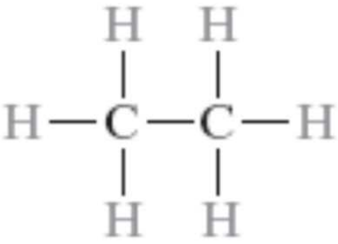
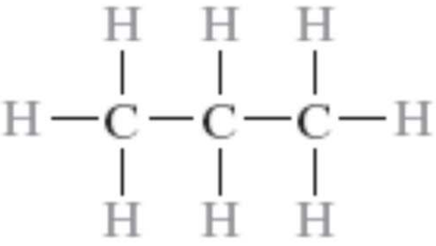
- i.e. made up of H and C (we also recognize Si bearing or 'silicone polymers')

- Saturated hydrocarbons
  - Each carbon bonded to four other atoms



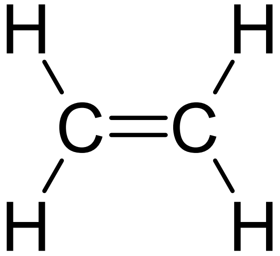
C_nH_{2n+2}

Compositions and Molecular Structures for Some of the Paraffin Compounds: C_nH_{2n+2}

Name	*Composition*	*Structure*	*Boiling Point (°C)*
Methane	CH_4		−164
Ethane	C_2H_6		−88.6
Propane	C_3H_8		−42.1
Butane	C_4H_{10}		−0.5
Pentane	C_5H_{12}		36.1
Hexane	C_6H_{14}		69.0

X qvdwxudwhg#K |gurfduerqv

- Double & triple bonds somewhat unstable
- Thus, can form new bonds
  - Double bond found in ethylene or ethene - C_2H_4



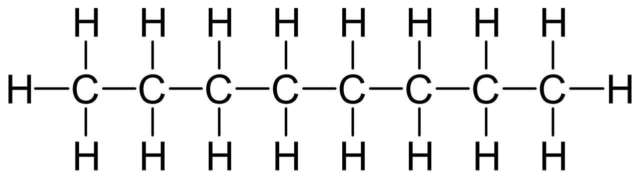
  - Triple bond found in acetylene or ethyne - C_2H_2

$$H-C\equiv C-H$$

Lvrp hulvp

- Isomerism
  - two compounds with same chemical formula can have quite different structures

    Ex: C_8H_{18}
    - n-octane



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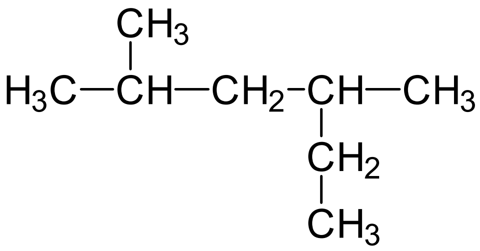
$= H_3C{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_3$

$\Downarrow$

$H_3C{-}(CH_2)_6{-}CH_3$

    - 2-methyl-4-ethyl pentane (isooctane)



$$\begin{array}{ccccccccc} & & CH_3 & & & & & & \\ & & | & & & & & & \\ H_3C & - & CH & - & CH_2 & - & CH & - & CH_3 \\ & & & & & & | & & \\ & & & & & & CH_2 & & \\ & & & & & & | & & \\ & & & & & & CH_3 & & \end{array}$$

Table 4.1 Compositions and Molecular Structures for Some of the Paraffin Compounds: C_nH_{2n+2}

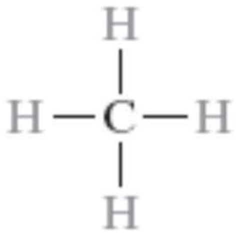
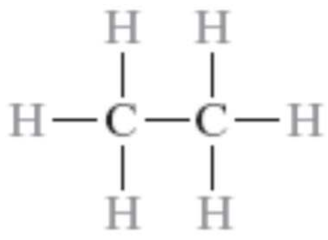
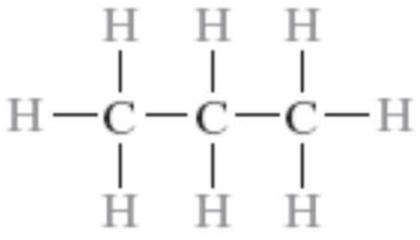
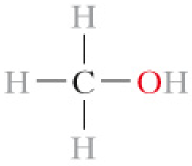
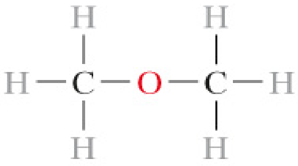
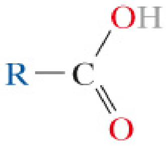
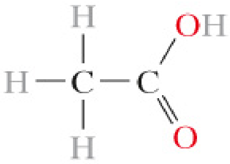
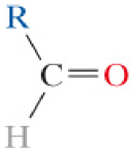
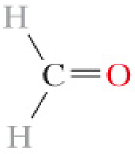
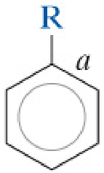
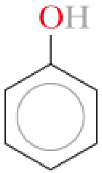
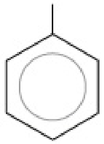
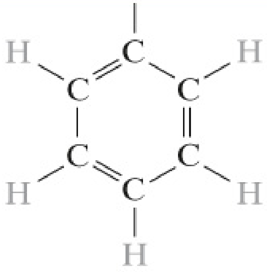
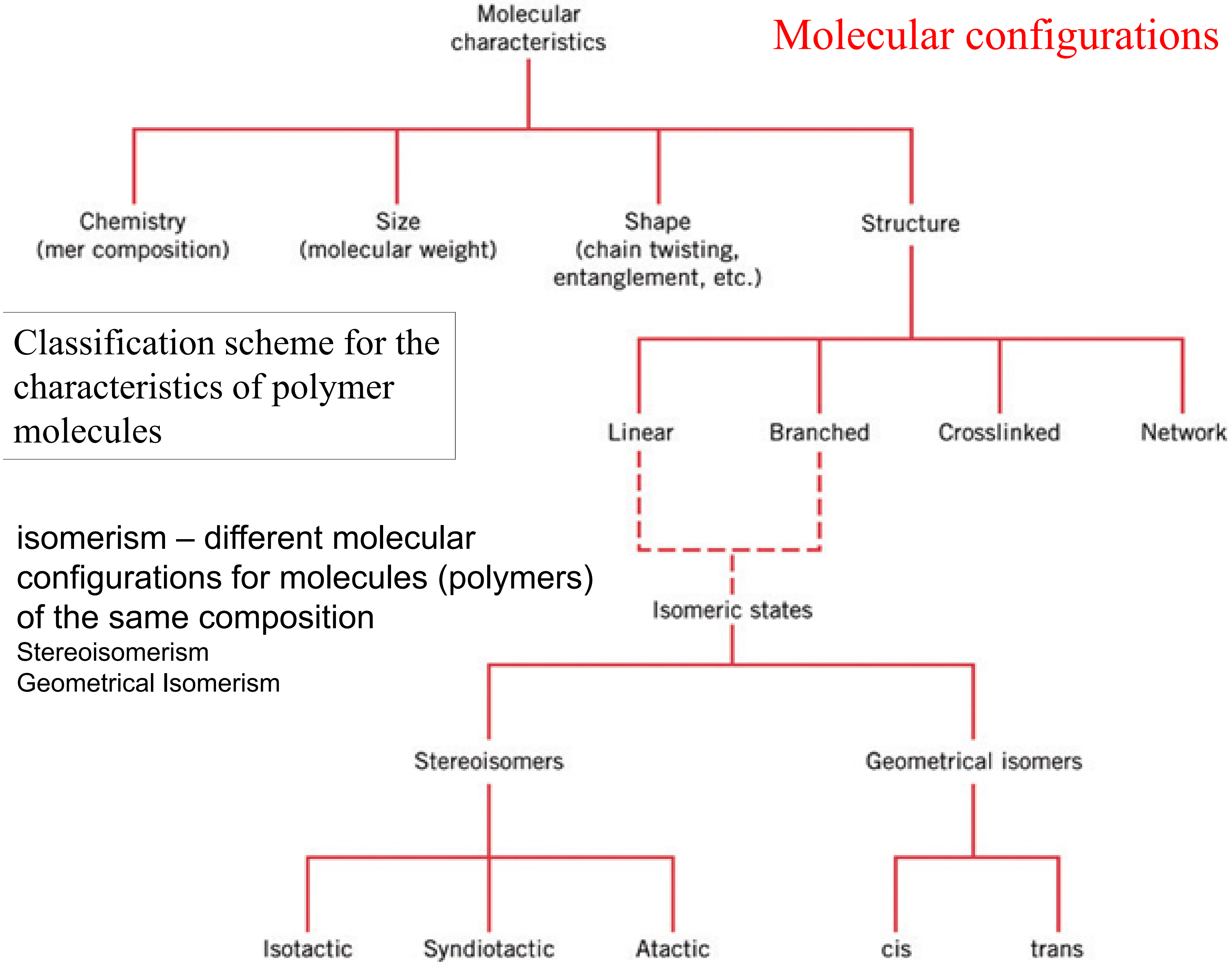
Name	*Composition*	*Structure*	*Boiling Point (°C)*
Methane	CH_4	 $\begin{array}{ccccc} & & H & & \\ & & \vert & & \\ H & - & C & - & H \\ & & \vert & & \\ & & H & & \end{array}$	−164
Ethane	C_2H_6	 $\begin{array}{ccccccc} & & H & & H & & \\ & & \vert & & \vert & & \\ H & - & C & - & C & - & H \\ & & \vert & & \vert & & \\ & & H & & H & & \end{array}$	−88.6
Propane	C_3H_8	 $\begin{array}{ccccccccc} & & H & & H & & H & & \\ & & \vert & & \vert & & \vert & & \\ H & - & C & - & C & - & C & - & H \\ & & \vert & & \vert & & \vert & & \\ & & H & & H & & H & & \end{array}$	−42.1
Butane	C_4H_{10}		−0.5
Pentane	C_5H_{12}		36.1
Hexane	C_6H_{14}		69.0

Table 4.2 **Some Common Hydrocarbon Groups**

Family	*Characteristic Unit*		*Representative Compound*
Alcohols	$R-OH$	 $\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-OH}$	Methyl alcohol
Ethers	$R-O-R'$	 $\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-O-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-H}$	Dimethyl ether
Acids			Acetic acid
Aldehydes			Formaldehyde
Aromatic hydrocarbons			Phenol

[a] The simplified structure  denotes a phenyl group, 

Molecular configurations



Classification scheme for the characteristics of polymer molecules

isomerism – different molecular configurations for molecules (polymers) of the same composition

Stereoisomerism

Geometrical Isomerism

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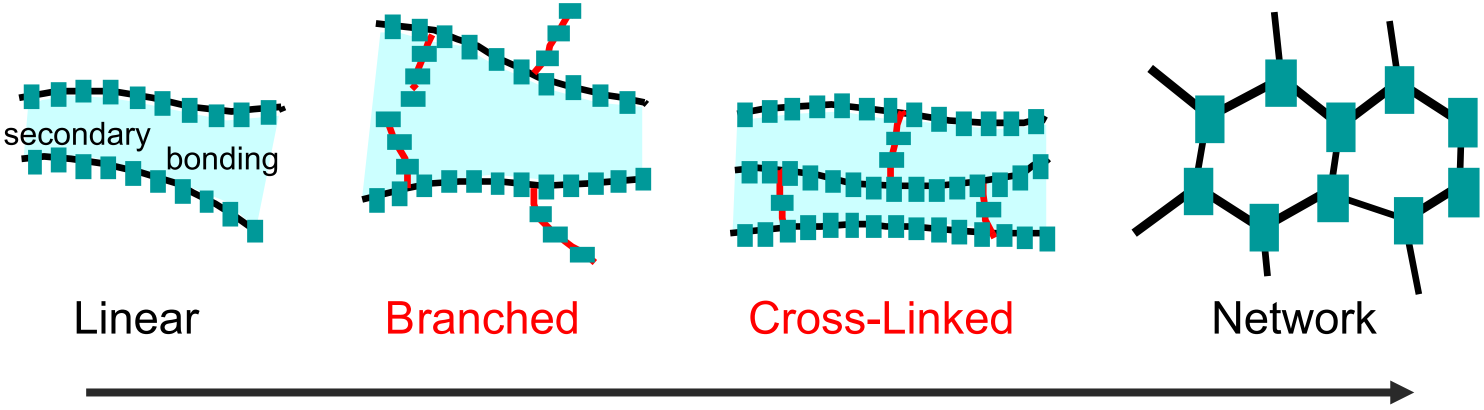
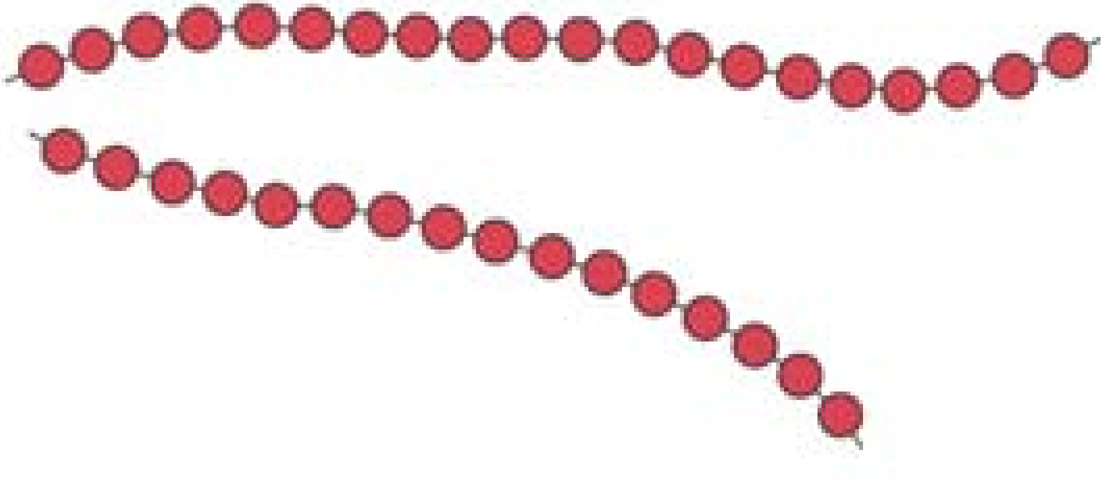
- Covalent chain configurations and strength:



Direction of increasing strength

Linear polymers

- – polymers in which the mer units are connected end-to-end along the whole length of the chain
- These types of polymers are often quite flexible
  - Van der waal's forces and H-bonding are the two main types of interactions between chains
  - Some examples – polyethylene, teflon, PVC, polypropylene



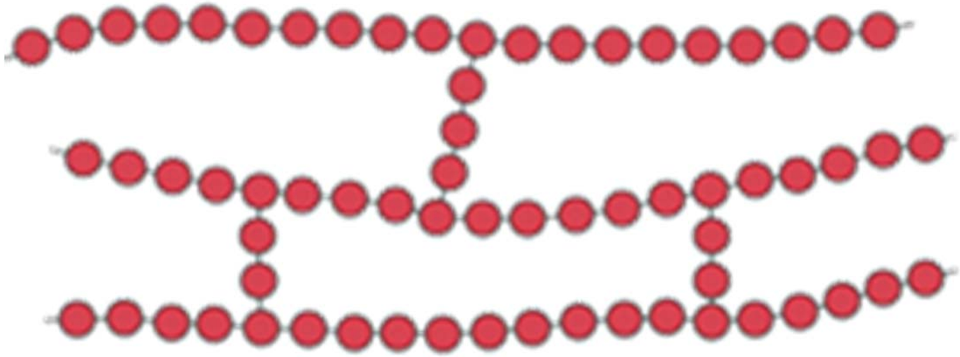
Branched polymers

- Polymer chains can branch:

- Or the fibers may aligned parallel, as in fibers and some plastic sheets.
- chains off the main chain (backbone)
    - – This leads to inability of chains to pack very closely together
        - » These polymers often have lower densities
  - These branches are usually a result of side-reactions during the polymerization of the main chain
    - – Most linear polymers can also be made in branched forms

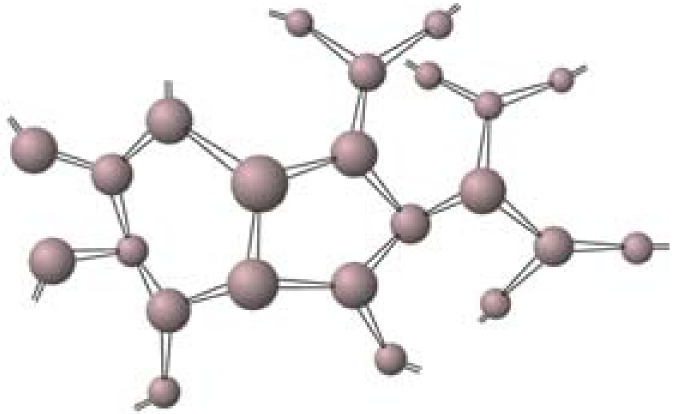
Crosslinked polymers

- Molecular structure
  - adjacent chains attached via covalent bonds
    - Carried out during polymerization or by a non-reversible reaction after synthesis (referred to as crosslinking)
    - Materials often behave very differently from linear polymers
    - Many “rubbery” polymers are crosslinked to modify their mechanical properties; in that case it is often called vulcanization
    - Generally, amorphous polymers are weak and cross-linking adds strength: vulcanized rubber is polyisoprene with sulphur cross-links:



Network polymers

- – polymers that are “trifunctional” instead of bifunctional
- – There are three points on the mer that can react
- – This leads to three-dimensional connectivity of the polymer backbone
  - Highly crosslinked polymers can also be classified as network polymers
  - Examples: epoxies, phenol-formaldehyde polymers



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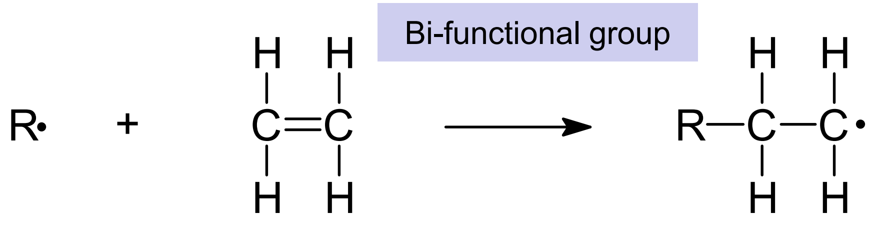
- Free radical polymerization

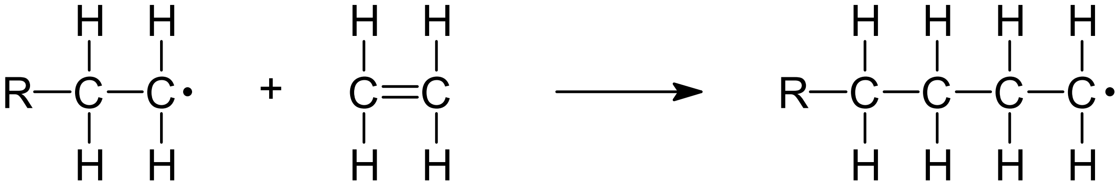

$$R\cdot + H_2C{=}CH_2 \longrightarrow R{-}CH_2{-}CH_2\cdot$$

Bi-functional group

free radical

monomer
(ethylene)

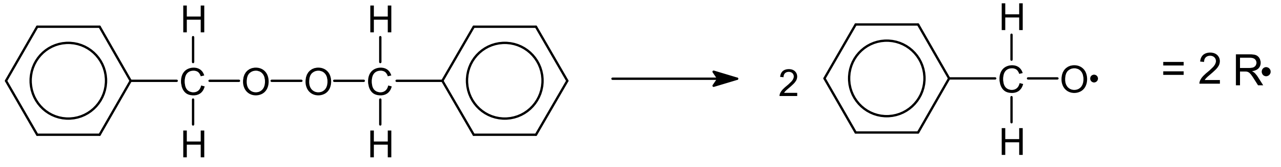
initiation


$$R{-}CH_2{-}CH_2\cdot + H_2C{=}CH_2 \longrightarrow R{-}CH_2{-}CH_2{-}CH_2{-}CH_2\cdot$$

propagation

dimer

- Initiator: example - benzoyl peroxide



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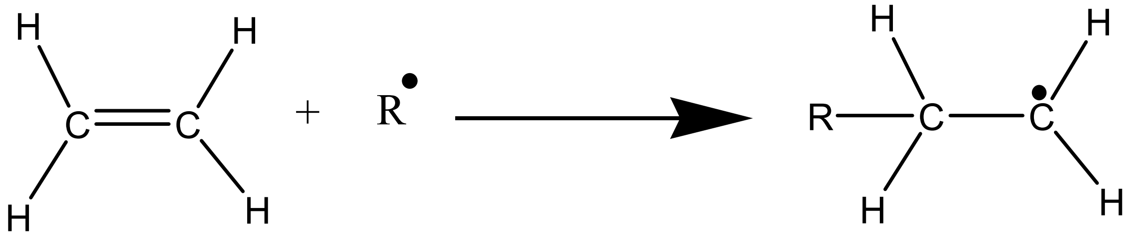
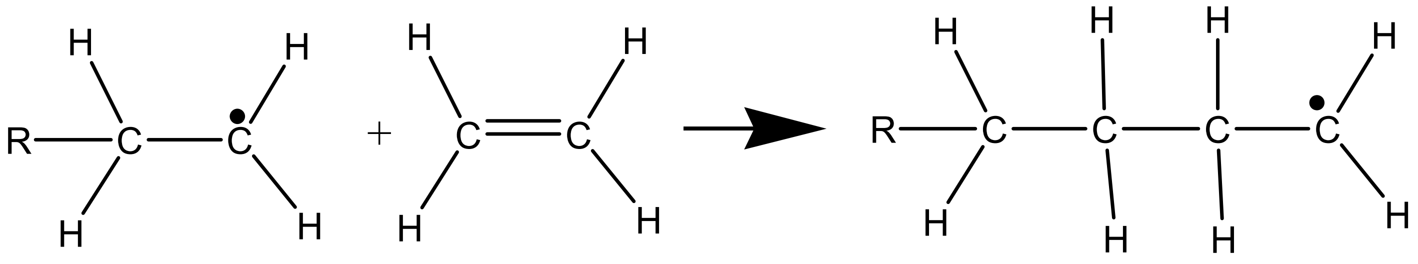
Example: ethylene

- Gas at STP
- To *__polymerize__* ethylene, typically increase T, P and/or add an initiator



Initiation

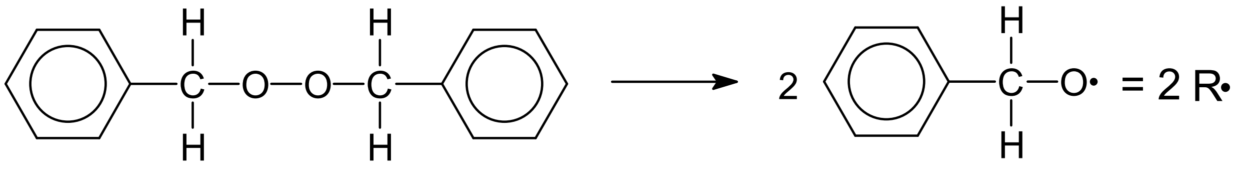


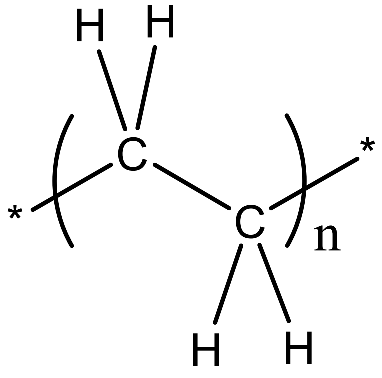
Propagation

After many additions of monomer to the growing chain…

R^* = *initiator;* activates the monomer to begin chain growth

Initiator: example - benzoyl peroxide





poly-ethylene

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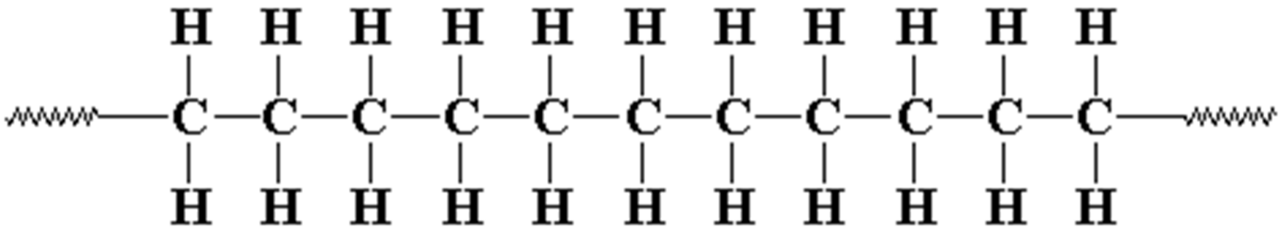
- Polymers are chain molecules. They are built up from simple units called ***monomers***.
- E.g. polyethylene is built from ethylene units:

$$\left[\!-CH_2-CH_2-\!\right]_n$$

which are assembled into long chains:



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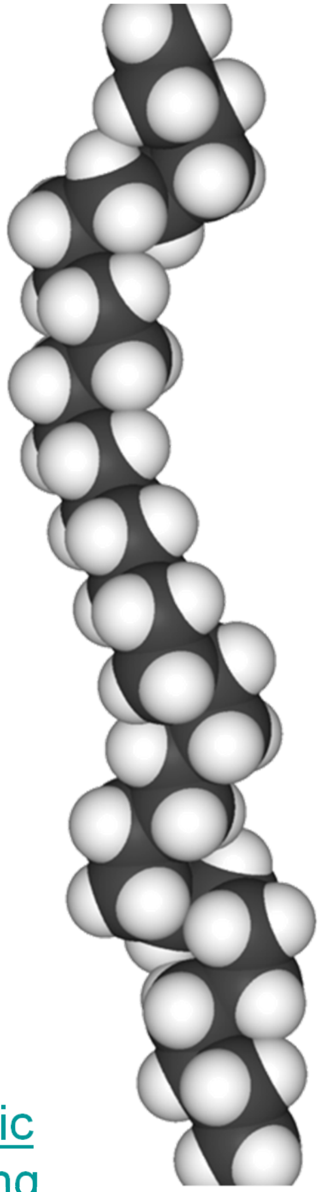
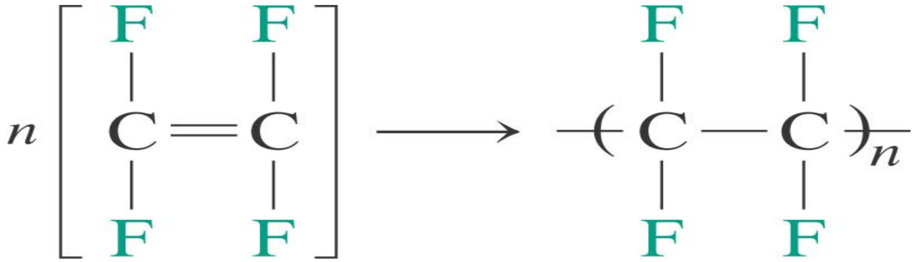


Polyethylene or **polythene** (IUPAC name **poly(ethene)**) is a thermoplastic commodity heavily used in consumer products (notably the plastic shopping bag). Over 60 million tons of the material are produced worldwide every year.

Tetrafluoroethylene monomer polymerize to form PTFE or polytetrafluoroethylene



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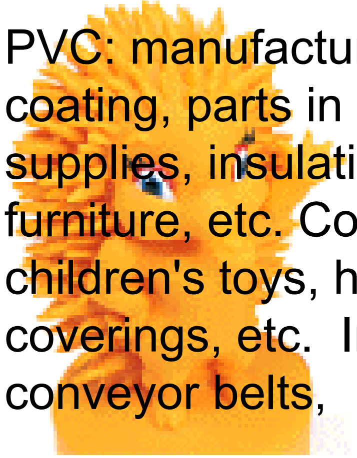
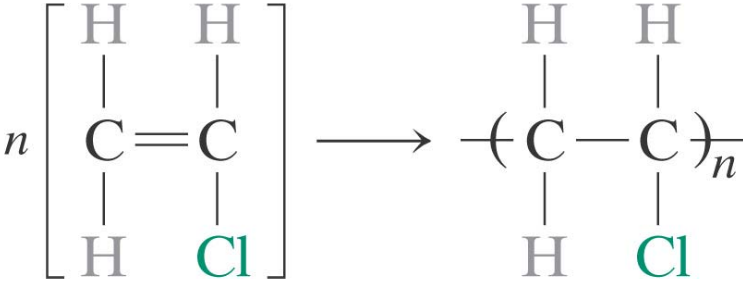
poly(tetrafluoroethene) or **poly(tetrafluoroethylene)** (**PTFE**) is a synthetic fluoropolymer. PTFE is the DuPont brand name **Teflon**. Melting: 327C

Vinyl chloride monomer leads to poly(vinyl chloride) or PVC





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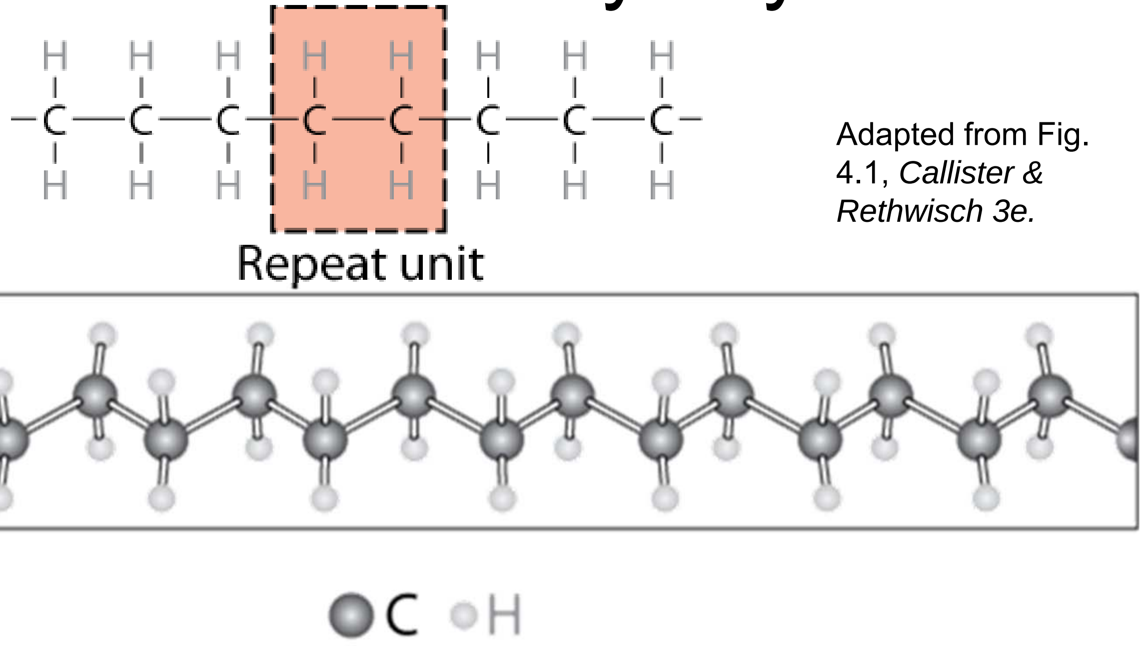
PVC: manufacturing toys, packaging, coating, parts in motor vehicles, office supplies, insulation, adhesive tapes, furniture, etc. Consumers: shoe soles, children's toys, handbags, luggage, seat coverings, etc. Industrial sectors: conveyor belts, printing rollers. Electric and electronic equipment: circuit boards, cables, electrical boxes, computer housing.

Chemistry and Structure of Polyethylene



Adapted from Fig. 4.1, *Callister & Rethwisch 3e.*

Note: polyethylene is a long-chain hydrocarbon
- paraffin wax for candles is short polyethylene

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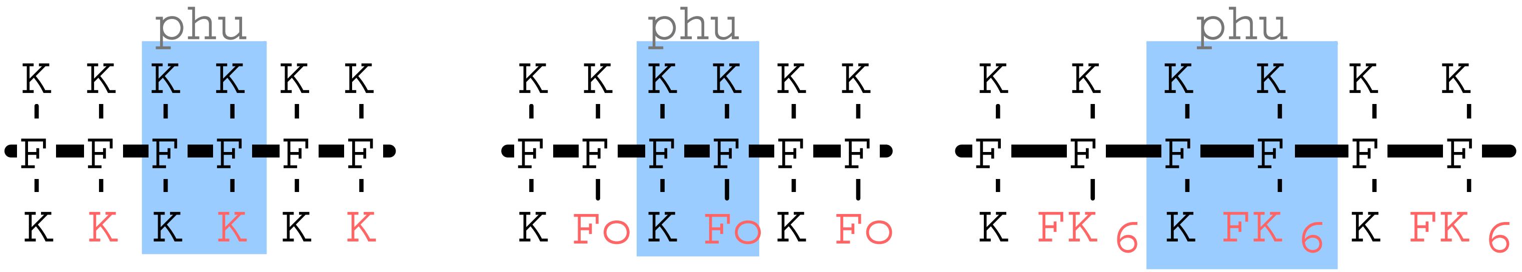

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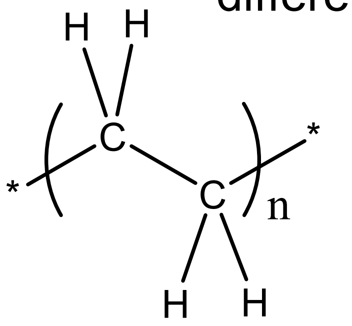
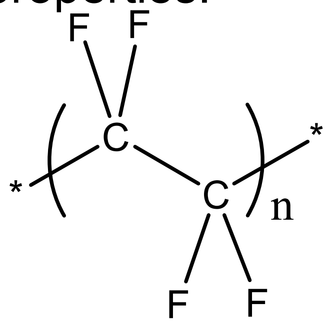
Dgdswhg#urp#Ilj1#7 15 /#*Fdoolvwhu#9h1*

Polymer chemistry

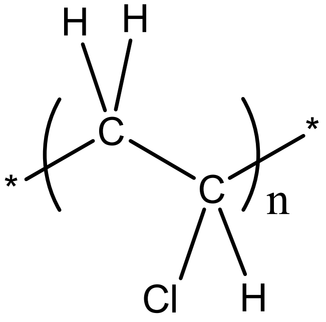
- In polyethylene (PE) synthesis, the monomer is ethylene
- Turns out one can use many different monomers
  - Different functional groups/chemical composition – polymers have very different properties!



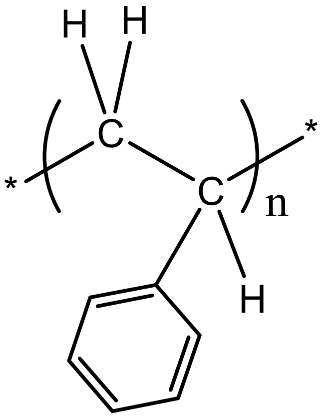
poly(ethylene)
(PE)



poly(tetrafluoroethylene)
(PTFE, teflon)

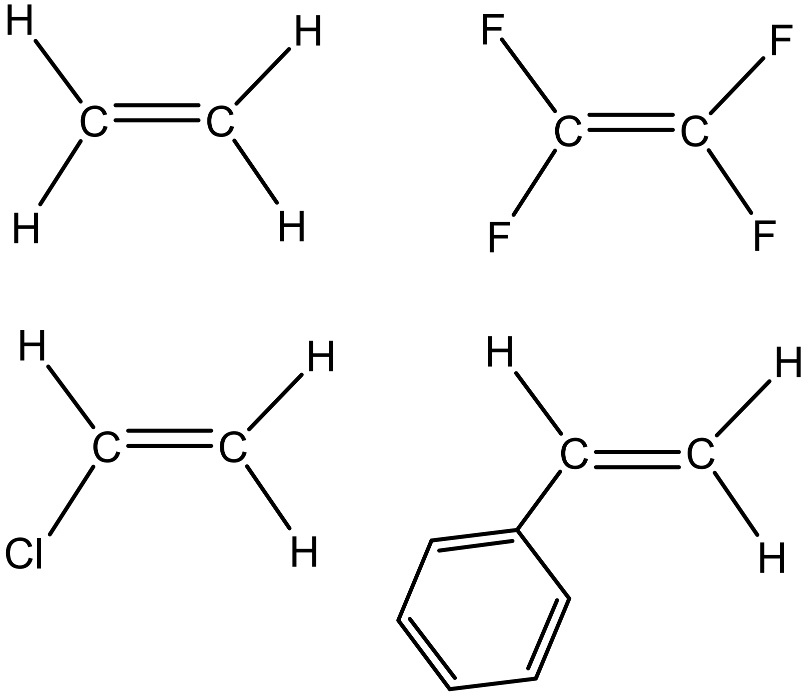


poly(vinylchloride)
(PVC)



poly(styrene)
(PS)

Monomers



Homopolymer and Copolymer

- Polymer chemistry
  - If formed from one monomer (all the repeat units are the same type) – this is called a *homopolymer*
  - If formed from multiple types of monomers (all the repeat units are not the same type) – this is called a *copolymer*

- Also note – the monomers shown before are referred to as bifunctional
  - Why? The reactive bond that leads to polymerization (the C=C double bond in ethylene) can react with *two* other units
  - Other monomers react with more than two other units – e.g. trifunctional monomers

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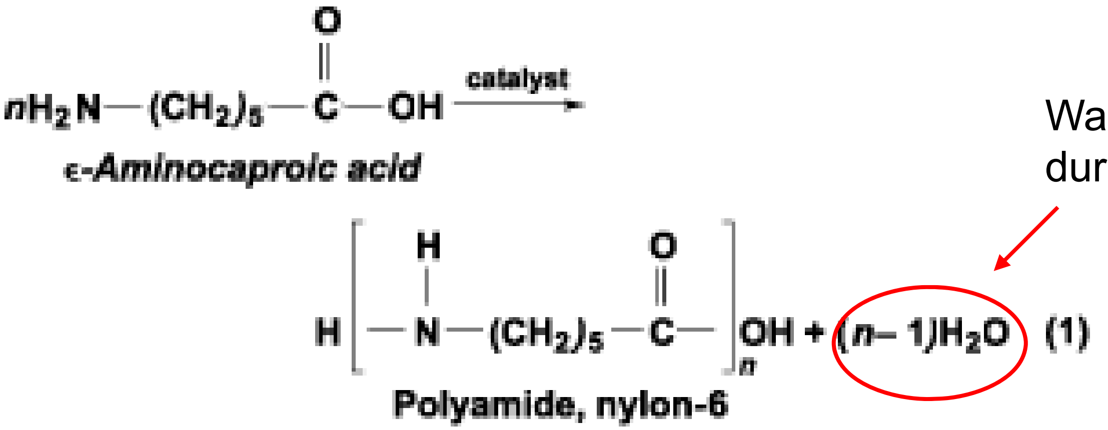

$$nH_2N-(CH_2)_5-\overset{\overset{O}{\|}}{C}-OH \xrightarrow{\text{catalyst}} H\left[-\overset{\overset{H}{|}}{N}-(CH_2)_5-\overset{\overset{O}{\|}}{C}-\right]_n OH + (n-1)H_2O \quad (1)$$

Water is “Condensed out”
during polymerization of Nylon

- Some of the original monomer’s materials are shed (condensed out) during polymerization process – thus the name: Step Process
- Process is (typically) conducted in the presence of a catalyst to speed up the ‘stepping’
- Water or CO_2 are commonly condensed out but other compounds can be condensed out including HCN, HCl and other acids

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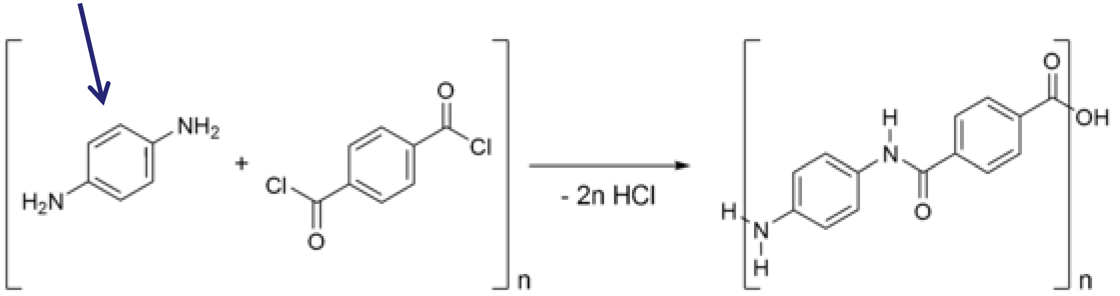
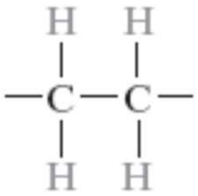
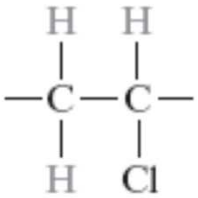
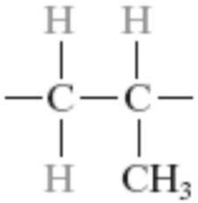

Poly-functional group

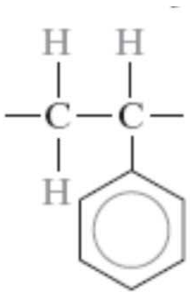
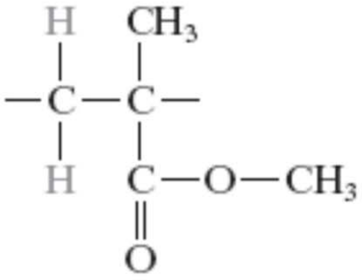
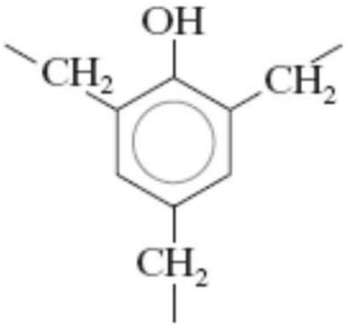
Kevlar is synthesised in solution from the monomers: 1,4-phenylene-diamine (*para*-phenylenediamine) and terephthaloyl chloride in a condensation reaction yielding hydrochloric acid as a byproduct.

Exon#ru#Frpprglw|#Sro|phuv

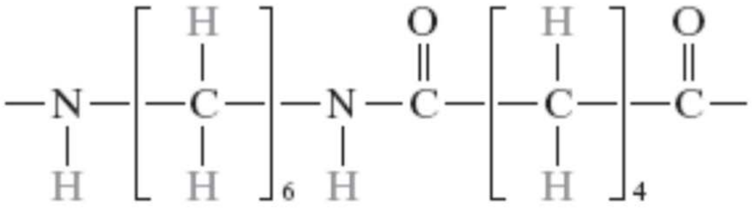
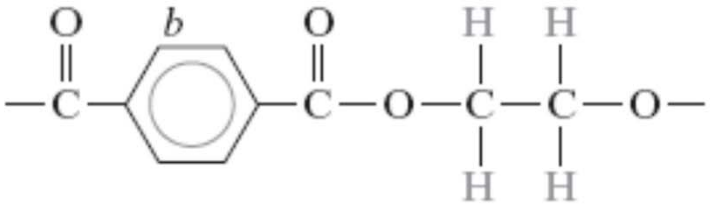
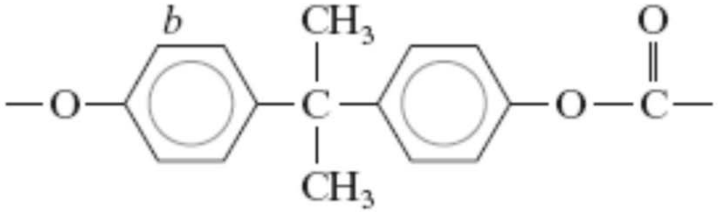
A Listing of Repeat Units for 10 of the More Common Polymeric Materials

Polymer	*Repeat Unit*
Polyethylene (PE)	 $-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-$
Poly(vinyl chloride) (PVC)	 $-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{Cl}{C}}-$
Polytetrafluoroethylene (PTFE)	 $-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-$
Polypropylene (PP)	 $-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{CH_3}{C}}-$

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

Polymer	*Repeat Unit*
Polystyrene (PS)	
Poly(methyl methacrylate) (PMMA)	
Phenol-formaldehyde (Bakelite)	

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

Polymer	*Repeat Unit*
Poly(hexamethylene adipamide) (nylon 6,6)	 $-\underset{\mathrm{H}}{\mathrm{N}}-\left[-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}-\right]_6-\underset{\mathrm{H}}{\mathrm{N}}-\overset{\mathrm{O}}{\overset{\Vert}{\mathrm{C}}}-\left[-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}-\right]_4-\overset{\mathrm{O}}{\overset{\Vert}{\mathrm{C}}}-$
Poly(ethylene terephthalate) (PET, a polyester)	
Polycarbonate (PC)	

Material Type	*Trade Names*	*Major Application Characteristics*	*Typical Applications*
		Thermoplastics	
Acrylonitrile-butadiene-styrene (ABS)	Abson Cycolac Kralastic Lustran Novodur Tybrene	Outstanding strength and toughness, resistant to heat distortion; good electrical properties; flammable and soluble in some organic solvents	Refrigerator linings, lawn and garden equipment, toys, highway safety devices
Acrylics [poly(methyl methacrylate)]	Acrylite Diakon Lucite Plexiglas	Outstanding light transmission and resistance to weathering; only fair mechanical properties	Lenses, transparent aircraft enclosures, drafting equipment, outdoor signs
Fluorocarbons (PTFE or TFE)	Teflon Fluon Halar Hostaflon TF Neoflon	Chemically inert in almost all environments, excellent electrical properties; low coefficient of friction; may be used to 260°C (500°F); relatively weak and poor cold-flow properties	Anticorrosive seals, chemical pipes and valves, bearings, antiadhesive coatings, high-temperature electronic parts
Polyamides (nylons)	Nylon Baylon Durethan Herox Nomex Ultramid Zytel	Good mechanical strength, abrasion resistance, and toughness; low coefficient of friction; absorbs water and some other liquids	Bearings, gears, cams, bushings, handles, and jacketing for wires and cables
Polycarbonates	Calibre Iupilon Lexan Makrolon Merlon	Dimensionally stable; low water absorption; transparent; very good impact resistance and ductility; chemical resistance not outstanding	Safety helmets, lenses, light globes, base for photographic film
Polyethylene	Alathon Alkathene Fortiflex Hi-fax Petrothene Rigidex Rotothene Zendel	Chemically resistant and electrically insulating; tough and relatively low coefficient of friction; low strength and poor resistance to weathering	Flexible bottles, toys, tumblers, battery parts, ice trays, film wrapping materials

Material Type	*Trade Names*	*Major Application Characteristics*	*Typical Applications*
Polypropylene	Herculon Meraklon Moplen Poly-pro Pro-fax Propak Propathene	Resistant to heat distortion; excellent electrical properties and fatigue strength; chemically inert; relatively inexpensive; poor resistance to UV light	Sterilizable bottles, packaging film, TV cabinets, luggage
Polystyrene	Carinex Dylene Hostyren Lustrex Styron Vestyron	Excellent electrical properties and optical clarity; good thermal and dimensional stability; relatively inexpensive	Wall tile, battery cases, toys, indoor lighting panels, appliance housings
Vinyls	Darvic Exon Geon Pliovic Saran Tygon Vista	Good low-cost, general-purpose materials; ordinarily rigid, but may be made flexible with plasticizers; often copolymerized; susceptible to heat distortion	Floor coverings, pipe, electrical wire insulation, garden hose, phonograph records
Polyester (PET or PETE)	Celanar Dacron Eastapak Hylar Melinex Mylar Petra	One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity, acids, greases, oils, and solvents	Magnetic recording tapes, clothing, automotive tire cords, beverage containers
		Thermosetting Polymers	
Epoxies	Araldite Epikote Epon Epi-rez Lekutherm Lytex	Excellent combination of mechanical properties and corrosion resistance; dimensionally stable; good adhesion; relatively inexpensive; good electrical properties	Electrical moldings, sinks, adhesives, protective coatings, used with fiberglass laminates
Phenolics	Bakelite Amberol Arofene Durite Resinox	Excellent thermal stability to over 150°C (300°F); may be compounded with a large number of resins, fillers, etc.; inexpensive	Motor housings, telephones, auto distributors, electrical fixtures
Polyesters	Aropol Baygal Derakane Laminac Selectron	Excellent electrical properties and low cost; can be formulated for room- or high-temperature use; often fiber reinforced	Helmets, fiberglass boats, auto body components, chairs, fans

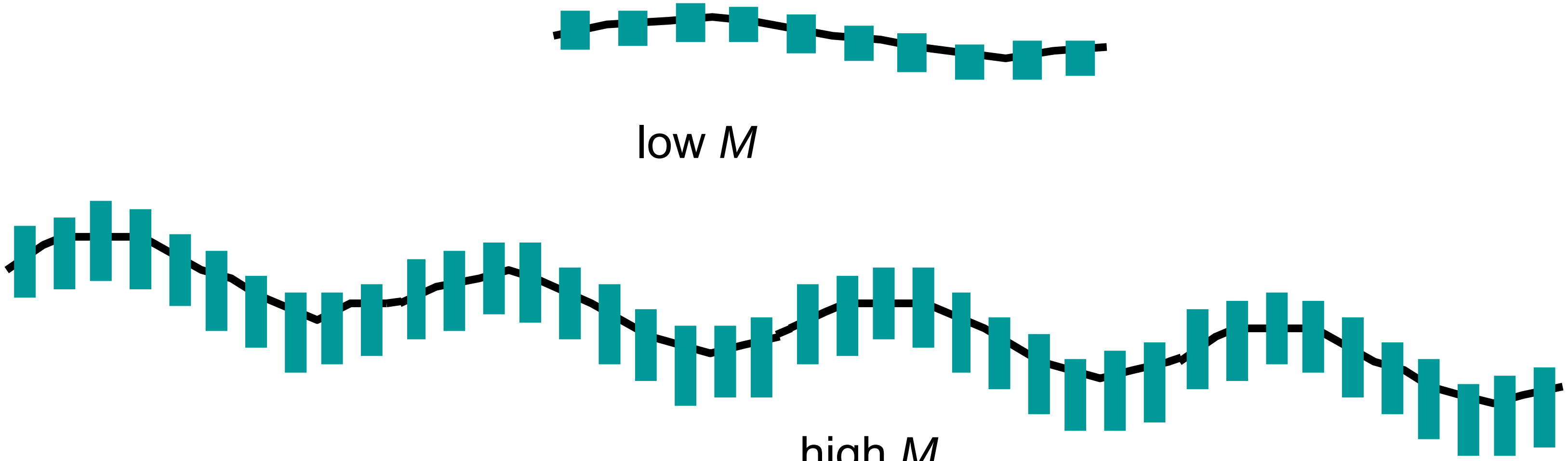
Source: Adapted from C. A. Harper (Editor), *Handbook of Plastics and Elastomers.* Copyright © 1975 by McGraw-Hill Book Company. Reproduced with permission.

Chemical Type	***Trade (Common) Names***	***Elongation (%)***	***Useful Temperature Range [°C (°F)]***	***Major Application Characteristics***	***Typical Applications***
Natural polyisoprene	Natural rubber (NR)	500–760	−60 to 120 (−75 to 250)	Excellent physical properties; good resistance to cutting, gouging, and abrasion; low heat, ozone, and oil resistance; good electrical properties	Pneumatic tires and tubes; heels and soles; gaskets
Styrene-butadiene copolymer	GRS, Buna S (SBR)	450–500	−60 to 120 (−75 to 250)	Good physical properties; excellent abrasion resistance; not oil, ozone, or weather resistant; electrical properties good, but not outstanding	Same as natural rubber
Acrylonitrile-butadiene copolymer	Buna A, Nitrile (NBR)	400–600	−50 to 150 (−60 to 300)	Excellent resistance to vegetable, animal, and petroleum oils; poor low-temperature properties; electrical properties not outstanding	Gasoline, chemical, and oil hose; seals and O-rings; heels and soles
Chloroprene	Neoprene (CR)	100–800	−50 to 105 (−60 to 225)	Excellent ozone, heat, and weathering resistance; good oil resistance; excellent flame resistance; not as good in electrical applications as natural rubber	Wire and cable; chem. tank linings; belts, hoses, seals, and gaskets
Polysiloxane	Silicone (VMQ)	100–800	−115 to 315 (−175 to 600)	Excellent resistance to high and low temperatures; low strength; excellent electrical properties	High- and low-temperature insulation; seals, diaphragms; tubing for food and medical uses

Sources: Adapted from C. A. Harper (Editor), *Handbook of Plastics and Elastomers.* Copyright © 1975 by McGraw-Hill Book Company, reproduced with permission; and Materials Engineering's *Materials Selector,* copyright Penton/IPC.

P ROHFXODU#Z HLJKW

Molecular weight, *M*: Mass of a mole of chains.



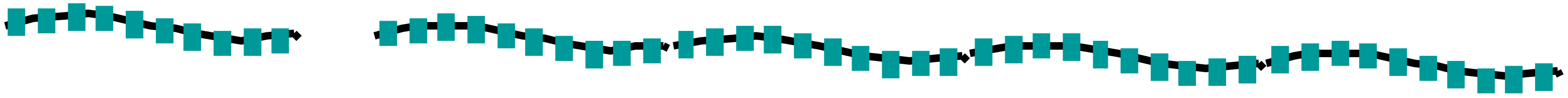
Not all chains in a polymer are of the same length i.e., there is a distribution of molecular weights

P rohfxodu#z hljkw

- The properties of a polymer depend on its length
- synthesis yields polymer distribution of lengths
- Define “average” molecular weight
- Two approaches are typically taken
  - Number average molecular weight (M_n)
  - Weight-average molecular weight (M_w)

P ROHFXODU#Z HLJKW

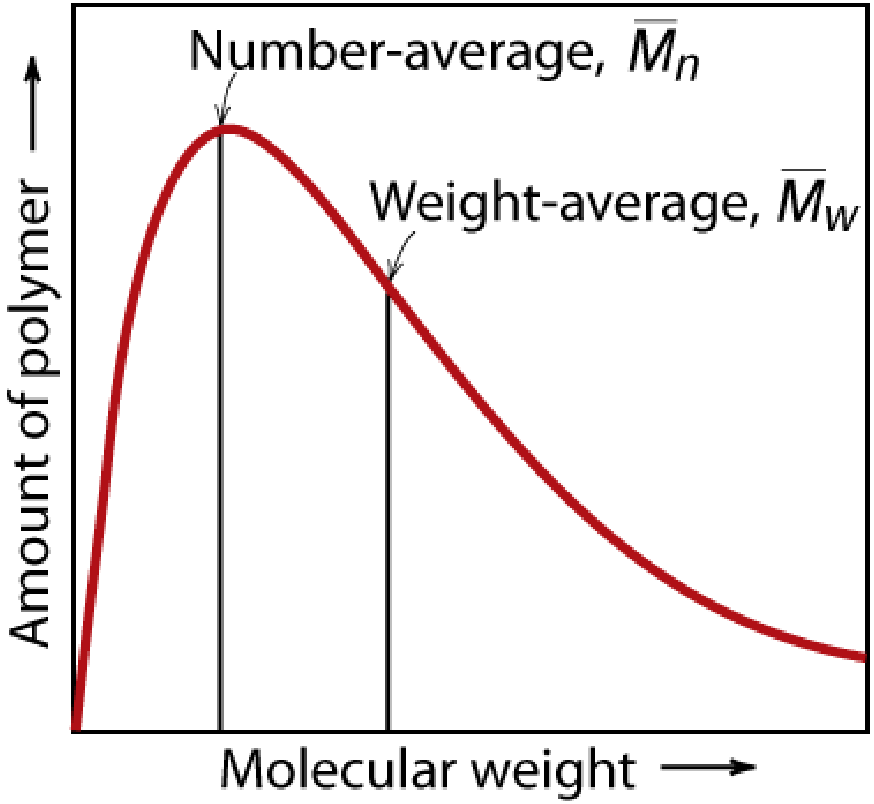
- **Molecular weight**, M_i: Mass of a *mole of chains*.



$$\overline{M}_n = \frac{\text{total wt of polymer}}{\text{total \# of molecules}}$$

$$\overline{M}_n = \Sigma x_i M_i$$
$$\overline{M}_w = \Sigma w_i M_i$$

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



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

G liihuhqw#P rohfxodu#Z hljkw#F dofxodwlrq#E dvlv

Example: average mass of a class

N_i	M_i	x_i	w_i
# of students	mass (lb)		
1	100	0.1	0.054
1	120	0.1	0.065
2	140	0.2	0.151
3	180	0.3	0.290
2	220	0.2	0.237
1	380	0.1	0.204
		$\overline{M}_n$	$\overline{M}_w$
		186 lb	216 lb

$$\overline{M}_n = \sum x_i M_i$$

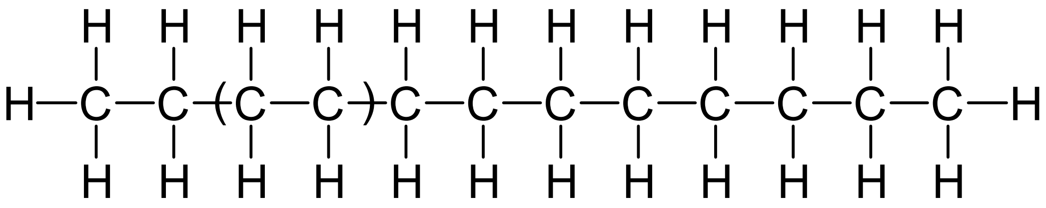
$$\overline{M}_w = \sum w_i M_i$$

$$x_i = N_i \Big/ \sum_{all\ i} N_i$$

$$w_i = N_i * M_i \Big/ \sum_{all\ i} N_i * M_i$$

Ghjuhh#ri#Sro|phul}dwlrq/#q

***n* = number of repeat units per chain**



$$\mathrm{H{-}CH_2{-}CH_2{-}(CH_2{-}CH_2){-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}CH_2{-}H}$$

$n_i = 6$

$$n_n = \sum x_i n_i = \frac{\overline{M}_n}{\overline{m}} \qquad n_w = \sum w_i n_i = \frac{\overline{M}_w}{\overline{m}}$$

where $\overline{m}$ = average molecular weight of repeat unit

$$\overline{m} = \Sigma f_i m_i$$

Chain fraction

mol. wt of repeat unit i

Sro|phuv#Ù Prohfxodu#Vkdsh

Conformation – Molecular orientation can be changed by rotation around the bonds

- note: no bond breaking needed

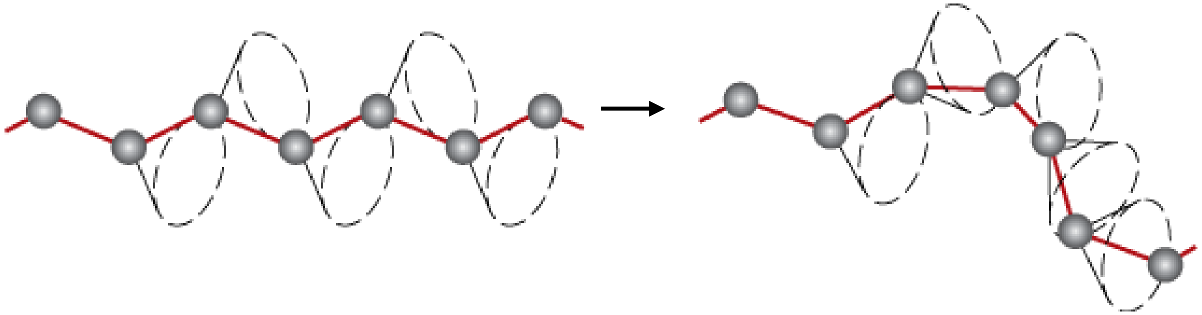
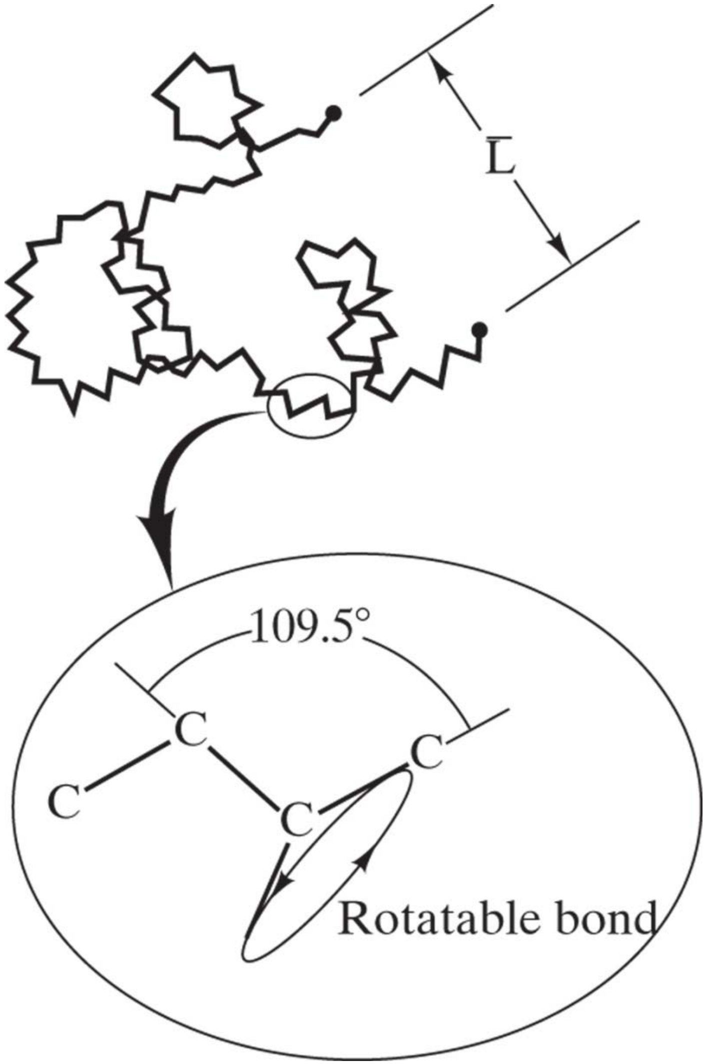


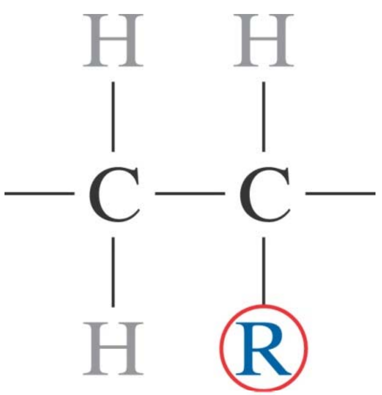
Figure 12.8 The length of kinked molecular chain is given by Equation 12.4, due to the free rotation of the C—C—C bond angle of 109.5°.



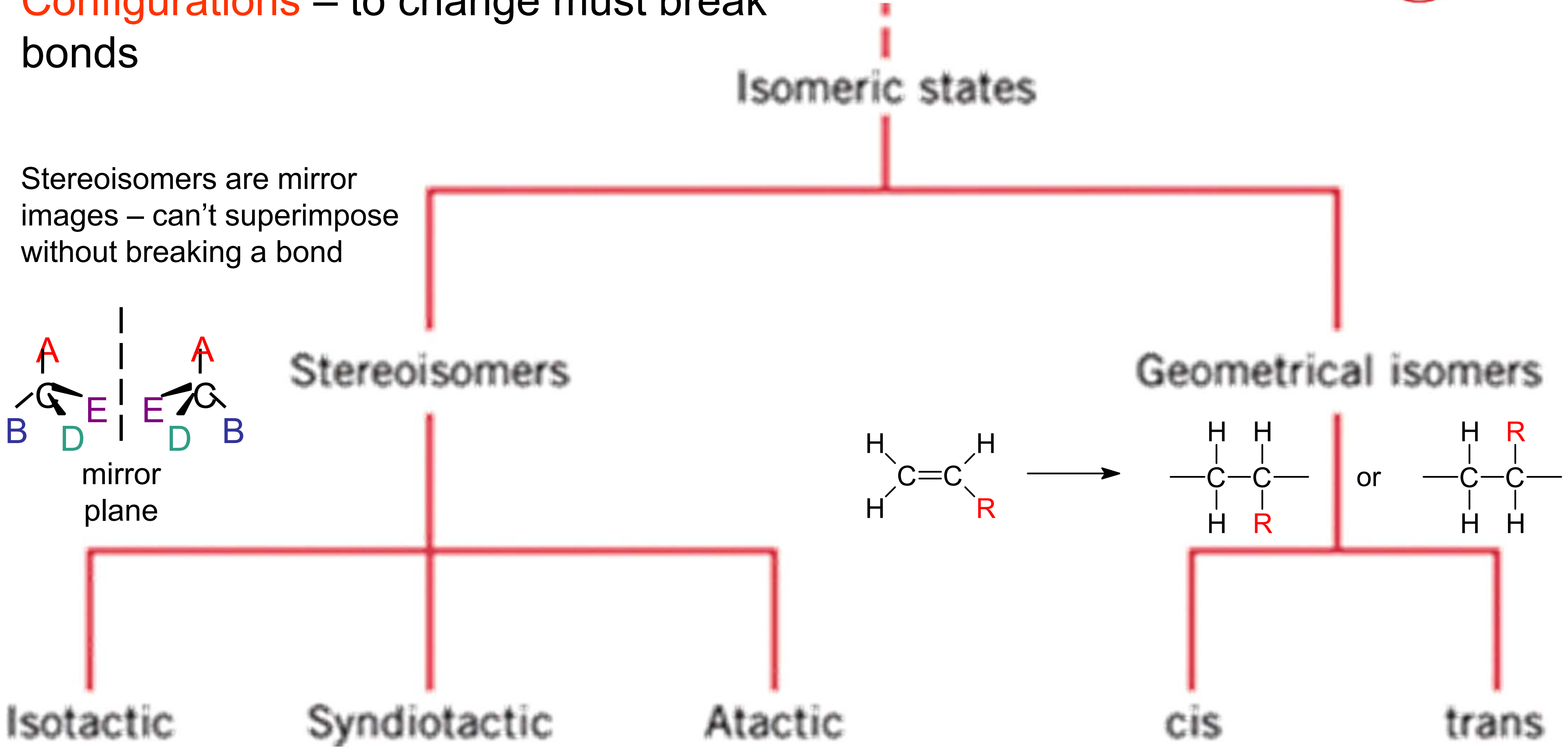
4.8 Molecular Configurations

Repeat unit

R = Cl, CH_3, etc



Configurations – to change must break bonds

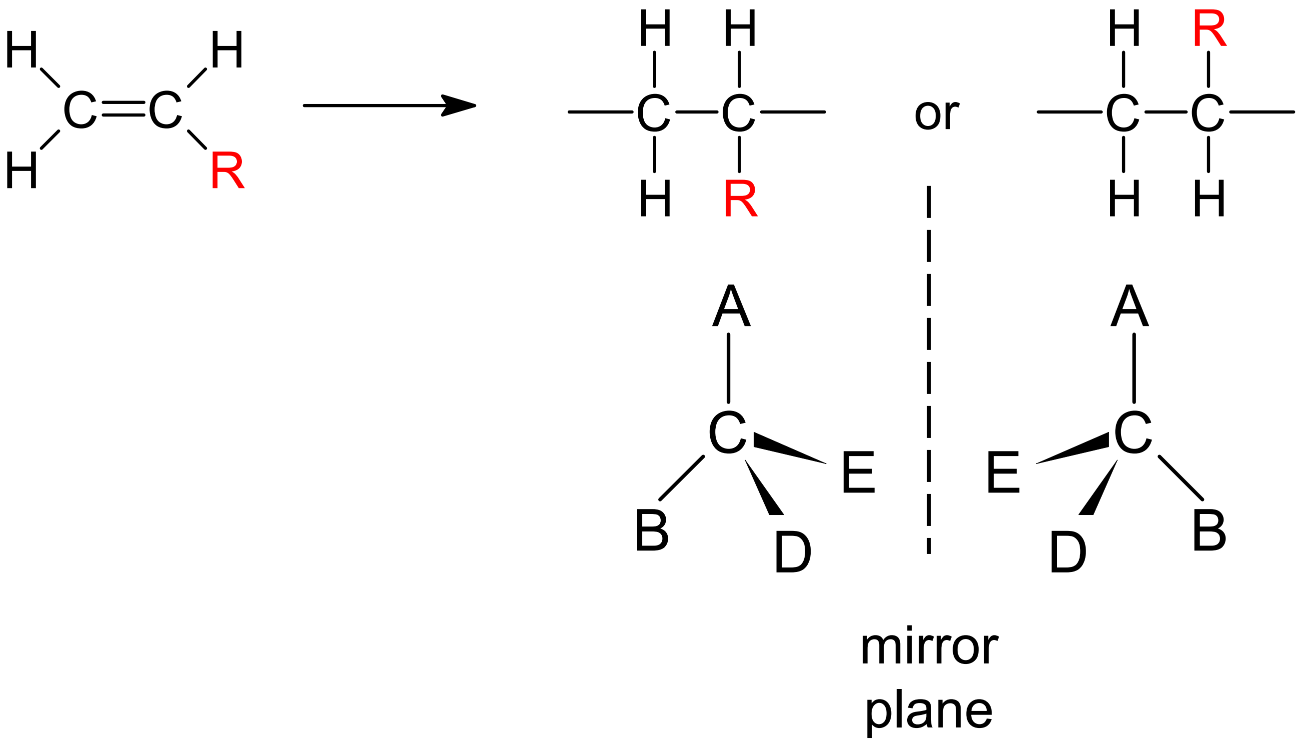


Stereoisomers are mirror images – can't superimpose without breaking a bond

S ro|p huv#Ù P rohfxodu#Vkdsh

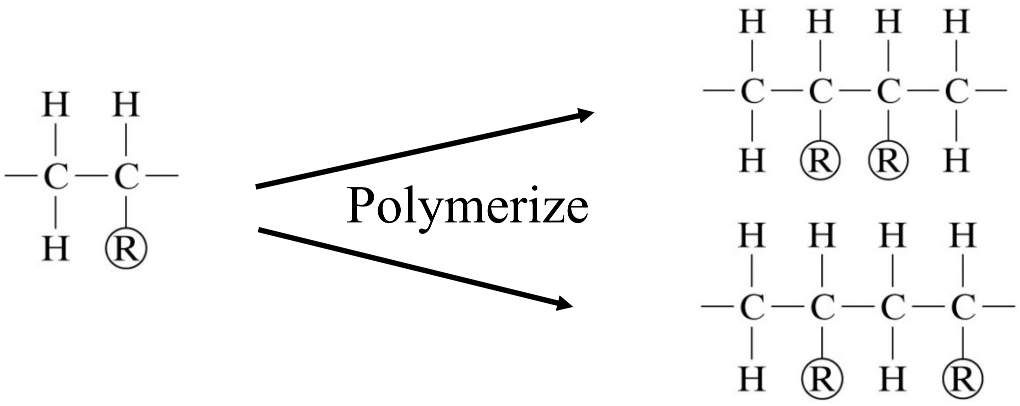
Configurations – to change must break bonds

- Stereoisomerism



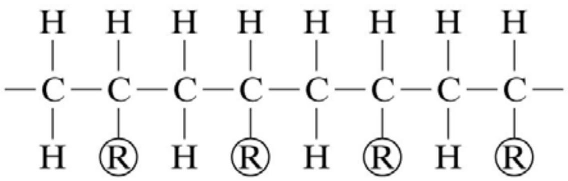
Polymer Molecular Configurations

ˇ#Uhjxodulw|#dqg#v|phwu|#ri#vlgh#jurxsv#diihfw#surshuwlhv



Can it crystallize?
Melting T?

ˇ#Vwhuhrlvrphulvp=#fdq#dgg#jhrphwulf#lvrphulvp#wrr,

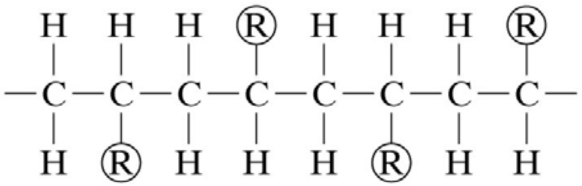


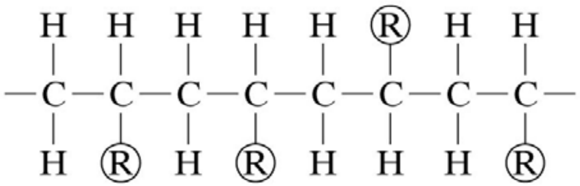
Isotactic

On one side

Syndiotactic

Alternating sides





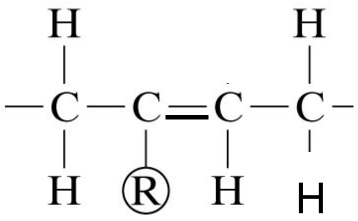
Atactic

Randomly placed

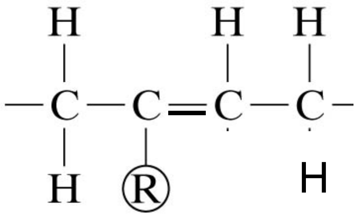
- Conversion from one stereoisomerism to another is *not* possible by simple rotation about single chain bond; bonds must be severed first, then reformed!

Polymer Geometrical Isomerism

˘#Uhjxodulw|#dqg#v|pphwu|#ri#vlgh#jurxsv#diihfw#surshuwlhv



cis-structure



trans-structure

with R= CH_3 to form rubber

Cis-polyisoprene **trans-polyisoprene**

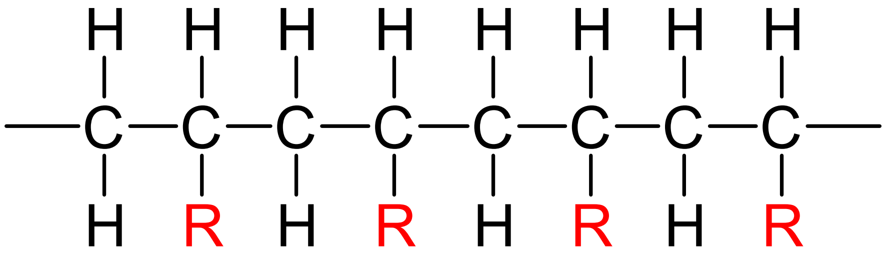
-Conversion from one ***isomerism*** to another is *not* possible by simple rotation about chain bond because double-bond is too rigid!

-See Figure 4.8 for taxonomy of polymer structures

Tacticity

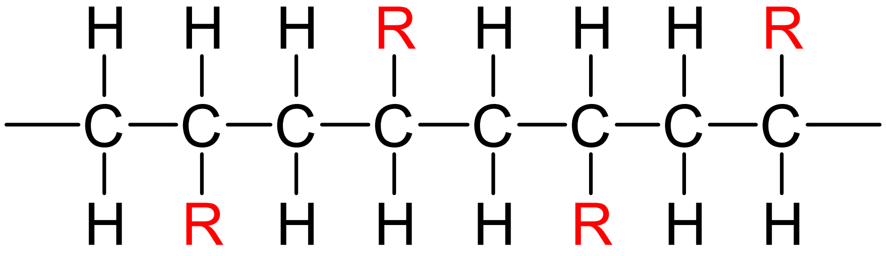
Tacticity – stereoregularity of chain

isotactic – all R groups on
same side of chain



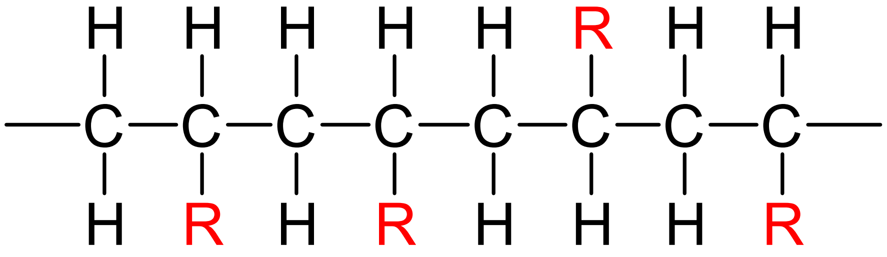
$$\begin{array}{ccccccccccccccccc}
 & H & & H & & H & & H & & H & & H & & H & & H & \\
 & | & & | & & | & & | & & | & & | & & | & & | & \\
- & C & - & C & - & C & - & C & - & C & - & C & - & C & - & C & - \\
 & | & & | & & | & & | & & | & & | & & | & & | & \\
 & H & & R & & H & & R & & H & & R & & H & & R &
\end{array}$$

syndiotactic – R groups
alternate sides



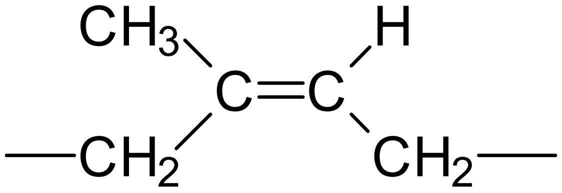
$$\begin{array}{ccccccccccccccccc}
 & H & & H & & H & & R & & H & & H & & H & & R & \\
 & | & & | & & | & & | & & | & & | & & | & & | & \\
- & C & - & C & - & C & - & C & - & C & - & C & - & C & - & C & - \\
 & | & & | & & | & & | & & | & & | & & | & & | & \\
 & H & & R & & H & & H & & H & & R & & H & & H &
\end{array}$$

atactic – R groups random



$$\begin{array}{ccccccccccccccccc}
 & H & & H & & H & & H & & H & & R & & H & & H & \\
 & | & & | & & | & & | & & | & & | & & | & & | & \\
- & C & - & C & - & C & - & C & - & C & - & C & - & C & - & C & - \\
 & | & & | & & | & & | & & | & & | & & | & & | & \\
 & H & & R & & H & & R & & H & & H & & H & & R &
\end{array}$$

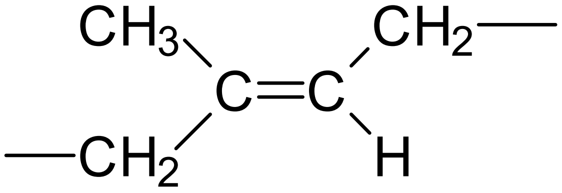
cis/trans Isomerism



cis

cis-isoprene
(natural rubber)

bulky groups on same
side of chain



trans

trans-isoprene
(gutta percha)

bulky groups on opposite
sides of chain

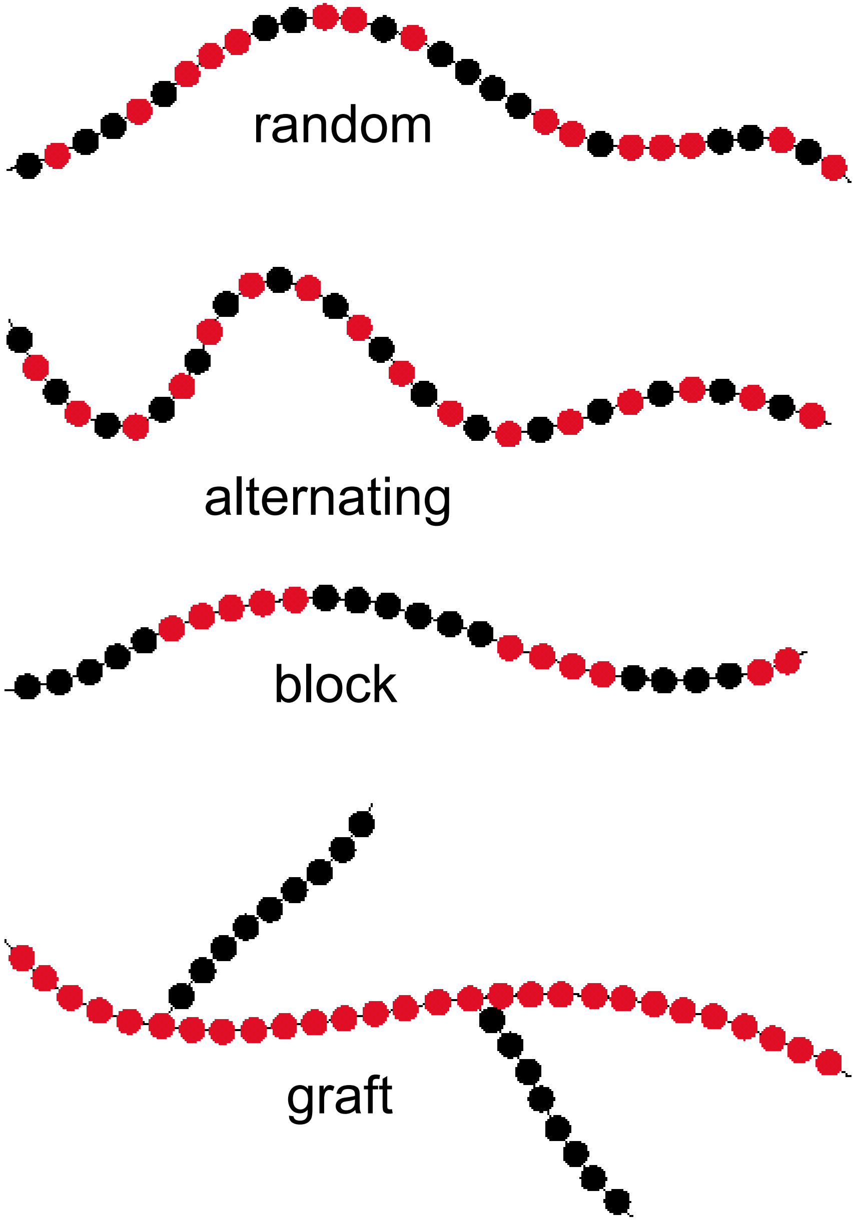
Frsro|p huv

two or more monomers polymerized together

- random – A and B randomly vary in chain
- alternating – A and B alternate in polymer chain
- block – large blocks of A alternate with large blocks of B
- graft – chains of B grafted on to A backbone

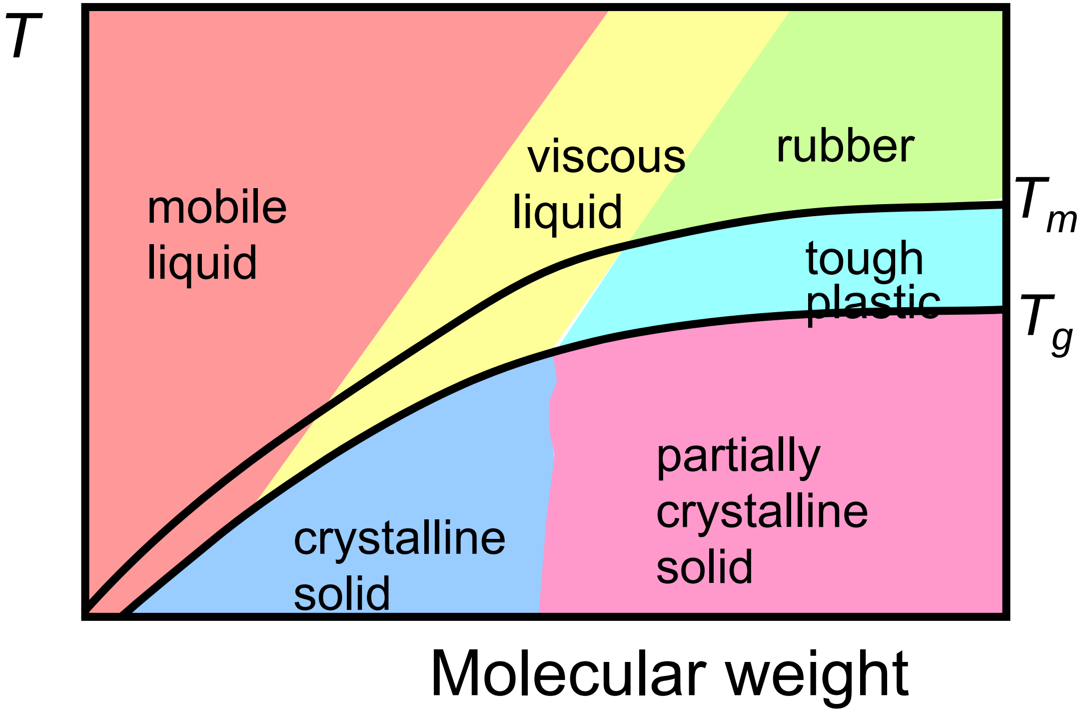
A – ●

B – ●



Thermoplastics vs. Thermosets

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



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.)

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

Polymer Additives

Improve mechanical properties, processability, durability, etc.

- Fillers
  - Added to improve tensile strength & abrasion resistance, toughness & decrease cost
  - ex: carbon black, silica gel, wood flour, glass, limestone, talc, etc.

- Plasticizers
  - Added to reduce the glass transition temperature T_g
  - commonly added to PVC - otherwise it is brittle

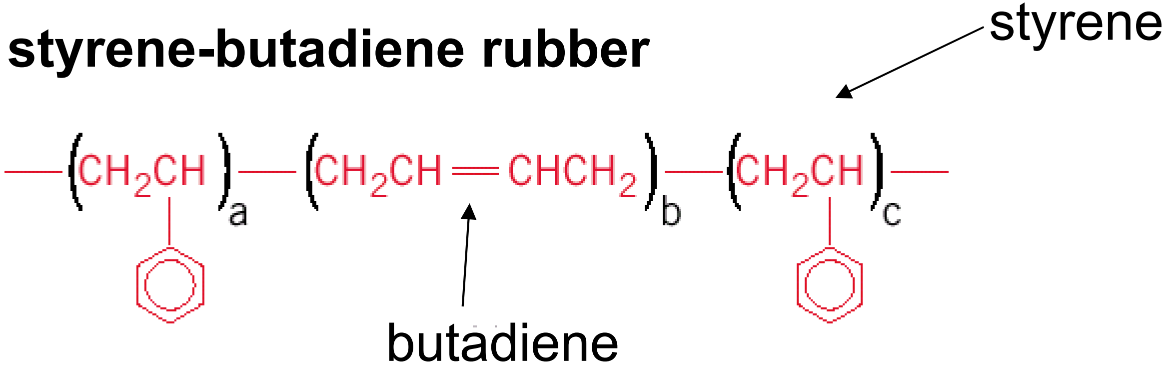
Polymer Additives

- Stabilizers
  - Antioxidants
  - UV protectants
- Lubricants
  - Added to allow easier processing
  - "slides" through dies easier – ex: Na stearate
- Colorants
  - Dyes or pigments
- Flame Retardants
  - Cl/F & B

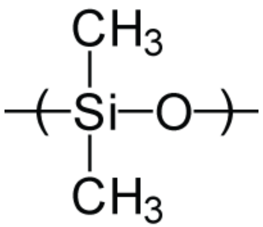
Polymer Types: Elastomers

Elastomers – rubber

- **Crosslinked materials**
  - **Natural rubber**
  - **Synthetic rubber and thermoplastic elastomers**
    - **SBR- styrene-butadiene rubber**



- Silicone rubber



$$-\!\left(\begin{array}{c}CH_3\\ |\\ Si-O\\ |\\ CH_3\end{array}\right)\!-$$

Polymer Types: Fibers

Fibers - length/diameter >100

- Textiles are main use
  - Must have high tensile strength
  - Usually highly crystalline & highly polar

- Formed by spinning
  - ex: extrude polymer through a spinnerette
    - Pt plate with 1000's of holes for nylon
    - ex: rayon – dissolved in solvent then pumped through die head to make fibers
  - the fibers are drawn
  - leads to highly aligned chains- fibrillar structure

Polymer Types

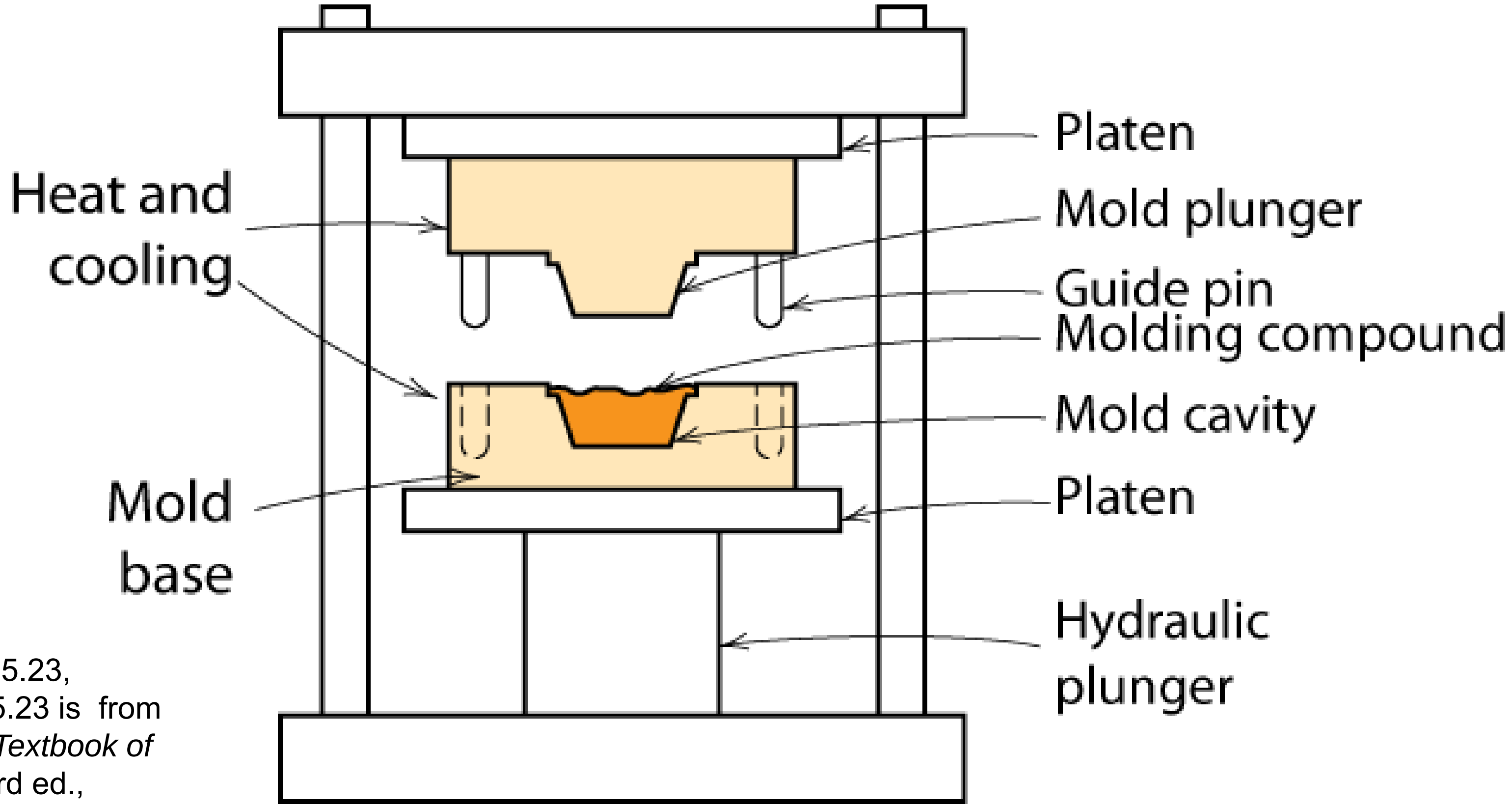
- Coatings – thin film on surface – i.e. paint, varnish
  - To protect item
  - Improve appearance
  - Electrical insulation
- Adhesives – produce bond between two adherands
  - Usually bonded by:
    1. Secondary bonds
    2. Mechanical bonding
- Films – blown film extrusion
- Foams – gas bubbles in plastic

Processing of Plastics

- Thermoplastic –
  - can be reversibly cooled & reheated, i.e. recycled
  - heat till soft, shape as desired, then cool
  - ex: polyethylene, polypropylene, polystyrene, etc.
- Thermoset
  - when heated forms a network
  - degrades (not melts) when heated
  - mold the prepolymer then allow further reaction
  - ex: urethane, epoxy

Processing Plastics - Molding

- **Compression and transfer molding**
  - **thermoplastic or thermoset**

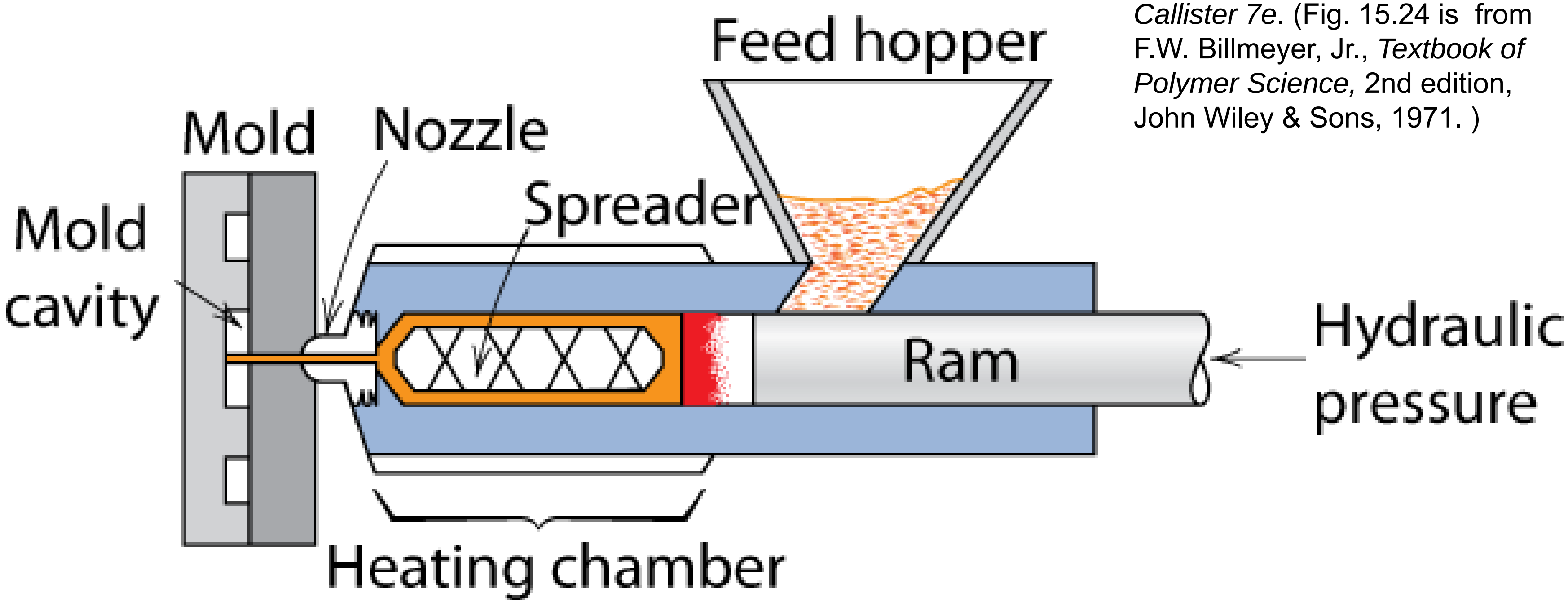


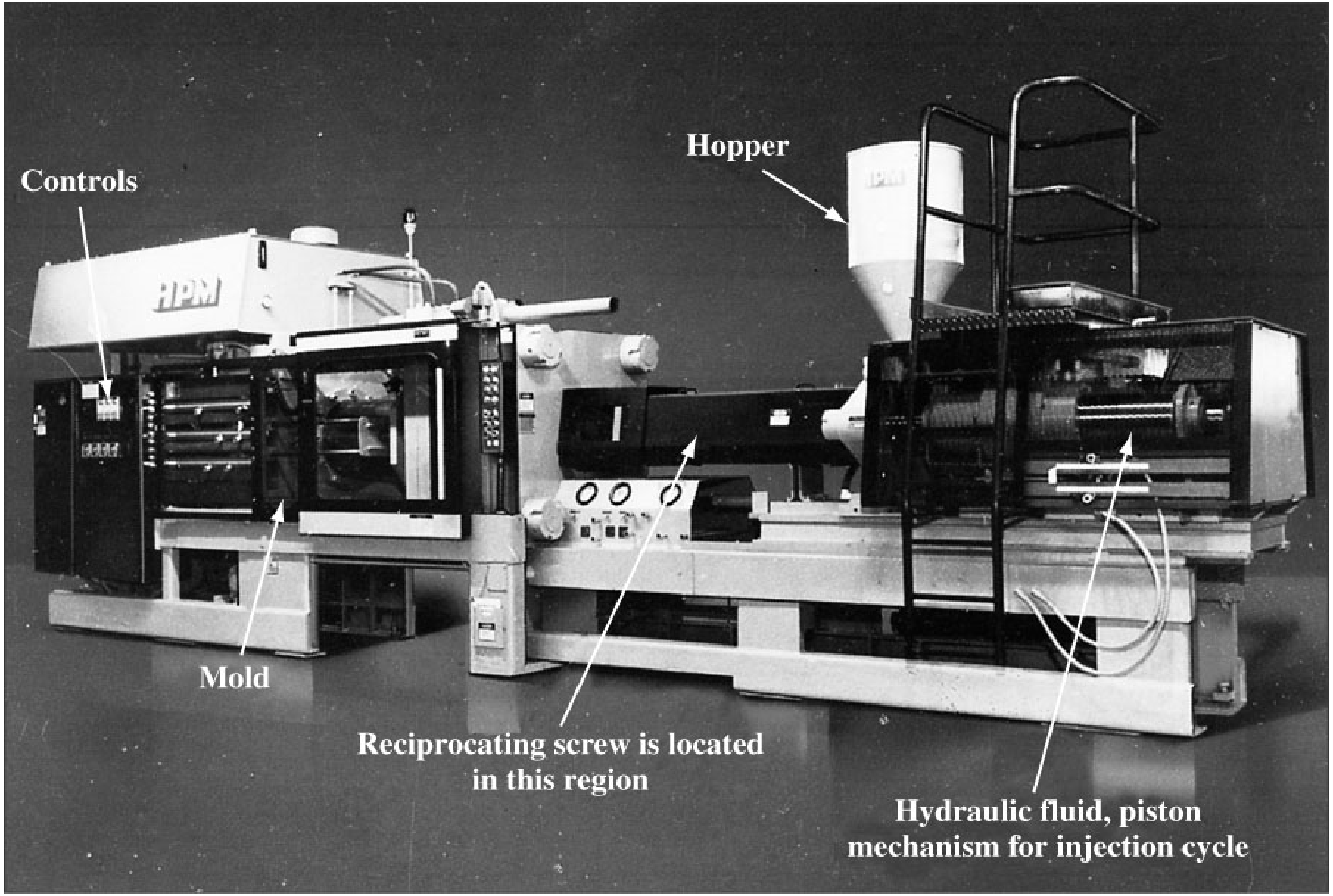
Adapted from Fig. 15.23, *Callister 7e*. (Fig. 15.23 is from F.W. Billmeyer, Jr., *Textbook of Polymer Science,* 3rd ed., John Wiley & Sons, 1984.)

Processing Plastics - Molding

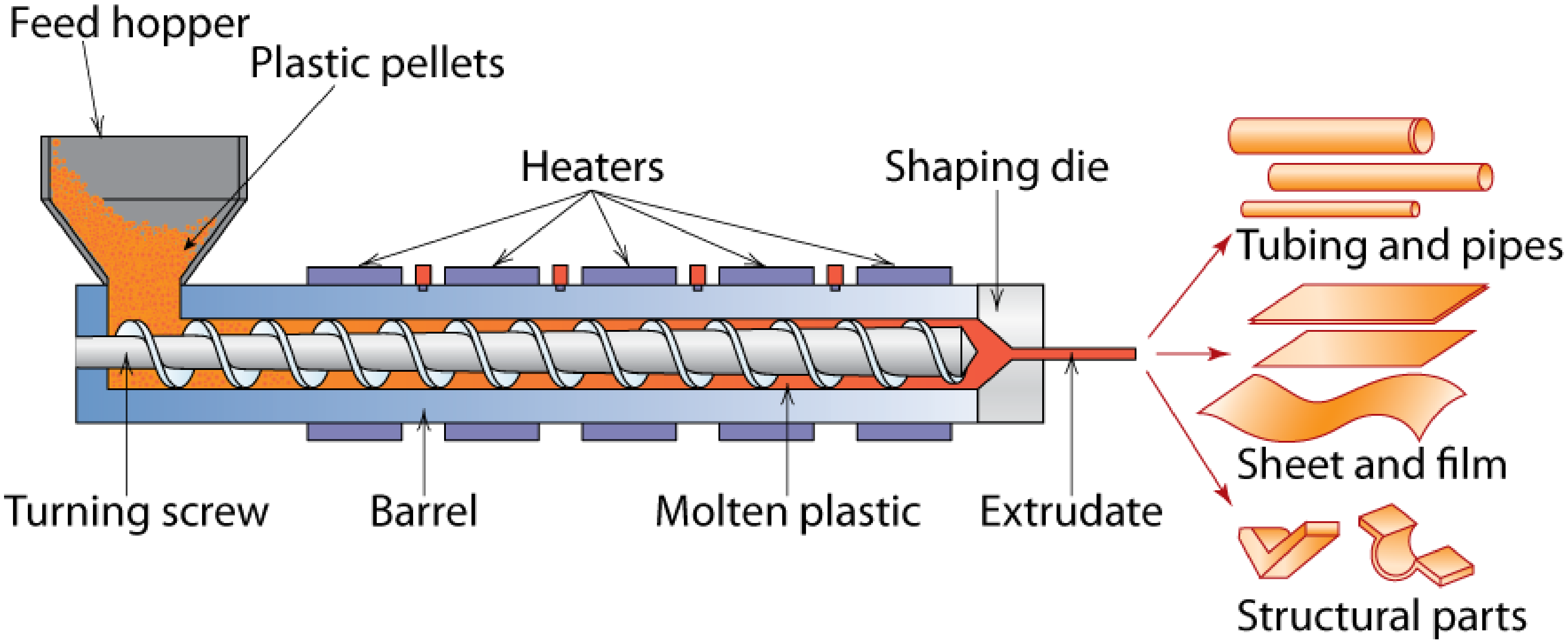
- Injection molding
  - thermoplastic & some thermosets

Adapted from Fig. 15.24, *Callister 7e*. (Fig. 15.24 is from F.W. Billmeyer, Jr., *Textbook of Polymer Science*, 2nd edition, John Wiley & Sons, 1971.)



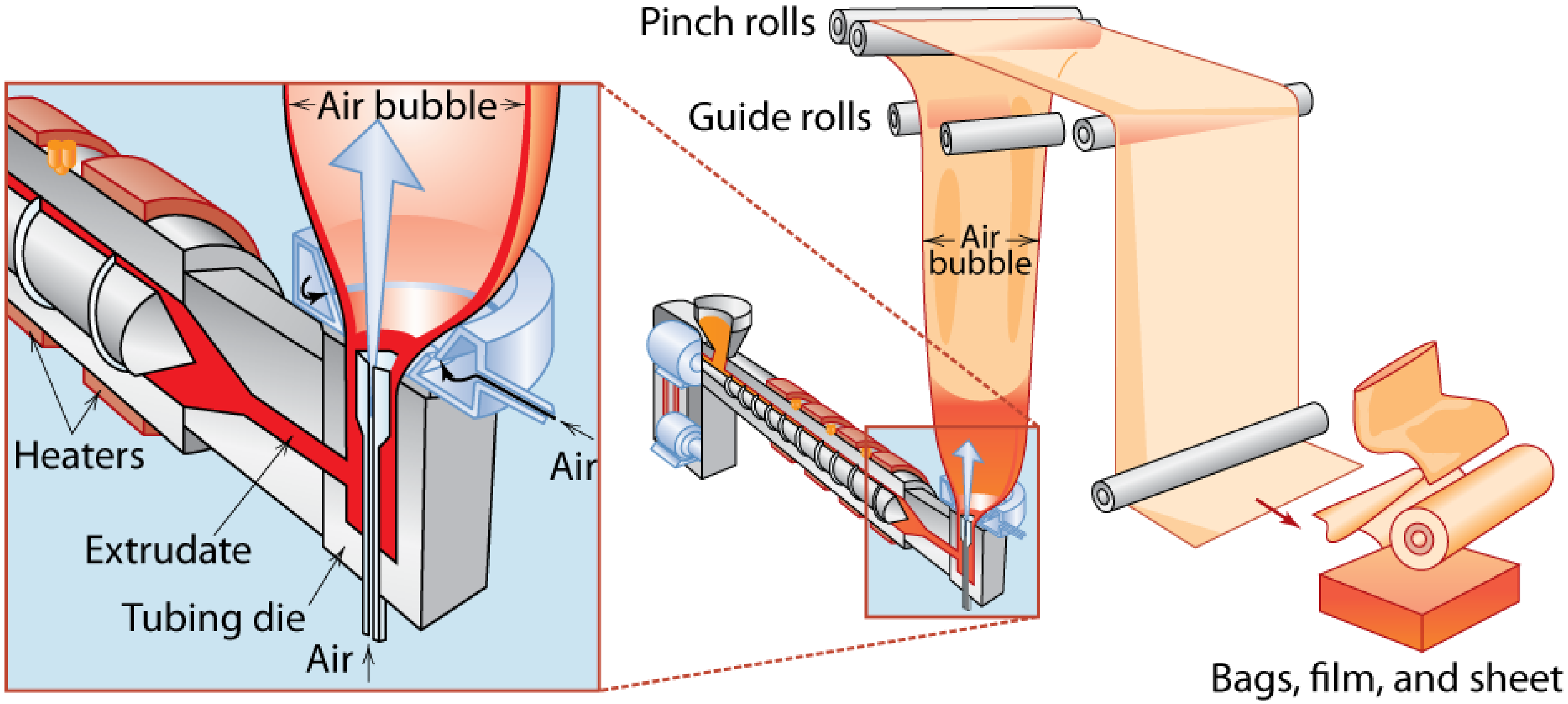

Controls
Hopper
HPM
Mold
Reciprocating screw is located in this region
Hydraulic fluid, piston mechanism for injection cycle

Processing Plastics – Extrusion



Adapted from Fig. 15.25,
Callister 7e. (Fig. 15.25 is from
Encyclopædia Britannica, 1997.)

Blown-Film Extrusion



(from *Encyclopædia Britannica*, 1997.)

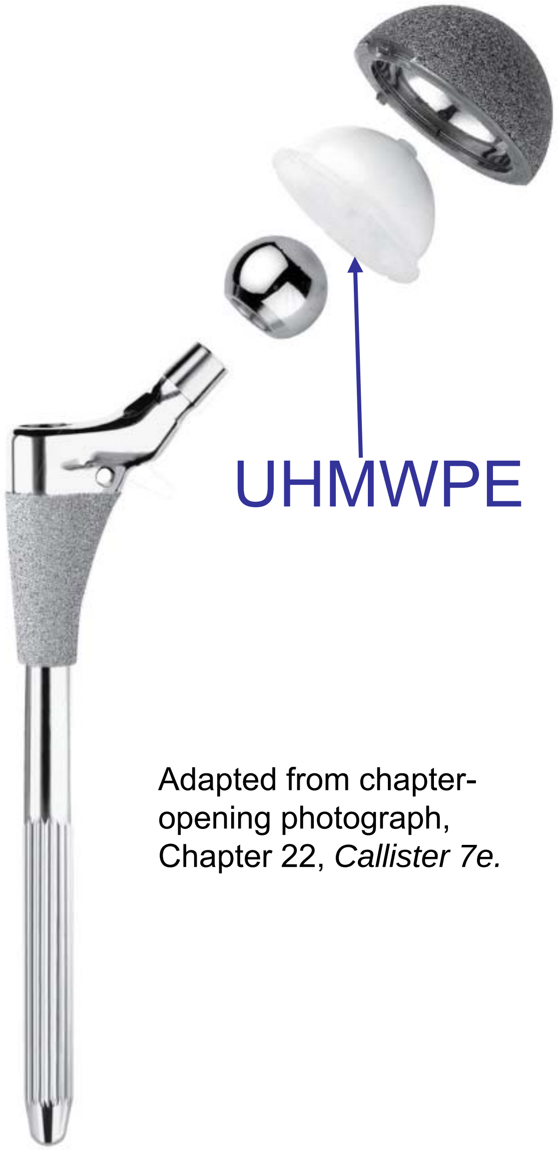
TABLE 12.10

The Relationship of Processing, Molecular Structure, and Mechanical Behavior for Polymers

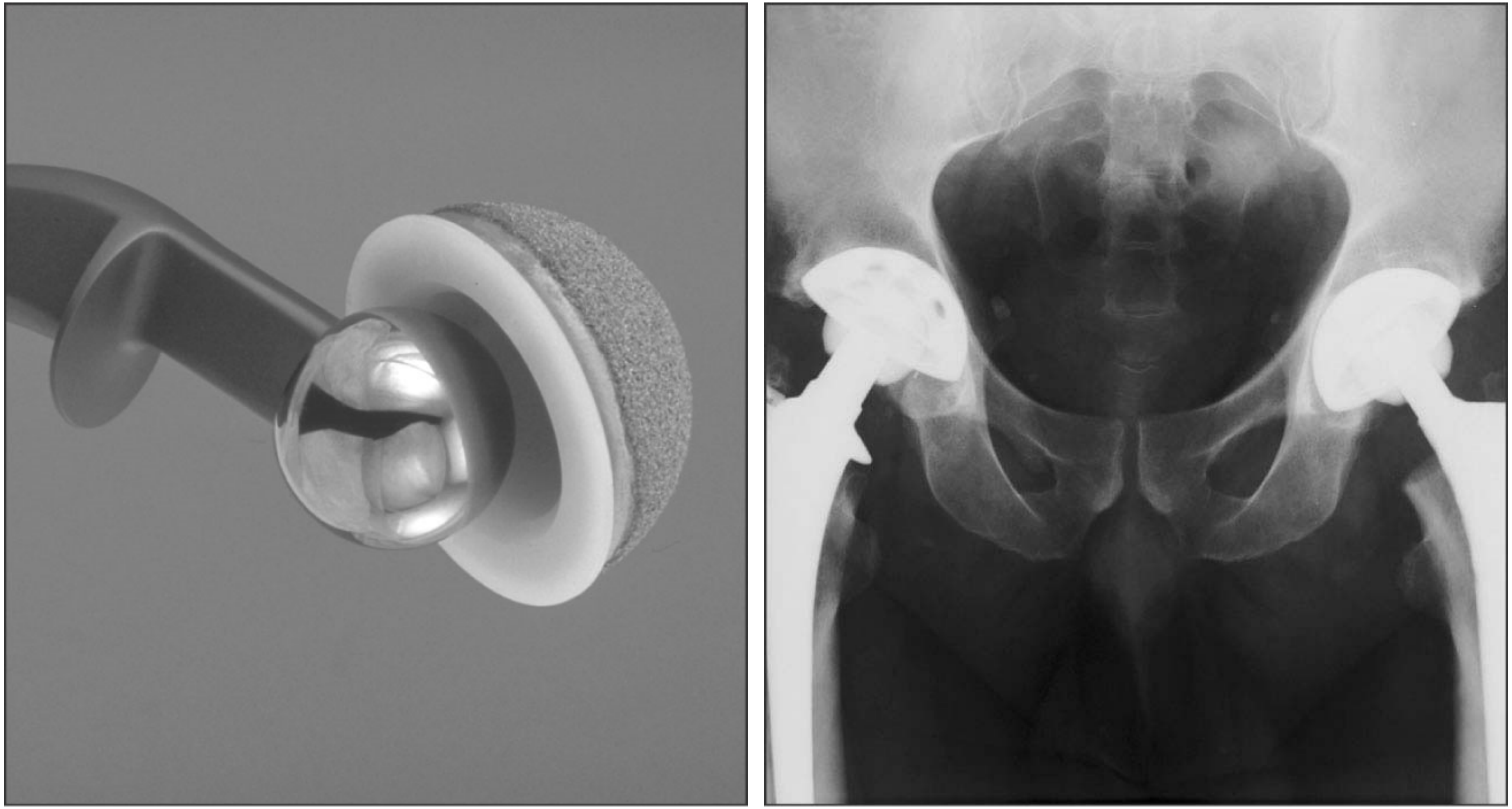
Category	Processing technique	Molecular structure	Mechanical effect
Thermoplastic polymers	Addition agent	Branching	Increased strength and stiffness
	Vulcanization	Cross-linking	Increased strength and stiffness
	Crystallization	Increased crystallinity	Increased strength and stiffness
	Plasticizer	Decreased molecular weight	Decreased strength and stiffness
	Filler	Restricted chain mobility	Increased strength and stiffness
Thermosetting polymers	Setting at elevated temperatures	Network formation	Rigid (remaining upon cooling)

Advanced Polymers

- Ultrahigh molecular weight polyethylene (UHMWPE)
  - Molecular weight
    ca. 4×10^6 g/mol
  - Excellent properties for variety of applications
    - bullet-proof vest, golf ball covers, hip joints, etc.



Adapted from chapter-opening photograph, Chapter 22, *Callister 7e.*



The Stem, femoral head, and the AC socket are made from Cobalt-chrome metal alloy or ceramic, AC cup made from polyethylene

ABS – A Polymerized "Alloy"

ABS, Acrylonitrile-Butadiene-Styrene

Made up of the 3 materials: acrylonitrile, butadiene and styrene. The material is located under the group styrene plastic. Styrene plastics are in volume one of the most used plastics.

Properties

The mechanical properties for ABS are good for impact resistance even in low temperatures. The material is stiff, and the properties are kept over a wide temperature range. The hardness and stiffness for ABS is lower than for PS and PVC.

Weather and chemical resistance

The weather resistance for ABS is restricted, but can be drastically improved by additives as black pigments. The chemical resistance for ABS is relatively good and it is not affected by water, non organic salts, acids and basic. The material will dissolve in aldehyde, ketone, ester and some chlorinated hydrocarbons.

Processing

ABS can be processed by standard mechanical tools as used for machining of metals and wood. The cutting speed need to be high and the cutting tools has to be sharp. Cooling is recommended to avoid melting of the material. If the surface finish is of importance for the product, the ABS can be treated with varnish, chromium plated or doubled by a layer of acrylic or polyester. ABS can be glued to it self by use of a glue containing dissolvent. Polyurethane based or epoxy based glue can be used for gluing to other materials.

A Processing Movie:

Calloway Golf:

Summary - Polymers

- General drawbacks to polymers:
  -- E, σ_y, K_c, $T_{application}$ are generally small.
  -- Deformation is often T and time dependent.
  -- Result: polymers benefit from composite reinforcement.

- Thermoplastics (PE, PS, PP, PC):
  -- Smaller E, σ_y, $T_{application}$
  -- Larger K_c
  -- Easier to form and recycle

- Elastomers (rubber):
  -- Large reversible strains!

- Thermosets (epoxies, polyesters):
  -- Larger E, σ_y, $T_{application}$
  -- Smaller K_c

Composites:

- A Composite material is a material system composed of two or more **macro constituents** that differ in shape and chemical composition and which are insoluble in each other. The history of composite materials dates back to early 20th century. In 1940, fiber glass was first used to reinforce epoxy.
- Applications:
  - Aerospace industry
  - Sporting Goods Industry
  - Automotive Industry
  - Home Appliance Industry

Advanced Aerospace Application:

Boeing 767 (and in 777, 787 airplanes w/ the latest, full wing box is composite):

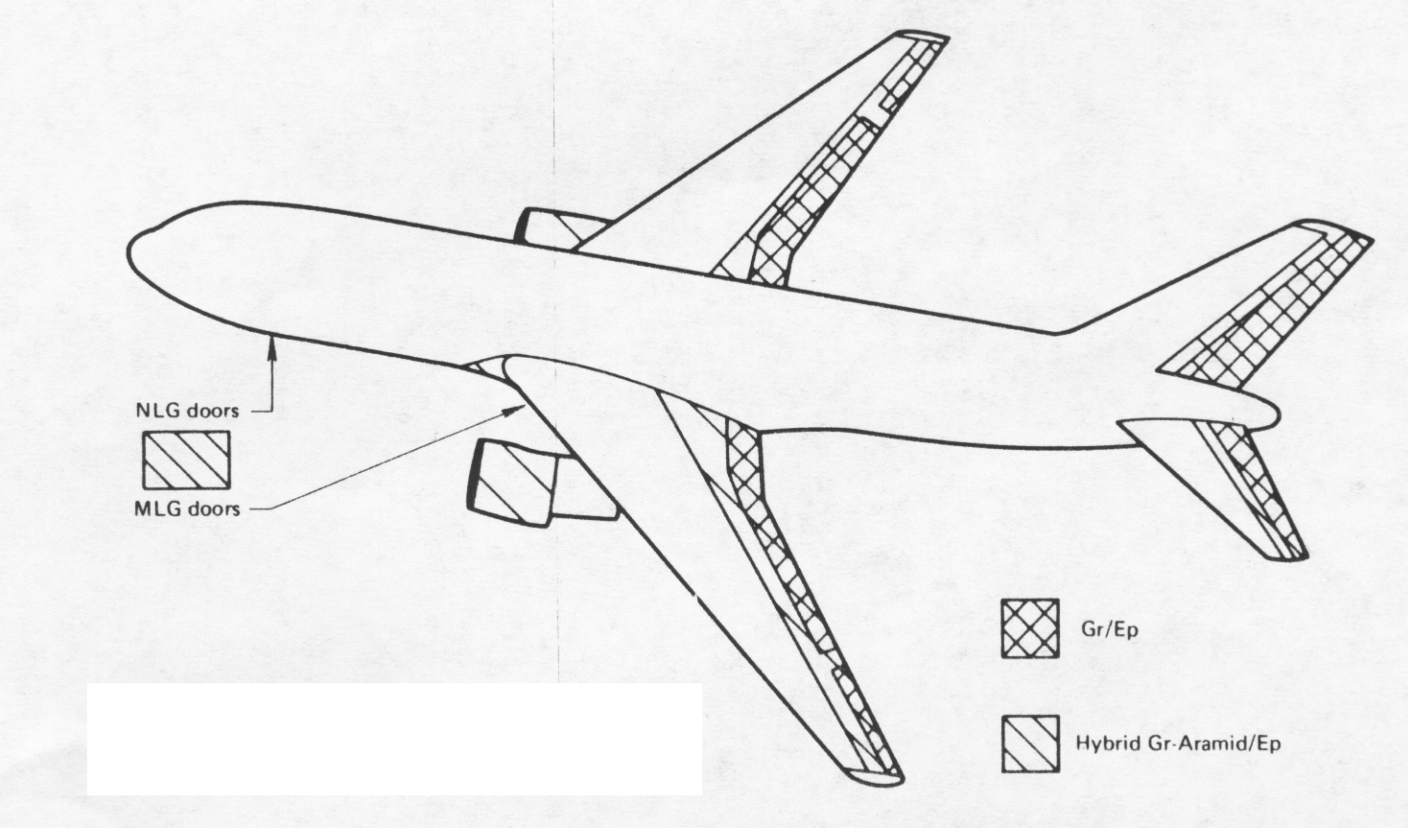
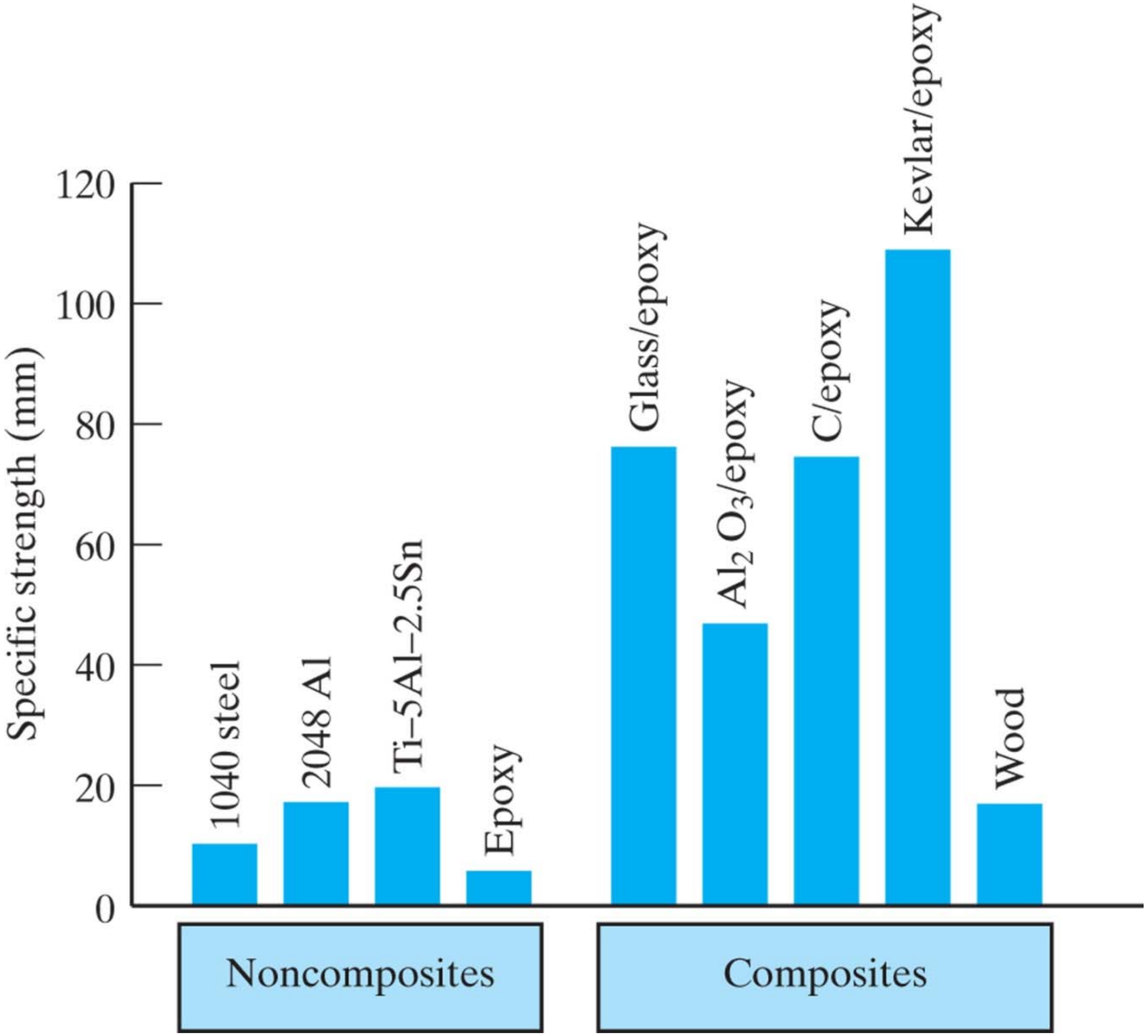


Figure 12.22 A bar graph plot of the data of Table 12.8 illustrates the substantial increase in specific strength (strength-to-weight ratio) possible with composites.



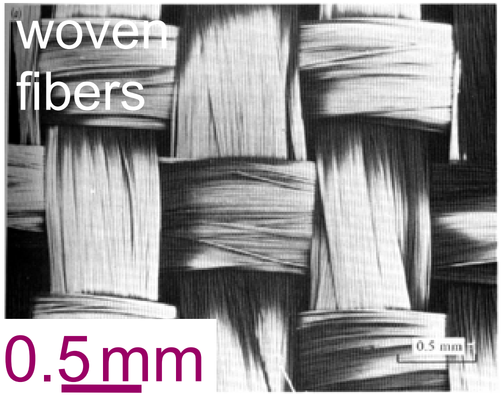
Terminology/Classification

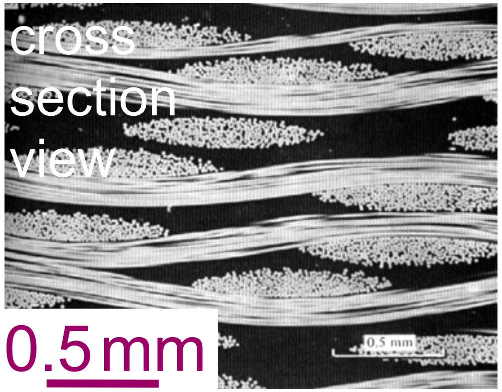
- Composites:
  -- Multiphase material w/significant proportions of each phase.
- Matrix:
  -- The continuous phase
  -- Purpose is to:
    - transfer stress to other phases
    - protect phases from environment

  -- Classification: MMC, CMC, PMC

  metal ceramic polymer
- Dispersed phase:
  -- Purpose: enhance matrix properties.
    MMC: increase σy, *TS*, creep resist.
    CMC: increase K_c
    PMC: increase E, σy, *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.

TABLE 12.2

Polymeric Matrix Materials for Fiberglass

Polymer	**Characteristics and applications**
Thermosetting	
Epoxies	High strength (for filament-wound vessels)
Polyesters	For general structures (usually fabric reinforced)
Phenolics	High-temperature applications
Silicones	Electrical applications (e.g., printed-circuit panels)
Thermoplastic	
Nylon 66	
Polycarbonate	Less common, especially good ductility
Polystyrene	

Source: Data from L. J. Broutman and R. H. Krock, Eds., *Modern Composite Materials*, Addison-Wesley Publishing Co., Inc., Reading, MA, 1967, Chapter 13.

TABLE 12.3

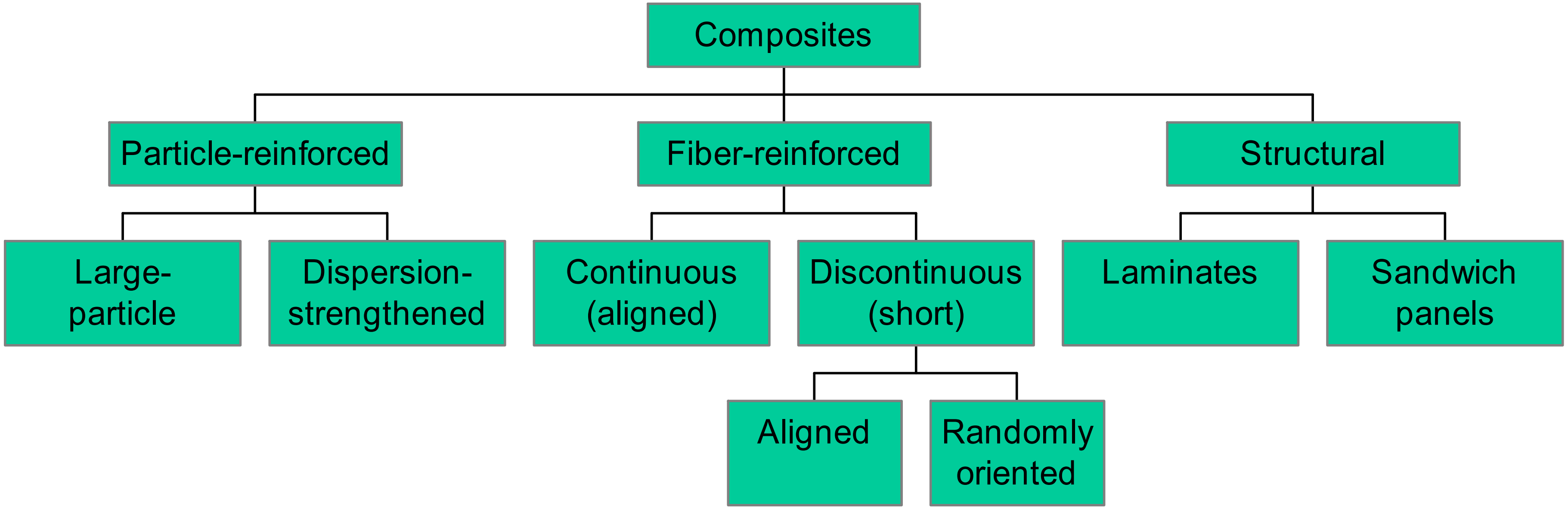
Advanced Composite Systems Other Than Fiberglass

Class	Fiber/Matrix
Polymer matrix	Para-aramid (Kevlar[a])/epoxy
	Para-aramid (Kevlar[a])/polyester
	C (graphite)/epoxy
	C (graphite)/polyester
	C (graphite)/polyetheretherketone (PEEK)
	C (graphite)/polyphenylene sulfide (PPS)
Metal matrix	B/Al
	C/Al
	Al_2O_3/Al
	Al_2O_3/Mg
	SiC/Al
	SiC/Ti (alloys)
Ceramic matrix	Nb/$MoSi_2$
	C/C
	C/SiC
	SiC/Al_2O_3
	SiC/SiC
	SiC/Si_3N_4
	SiC/Li–Al–silicate (glass-ceramic)

[a] Trade name, Du Pont.

Source: Data from K. K. Chawla, University of Alabama, Birmingham; A. K. Dhingra, the Du Pont Company; and A. J. Klein, ASM International.

Composite Survey



Composites

Particle-reinforced

Fiber-reinforced

Structural

Large-particle

Dispersion-strengthened

Continuous (aligned)

Discontinuous (short)

Laminates

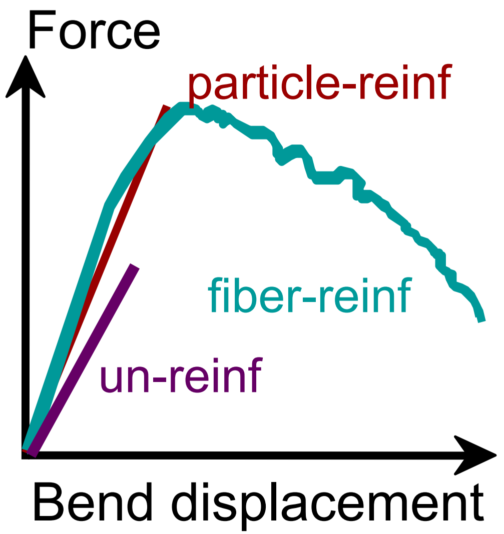
Sandwich panels

Aligned

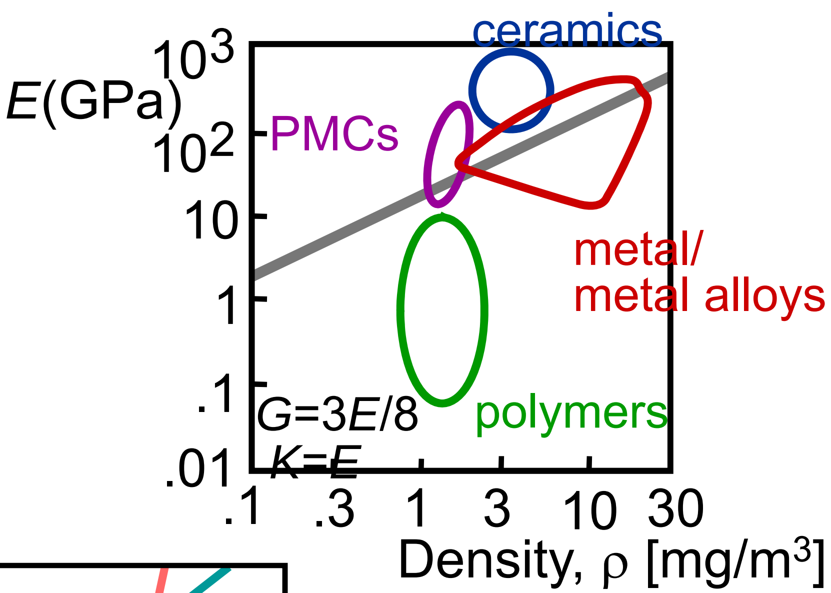
Randomly oriented

Composite Benefits

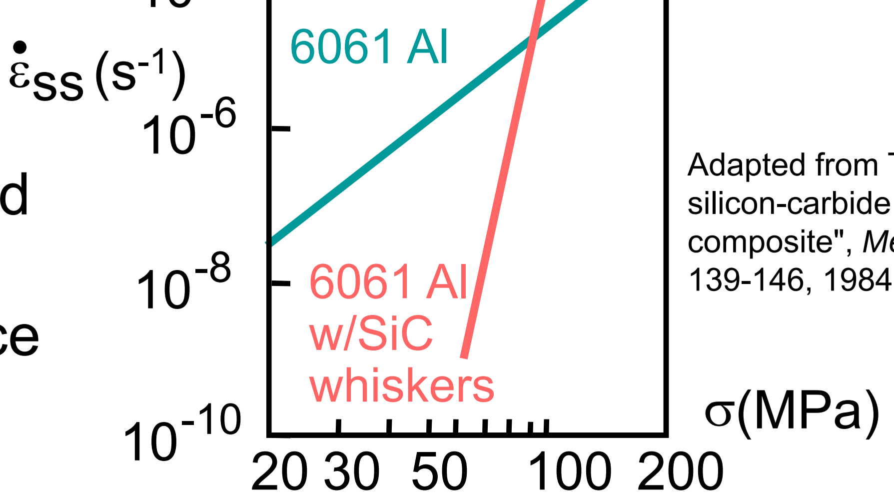
- CMCs: Increased toughness



- 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.

TABLE 12.7

Mechanical Properties of Common Composite Systems

Class	E [MPa (ksi)]	T.S. [MPa (ksi)]	Flexural strength [MPa (ksi)]	Compressive strength [MPa (ksi)]	Percent elongation at failure	K_{IC}[a] (MPa $\sqrt{m}$)
Polymer–matrix						
E-glass (73.3 vol %) in epoxy (parallel loading of continuous fibers)[b]	$56 \times 10^3 (8.1 \times 10^3)$	1,640 (238)	—	—	2.9	42–60
Al_2O_3 whiskers (14 vol %) in epoxy[b]	$41 \times 10^3 (6 \times 10^3)$	779 (113)	—	—	—	—
C (67 vol %) in epoxy (parallel loading)[c]	$221 \times 10^3 (32 \times 10^3)$	1,206 (175)	—	—	—	—
Kevlar[d] (82 vol %) in epoxy (parallel loading)[c]	$86 \times 10^3 (12 \times 10^3)$	1,517 (220)	—	—	—	—
B (70 vol %) in epoxy (parallel loading of continuous filaments)[b]	$210–280 \times 10^3$ $(30–40 \times 10^3)$[c]	1,400–2,100 (200–300)[c]	—	—	—	46
Metal matrix						
Al_2O_3 (10 vol %) dispersion-strengthened aluminum[b]	—	330 (48)	—	—	—	—
W (50 vol %) in copper (parallel loading of continuous filaments)[b]	$260 \times 10^3 (38 \times 10^3)$	1,100 (160)	—	—	—	—
W particles (50 vol %) in copper[b]	$190 \times 10^3 (27 \times 10^3)$	380 (55)	—	—	—	—
Ceramic–matrix						
SiC whiskers in Al_2O_3[e]	—	—	800 (116)	—	—	8.7
SiC fibers in SiC[e]	—	—	750 (109)	—	—	25.0
SiC whiskers in reaction-bonded Si_3N_4[e]	—	—	900 (131)	—	—	20.0

[a] Source: Data from M. F. Ashby and D. R. H. Jones, *Engineering Materials—An Introduction to Their Properties and Applications*, Pergamon Press, Inc., Elmsford, NY, 1980.

[b] L. J. Broutman and R. H. Krock, Eds., *Modern Composite Materials*, Addison-Wesley Publishing Co., Inc., Reading, MA, 1967.

[c] A. K. Dhingra, Du Pont Company.

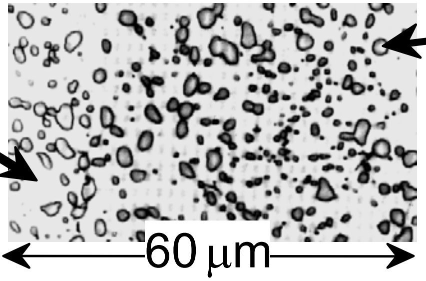
[d] Trade name, Du Pont.

[e] A. J. Klein, *Advanced Materials and Processes 2*, 26 (1986).

Composite Survey: Particle-I

Particle-reinforced | Fiber-reinforced | Structural

- Examples:
  - Spheroidite steel

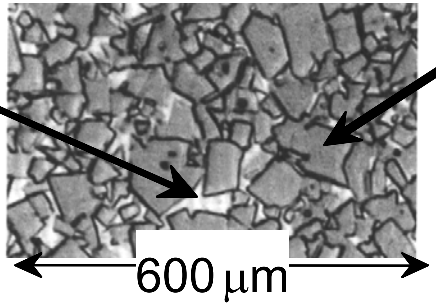


matrix: ferrite (α) (ductile)

particles: cementite (Fe_3C) (brittle)

(copyright United States Steel Corporation, 1971.)

  - WC/Co cemented carbide



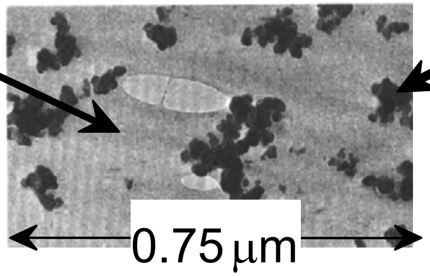
matrix: cobalt (ductile)

V_m: 5-12 vol%!

particles: WC (brittle, hard)

(courtesy Carboloy Systems, Department, General Electric Company.)

  - Automobile tires



matrix: rubber (compliant)

particles: C (stiffer)

(courtesy Goodyear Tire and Rubber Company.)

Composite Survey: Particle-II

Particle-reinforced   Fiber-reinforced   Structural

Concrete – gravel + sand + cement

- Why sand *and* gravel?   Sand packs into gravel voids

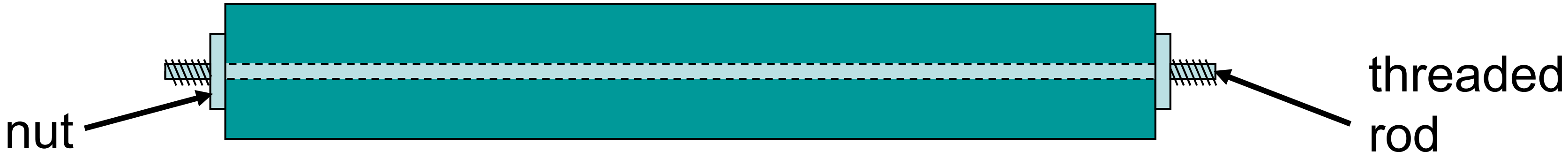
Reinforced concrete - Reinforce with steel rebar or remesh

- increases strength - even if cement matrix is cracked

Prestressed concrete - remesh under tension during setting of concrete. Tension release puts concrete under compressive force

- Concrete much stronger under compression.
- Applied tension must exceed compressive force

Post tensioning – tighten nuts to put under rod under tension but concrete under compression



Composite Survey: Particle-III

- **Particle-reinforced**
- Fiber-reinforced
- Structural

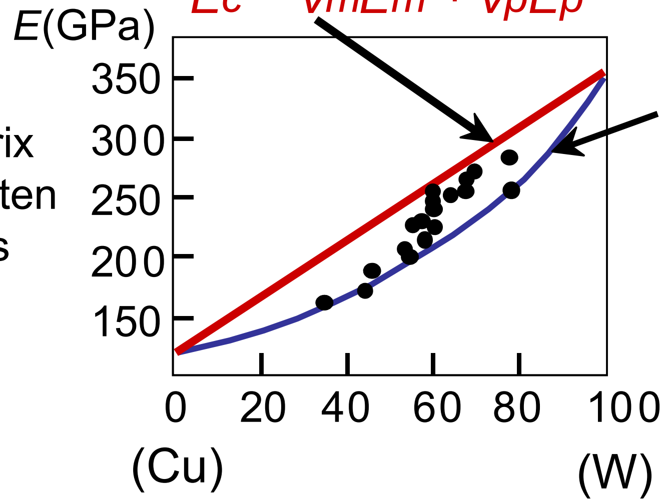
- Elastic modulus, E_c, of composites:

  -- two approaches.

upper limit: "rule of mixtures"

$$E_c = V_m E_m + V_p E_p$$

Data:
Cu matrix
w/tungsten
particles



lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.

- Application to other properties:

  -- Electrical conductivity, σ_e: Replace E in the above equations with σ_e.

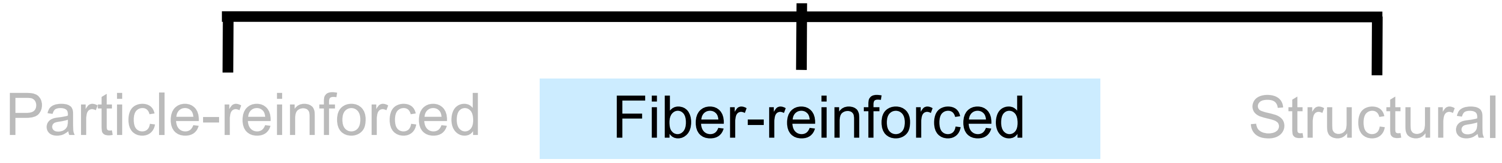
  -- Thermal conductivity, k: Replace E in above equations with k.

Composite Survey: Fiber

Particle-reinforced Fiber-reinforced Structural

- Fibers themselves are very strong
  - Provide significant strength improvement to material
  - **Ex: fiber-glass**
    - **Continuous glass filaments in a polymer matrix**
    - **Strength due to fibers**
    - **Polymer simply holds them in place and environmentally protects them**

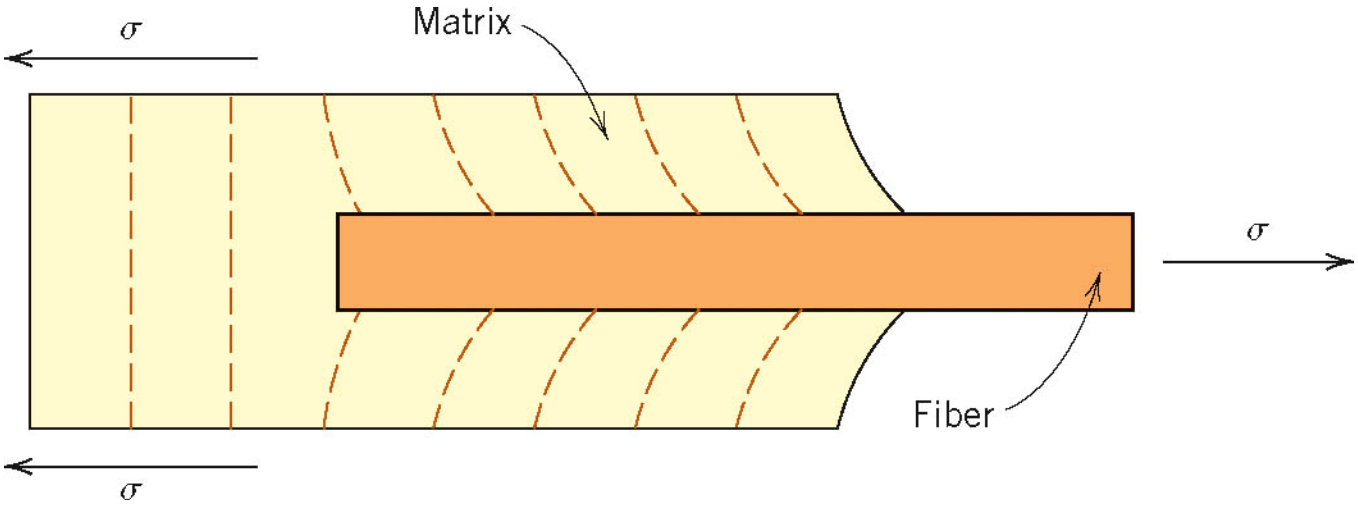
Composite Survey: Fiber



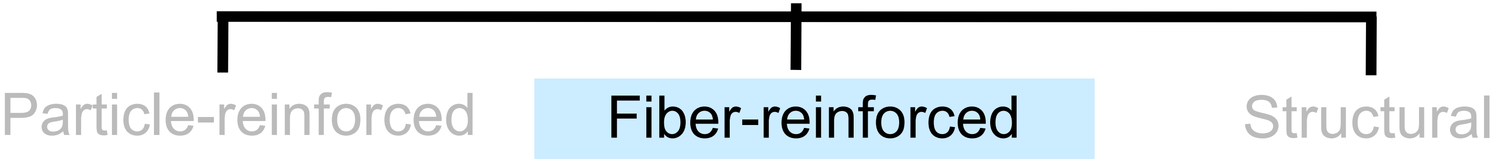
Particle-reinforced
Fiber-reinforced
Structural

- Fiber Materials
  - Whiskers - Thin single crystals - large length to diameter ratio
    - graphite, SiN, SiC
    - high crystal perfection – extremely strong, strongest known materials!
    - 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 Loading Effect under Stress:



Composite Survey: Fiber



Particle-reinforced

Fiber-reinforced

Structural

- Critical fiber length (l_C) for effective stiffening & strengthening:

fiber strength in tension

fiber diameter

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

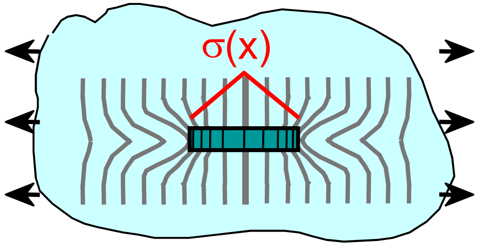
shear strength of **fiber-matrix** interface

- Ex: **For fiberglass**, a fiber length > 15 mm is needed since this length provides a “Continuous fiber” based on *usual glass fiber properties*

- Why? Longer fibers carry stress more efficiently!

Shorter, thicker fiber:

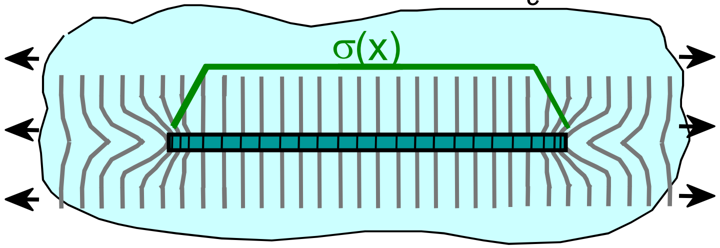
$$\text{fiber length} < 15\,\frac{\sigma_f d}{\tau_c}$$



Poorer fiber efficiency

Longer, thinner fiber:

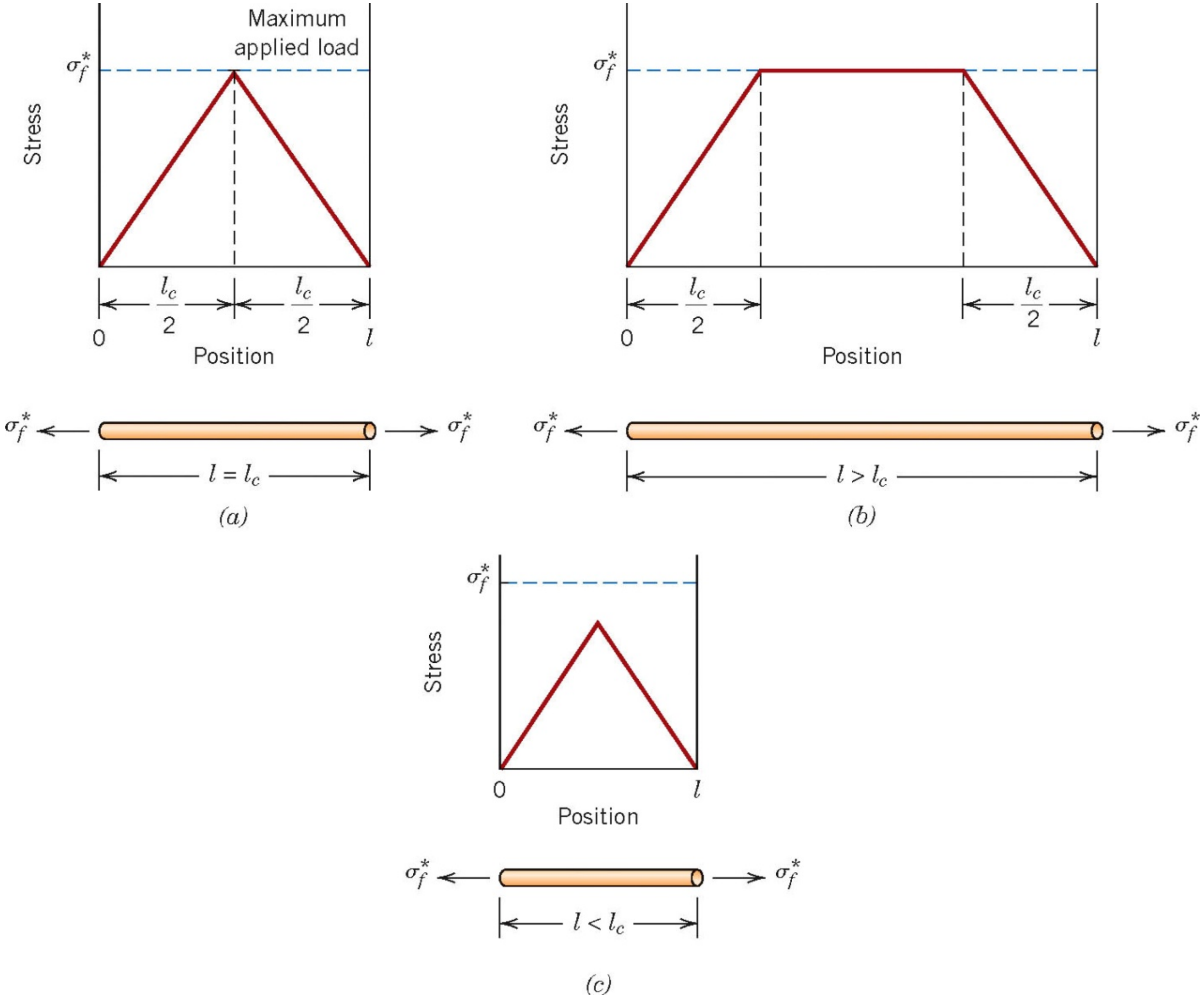
$$\text{fiber length} > 15\,\frac{\sigma_f d}{\tau_c}$$



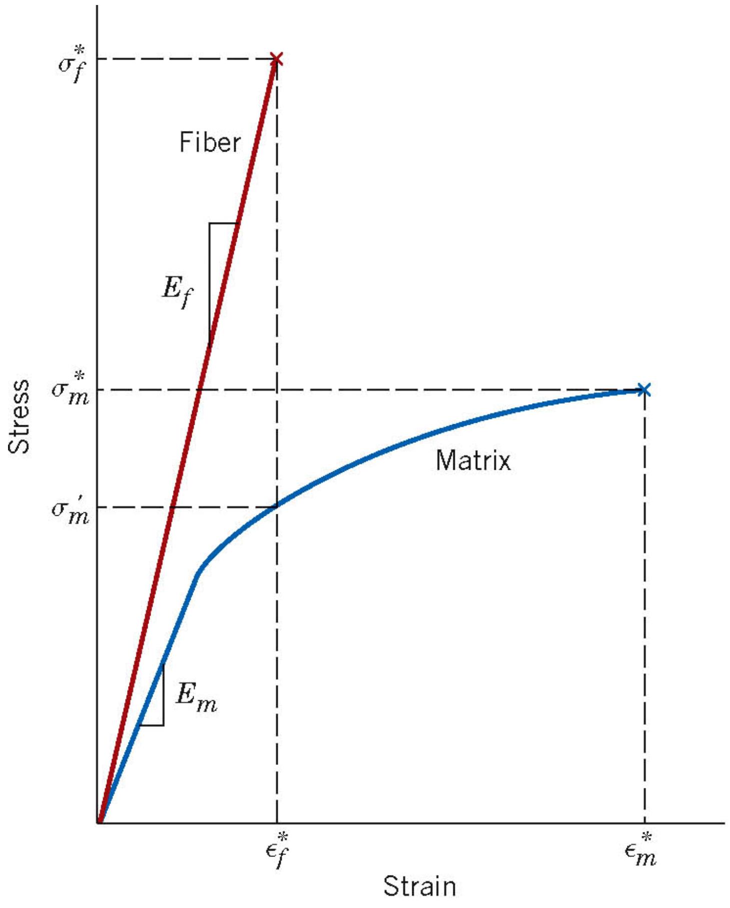
Better fiber efficiency

Fiber Load Behavior under Stress:

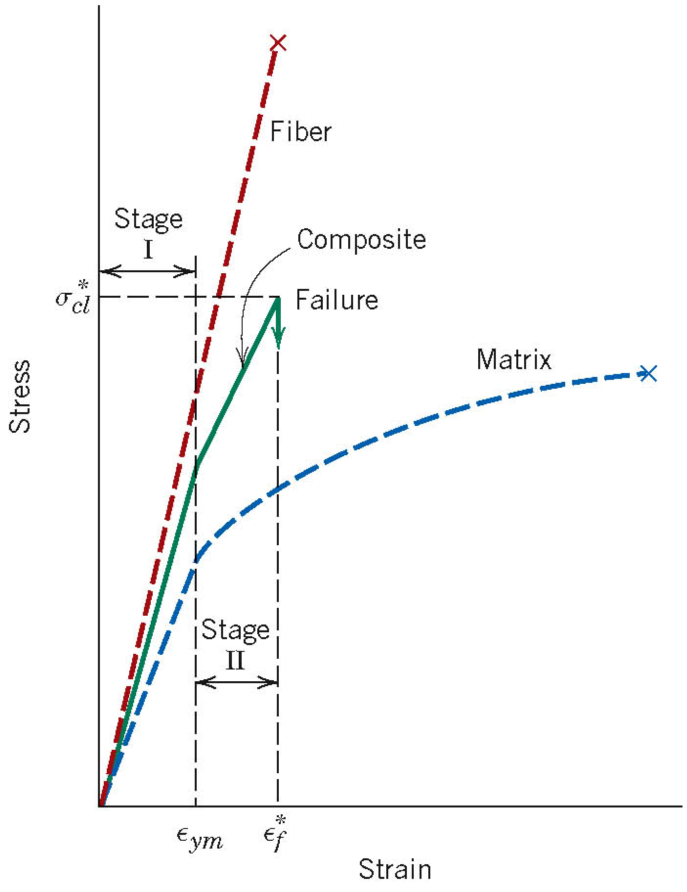
$$l_c = \frac{\sigma^*_f d}{2\tau_c}$$



Behavior under load for Fibers & Matrix

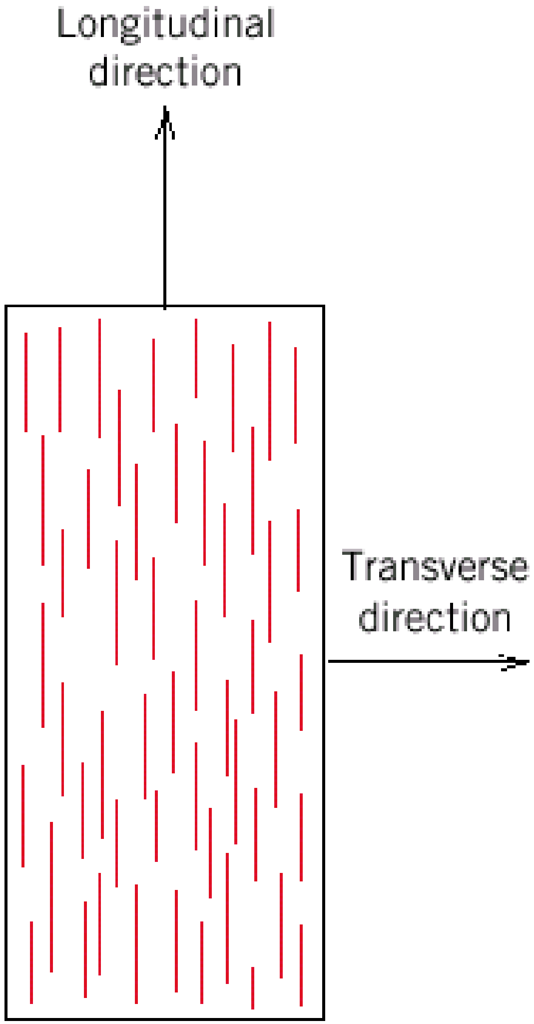


(a)



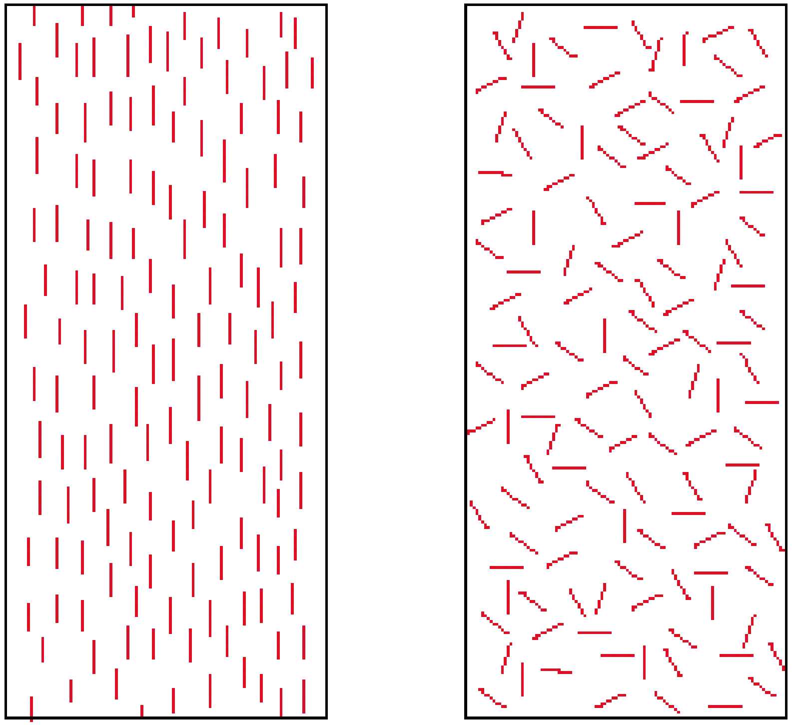
(b)

Fiber Alignment



aligned
continuous

Adapted from Fig. 16.8, *Callister 7e*.



aligned random
discontinuous

Composite Strength: *Longitudinal Loading*

Continuous fibers - Estimate fiber-reinforced composite strength for long continuous fibers in a matrix

- Longitudinal deformation

$$\sigma_c = \sigma_m \underset{\uparrow}{V_m} + \sigma_f \underset{\nearrow}{V_f} \qquad \text{but} \qquad \varepsilon_c \underset{\nearrow}{=} \varepsilon_m = \varepsilon_f$$

volume fraction

isostrain

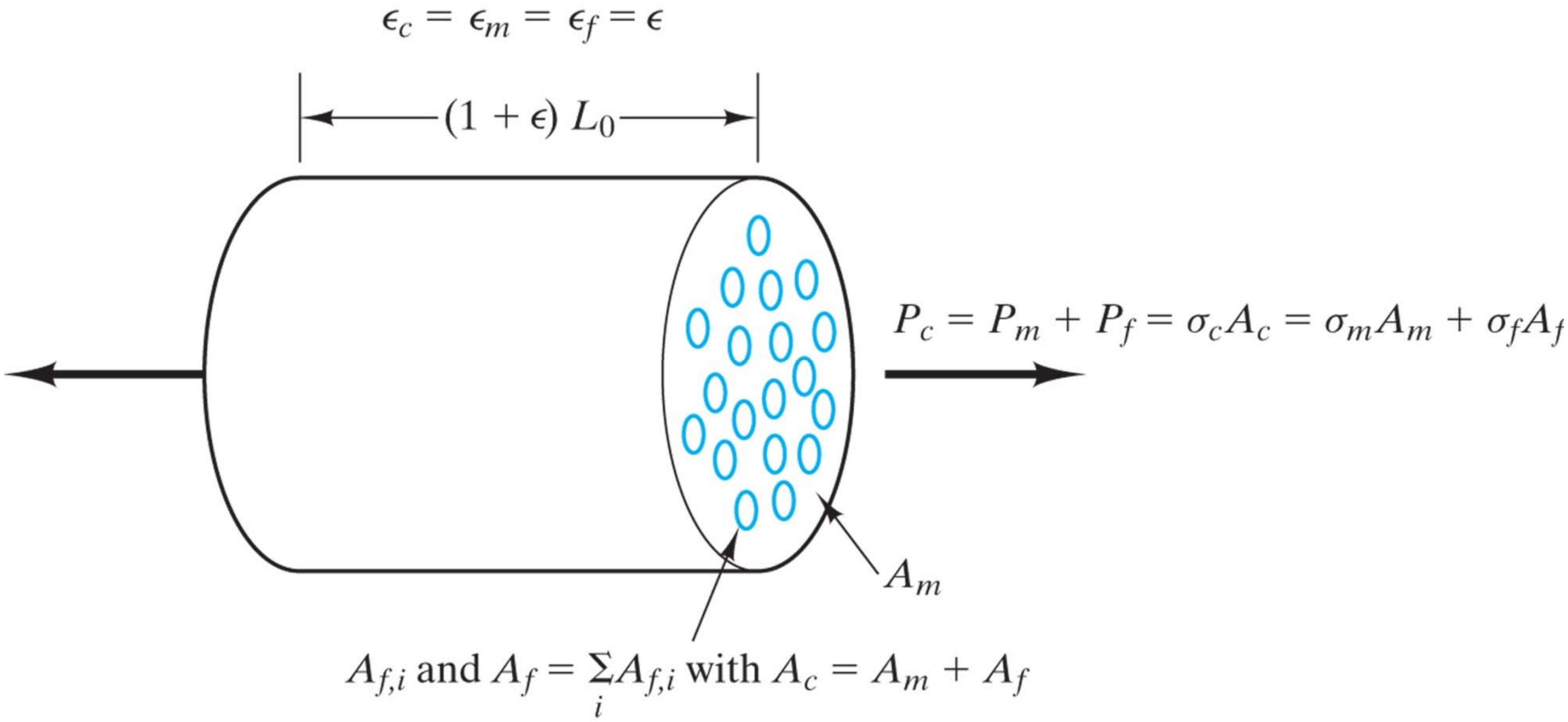
$$\therefore \quad \boxed{E_{ce} = E_m V_m + E_f V_f}$$

longitudinal (extensional) modulus

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

f = fiber
m = matrix

Remembering: $E = \sigma/\varepsilon$ and note, this model corresponds to the “upper bound” for particulate composites


$\epsilon_c = \epsilon_m = \epsilon_f = \epsilon$
$(1 + \epsilon)\, L_0$
$P_c = P_m + P_f = \sigma_c A_c = \sigma_m A_m + \sigma_f A_f$
A_m
$A_{f,i}$ and $A_f = \sum_i A_{f,i}$ with $A_c = A_m + A_f$

Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of the load and are in a state of 'isostress'

$\sigma_c = \sigma_m = \sigma_f = \sigma$

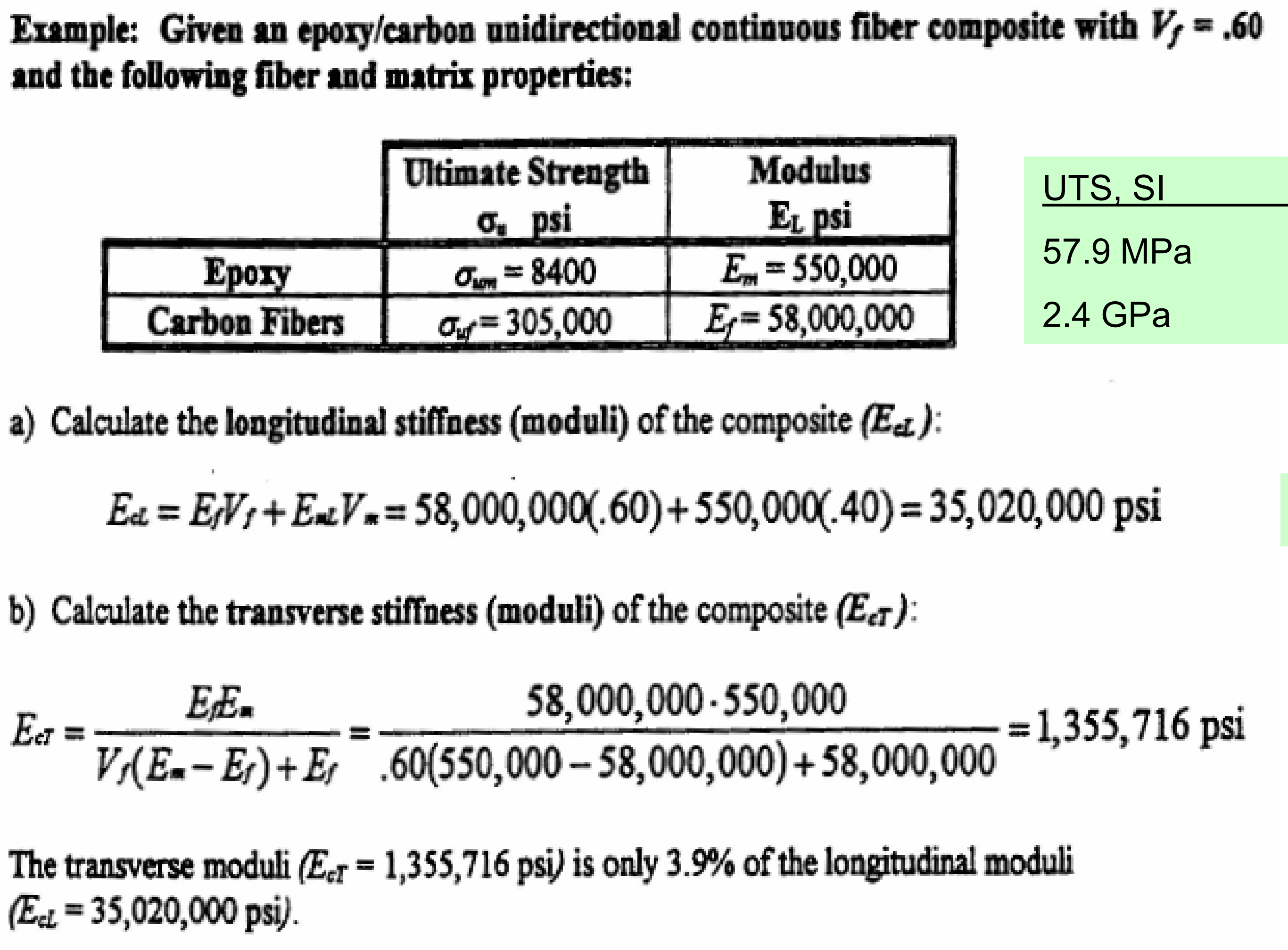
$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$

$$\therefore \quad \boxed{\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}}$$

transverse modulus

Remembering: $E = \sigma/\varepsilon$
and note, this model corresponds to the "lower bound" for particulate composites

An Example:



Example: Given an epoxy/carbon unidirectional continuous fiber composite with $V_f = .60$ and the following fiber and matrix properties:

	Ultimate Strength σ_u **psi**	**Modulus** E_L **psi**
Epoxy	$\sigma_{um} = 8400$	$E_m = 550{,}000$
Carbon Fibers	$\sigma_{uf} = 305{,}000$	$E_f = 58{,}000{,}000$

UTS, SI	Modulus, SI
57.9 MPa	3.8 GPa
2.4 GPa	399.9 GPa

a) Calculate the **longitudinal stiffness (moduli)** of the composite (E_{cL}):

$$E_{cL} = E_f V_f + E_m V_m = 58{,}000{,}000(.60) + 550{,}000(.40) = 35{,}020{,}000 \text{ psi}$$

(241.5 GPa)

b) Calculate the **transverse stiffness (moduli)** of the composite (E_{cT}):

$$E_{cT} = \frac{E_f E_m}{V_f(E_m - E_f) + E_f} = \frac{58{,}000{,}000 \cdot 550{,}000}{.60(550{,}000 - 58{,}000{,}000) + 58{,}000{,}000} = 1{,}355{,}716 \text{ psi}$$

(9.34 GPa)

The transverse moduli (E_{cT} = 1,355,716 psi) is only 3.9% of the longitudinal moduli (E_{cL} = 35,020,000 psi).

Note: 6870 N/m^2 (pascal) per psi!

Composite Strength

Particle-reinforced | **Fiber-reinforced** | Structural

- Estimate of E_c and *TS* for **discontinuous** fibers:

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

-- Elastic modulus in fiber direction:

$$E_c = E_m V_m + K E_f V_f$$

efficiency factor:

-- aligned 1D: $K = 1$ (aligned $||$)
-- aligned 1D: $K = 0$ (aligned $\perp$)
-- random 2D: $K = 3/8$ (2D isotropy)
-- random 3D: $K = 1/5$ (3D isotropy)

From: H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.

-- *TS* in fiber direction:

$$(TS)_c = (TS)_m V_m + (TS)_f V_f \qquad \text{(aligned 1D)}$$

Looking at strength:

$$l > l_C$$

$$\sigma_{cd}^{*} = \sigma_f^{*} V_f \left(1 - \frac{l_C}{2l}\right) + \sigma_m^{'}\left(1 - V_f\right)$$

where σ_f^{*} is fiber fracture strength

& $\sigma_m^{'}$ is matrix stress when composite fails

$$l < l_C$$

$$\sigma_{cd'}^{*} = \frac{l\tau_C}{d} V_f + \sigma_m^{'}\left(1 - V_f\right)$$

where: d is fiber diameter &

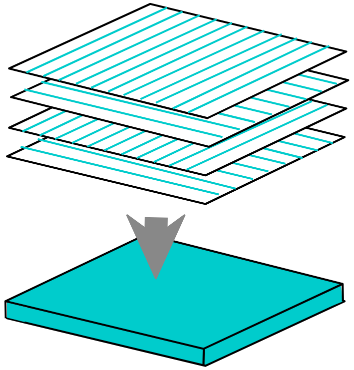
τ_C is smaller of Matrix Fiber shear strength

or matrix shear yield strength

Composite Survey: Structural

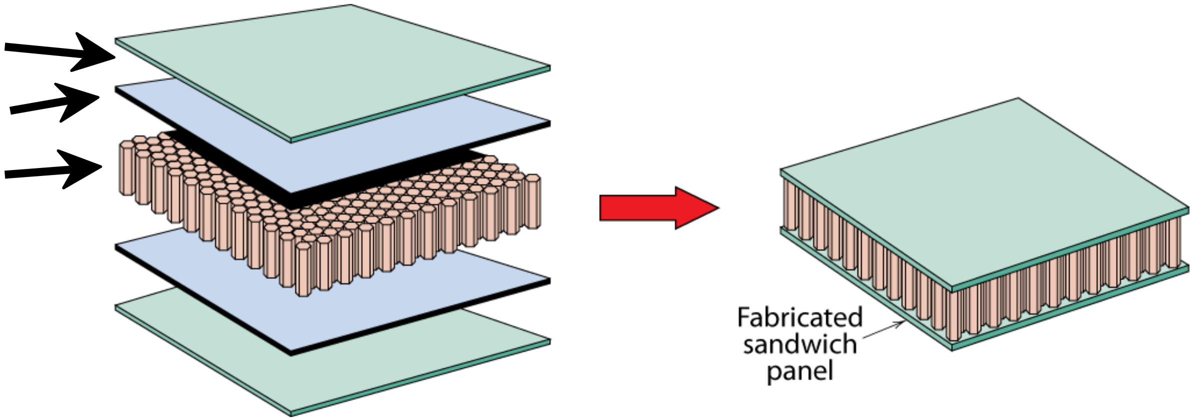
Particle-reinforced | Fiber-reinforced | **Structural**

- Stacked and bonded fiber-reinforced sheets
  - -- stacking sequence: e.g., 0°/90° or 0°/45°/90°
  - -- benefit: balanced, in-plane stiffness



Adapted from Fig. 16.16, *Callister 7e*.

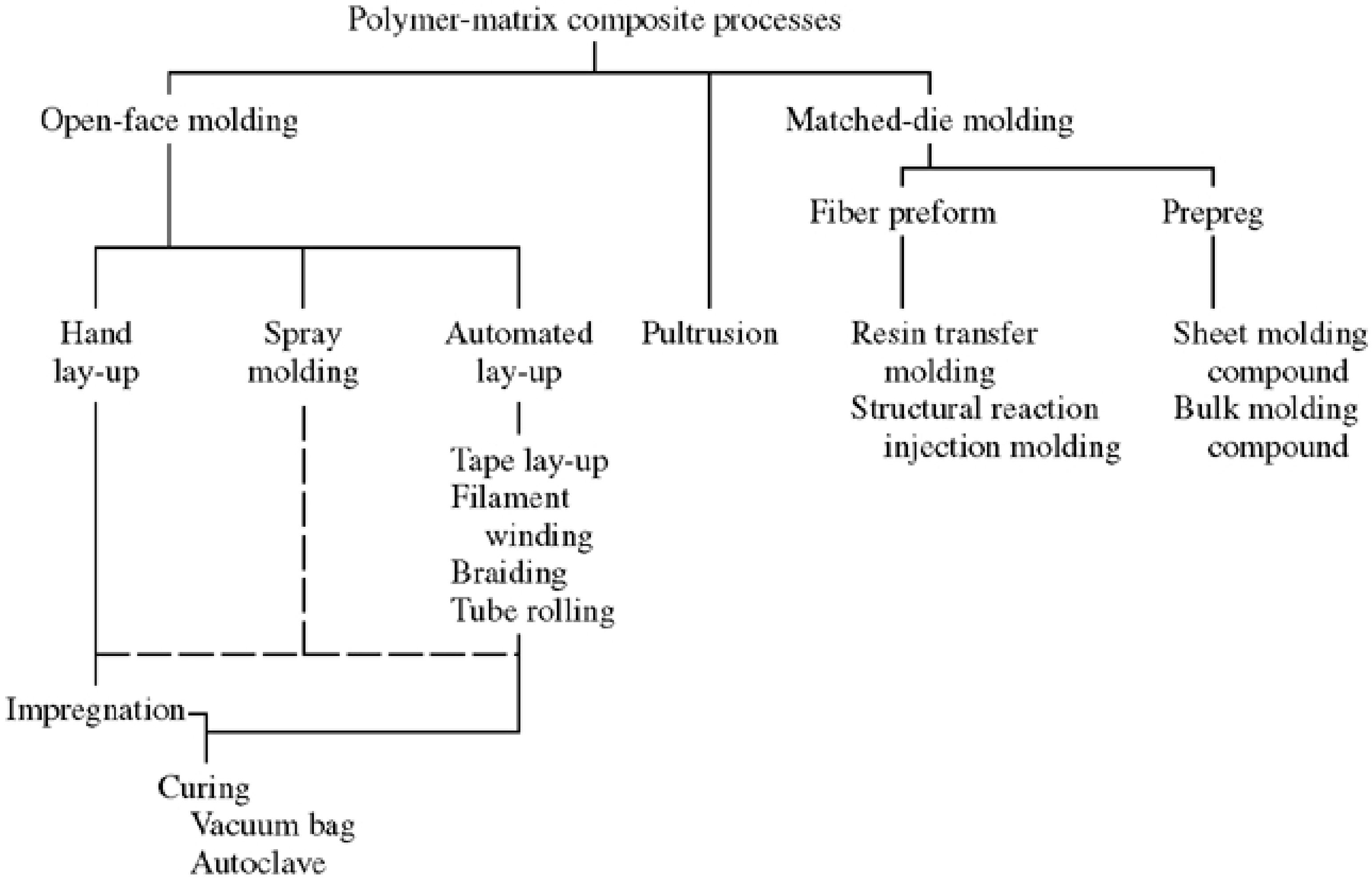
- Sandwich panels
  - -- low density, honeycomb core
  - -- benefit: light weight, large bending stiffness



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 Manufacturing Processes

- Particulate Methods: Sintering
- Fiber reinforced: Several
- Structural: Usually Hand lay-up and atmospheric curing or vacuum curing



Polymer-matrix composite processes

Open-face molding

Pultrusion

Matched-die molding

Fiber preform

Prepreg

Hand lay-up

Spray molding

Automated lay-up

Tape lay-up
Filament winding
Braiding
Tube rolling

Resin transfer molding
Structural reaction injection molding

Sheet molding compound
Bulk molding compound

Impregnation

Curing
Vacuum bag
Autoclave

Open Mold Processes

Only one mold (male or female) is needed and may be made of any material such as wood, reinforced plastic or , for longer runs, sheet metal or electroformed nickel. The final part is usually very smooth.

Shaping. Steps that may be taken for high quality

1. Mold release agent (silicone, polyvinyl alcohol, fluorocarbon, or sometimes, plastic film) is first applied.
2. Unreinforced surface layer (gel coat) may be deposited for best surface quality.

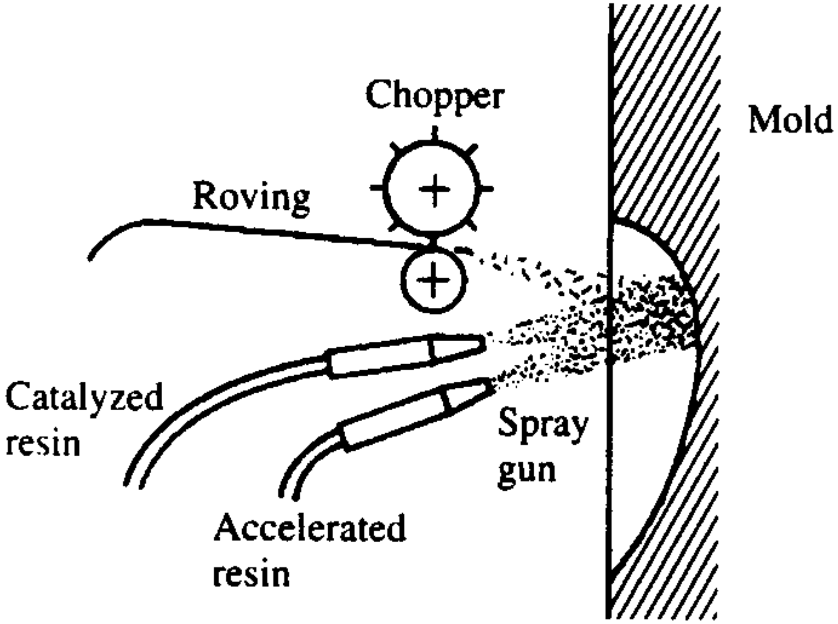
Hand Lay-Up: The resin and fiber (or pieces cut from prepreg) are placed manually, air is expelled with squeegees and if necessary, multiple layers are built up.

- Hardening is at room temperature but may be improved by heating.
- Void volume is typically 1%.
- Foam cores may be incorporated (and left in the part) for greater shape complexity. Thus essentially all shapes can be produced.
- Process is slow (deposition rate around 1 kg/h) and labor-intensive
- Quality is highly dependent on operator skill.
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

SPRAY-UP MOLDING

A spray gun supplying resin in two converging streams into which roving is chopped

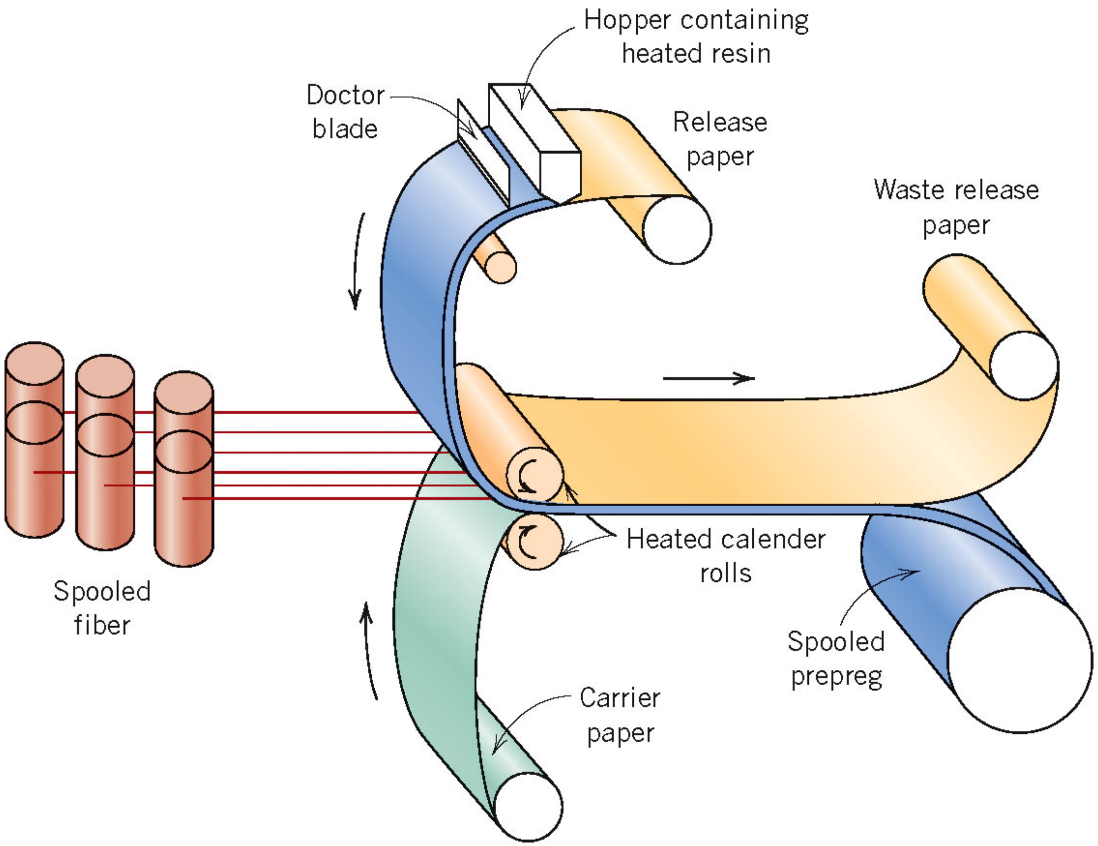
- Automation with robots results in highly reproducible production
- Labor costs are lower



Tape-Laying Machines (Automated Lay-Up)

Cut and lay the ply or prepreg under computer control and without tension; may allow reentrant shapes to be made.

- Cost is about half of hand lay-up
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.



PREPREG PRODUCTION PROCESSES

- Prepreg is the composite industry’s term for continuous fiber reinforcement pre-impregnated with a polymer resin that is only partially cured.
- Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin.
- This is the composite form most widely used for structural applications

PrePreg Process

- Manufacturing begins by collimating a series of spool-wound continuous fiber tows.
- Tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers (calendering).
- The release paper sheet has been coated with a thin film of heated resin solution to assure thorough impregnation of the fibers.

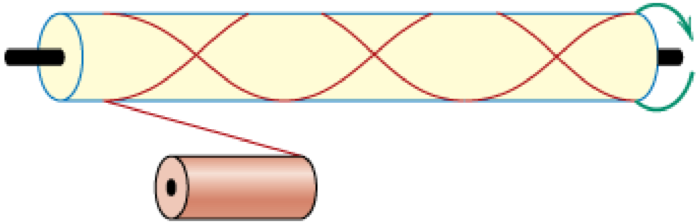
PrePreg Process

- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin
- Prepared for packaging by winding onto a cardboard core.
- Typical tape thicknesses range between 0.08 and 0.25 mm
- Tape widths range between 25 and 1525 mm.
- Resin content lies between about 35 and 45 vol%

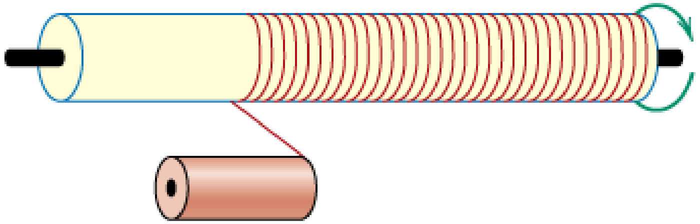
PrePreg Process

- The prepreg is stored at 0°C (32 °F) or lower because matrix undergoes curing reactions at room temperature. Also the time in use at room temperature must be minimized. Life time is about 6 months if properly handled.
- Both thermoplastic and thermosetting resins are utilized: carbon, glass, and aramid fibers are the common reinforcements.
- Actual fabrication begins with the lay-up. Normally a number of plies are laid up to provide the desired thickness.
- The lay-up can be by hand or automated.

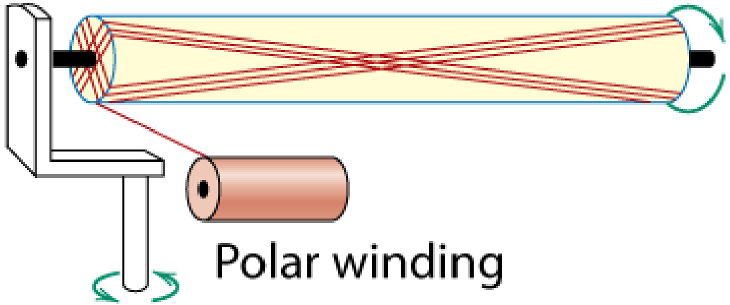
- Filament Winding
  - Ex: pressure tanks
  - Continuous filaments wound onto mandrel



Helical winding



Circumferential winding



Polar winding

from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.

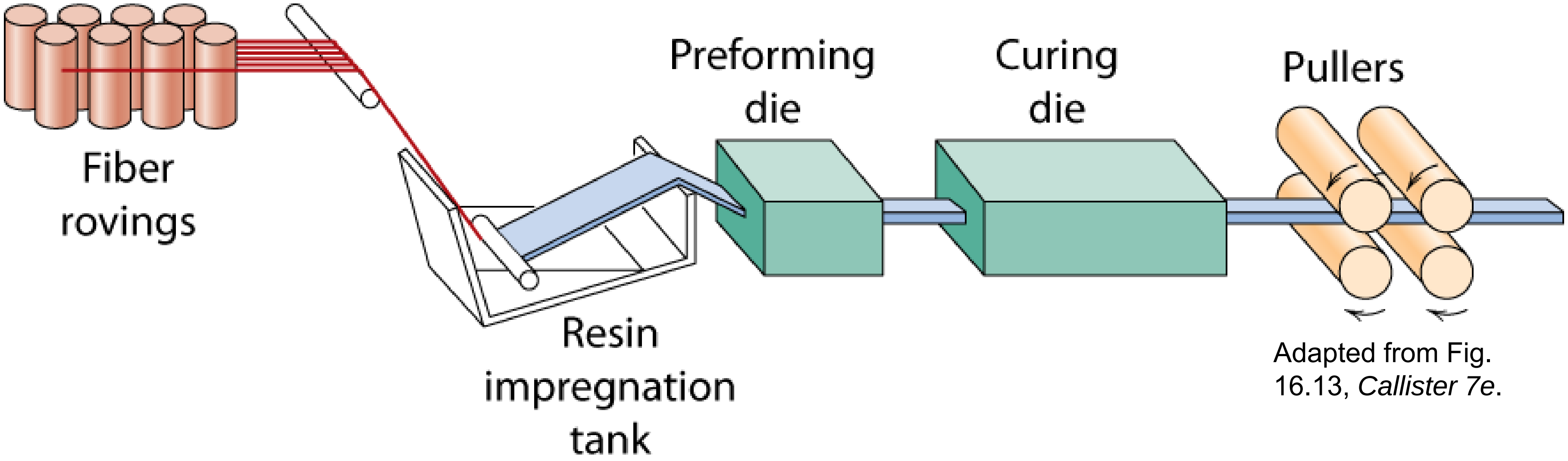
Filament Winding Characteristics

- Because of the tension, only relatively simple shapes can be produced.
- CNC winding machines with several degrees of freedom (sometimes 7) are frequently employed.
- The filament (or tape, tow, or band) is either precoated with the polymer or is drawn through a polymer bath so that it picks up polymer on its way to the winder.
- Void volume can be higher (3%)
- The cost is about half that of tape laying
- Productivity is high (50 kg/h).
- Applications include: fabrication of composite pipes, tanks, and pressure vessels. Carbon fiber reinforced rocket motor cases used for Space Shuttle and other rockets are made this way.

Composite Production Methods:

Pultrusion

- Continuous fibers pulled through resin tank, then into preforming die & oven to cure



Adapted from Fig. 16.13, *Callister 7e*.

- Production rates around 1 m/min.
- Applications are to sporting goods (golf club shafts), vehicle drive shafts (because of the high damping capacity), nonconductive ladder rails for electrical service, and structural members for vehicle and aerospace applications.

Summary: Composites

- Composites are classified according to:
  - -- the matrix material (CMC, MMC, PMC)
  - -- the reinforcement geometry (particles, fibers, layers).
- Composites enhance matrix properties:
  - -- MMC: enhance σ_y, *TS*, creep performance
  - -- CMC: enhance K_c
  - -- PMC: enhance *E*, σ_y, *TS*, creep performance
- Particulate-reinforced:
  - -- Elastic modulii can be estimated.
  - -- Properties are isotropic.
- Fiber-reinforced:
  - -- Elastic modulus and *TS* can be estimated wrt fiber dir.
  - -- Properties can be isotropic or anisotropic.
- Structural:
  - -- Based on build-up of sandwiches in layered form.

Summary

- #Sro|phuv#duh#sduw#fu|vwdoolqh dqg#sduw#dpruskrxv1
- Wkh#pruh#Šoxps|õ#dqg#eudqfkhg wkh#sro|phu/#wkh#ohvv#ghqvh#dqg#ohvv#fu|vwdoolqh1
- Wkh#pruh#furvvolqnlqj wkh#vwliihu wkh#sro|phu1#Dqg/# qhwzrunhg sro|phuv#duh#olnh#khdylo|#furvvolqnhg#rqhv1
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