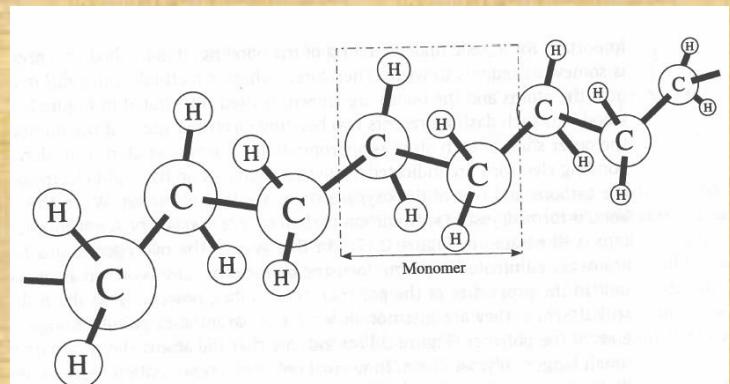


Structure and Properties of Engineering Polymers

Lecture: Mechanical Properties: Macro Viewpoint

Nikolai V. Priezjev



Textbook: *Plastics: Materials and Processing* (Third Edition), by A. Brent Young (Pearson, NJ, 2006).

Mechanical Properties: Macro Viewpoint

- Mechanical properties of solids (forces, elastic behavior)
- Mechanical properties of liquids – viscous flows (Newtonian non-Newtonian regimes, viscosity measurements)
- Viscoelastic materials (definitions, time dependence, short-range, long-range interactions)
- Plastic stress-strain behavior definitions, mechanical models
- Creep, toughness, impact strength, hardness
- Reinforcements, fillers, toughness modifiers

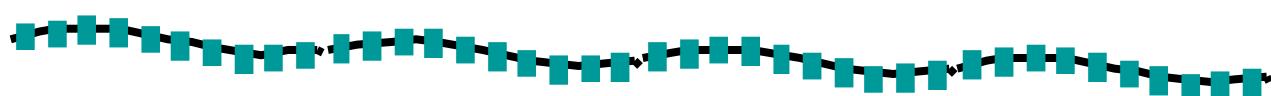
Reading: Chapter 4 of *Plastics: Materials and Processing* by A. Brent Strong

Molecular Weight, Crystallinity and Properties

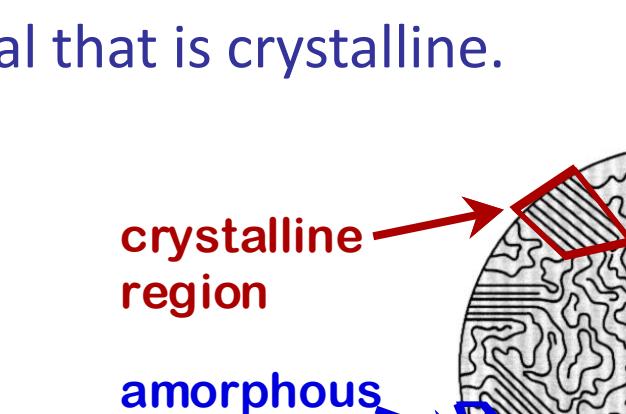
- **Molecular weight M_w :** Mass of a mole of chains.



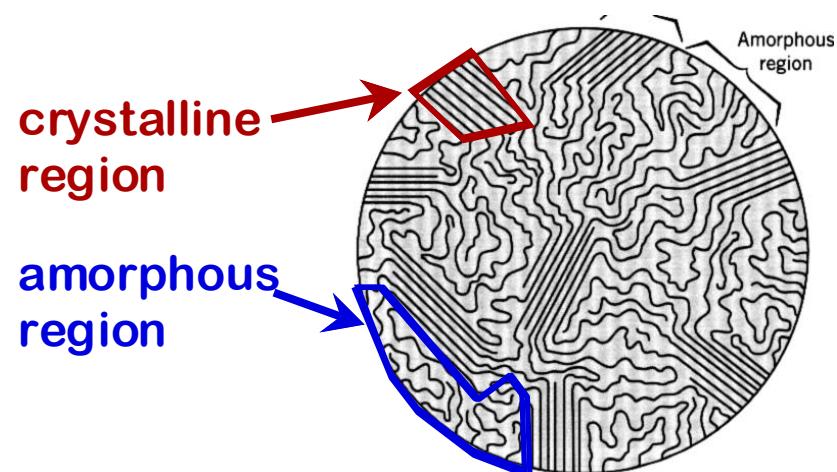
smaller M_w



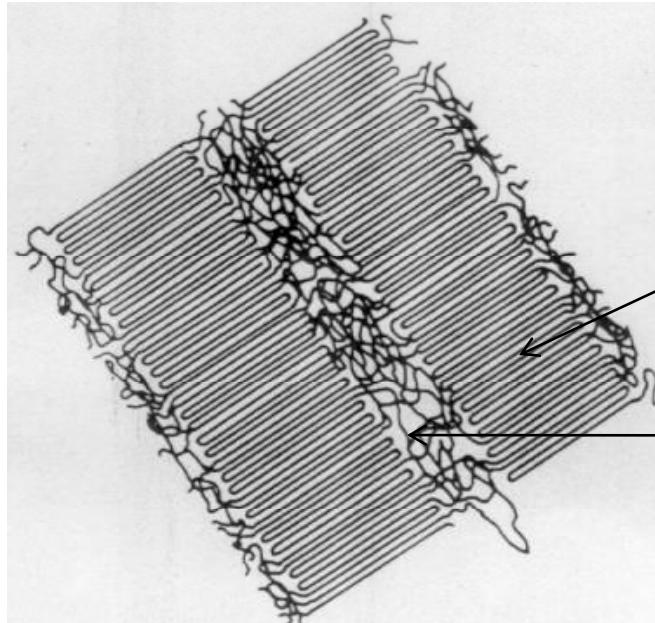
larger M_w

- Tensile strength (TS):
 - often increases with M_w .
 - Why? Longer chains are entangled (anchored) better.
 - % Crystallinity: % of material that is crystalline.
 - TS and E often increase with % crystallinity.
 - Annealing causes crystalline regions to grow. % crystallinity increases.

The diagram illustrates a cross-section of a polymer chain. It features a central region with a regular, grid-like pattern of lines, representing a crystalline lattice. This is surrounded by a region with a more irregular, wavy pattern, representing the amorphous state. A red arrow points to the crystalline region with the label "crystalline region". A blue arrow points to the amorphous region with the label "amorphous region".



“Semicrystalline” Polymers

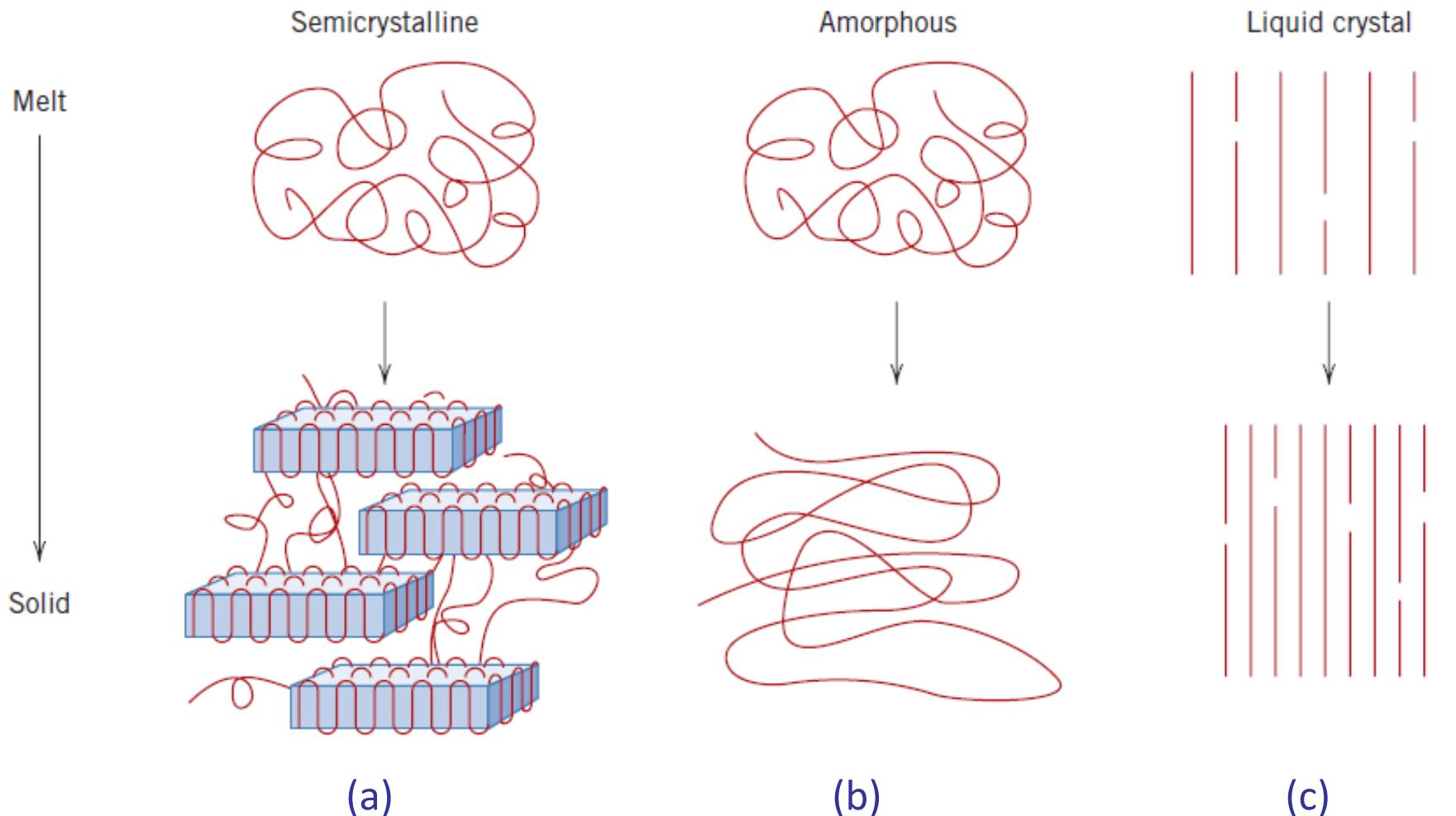


Oriented chains with long-range order

Amorphous disordered polymer chains in
the “intercrystalline” region

~10 nm spacing

Molecular structures in both melt and solid states

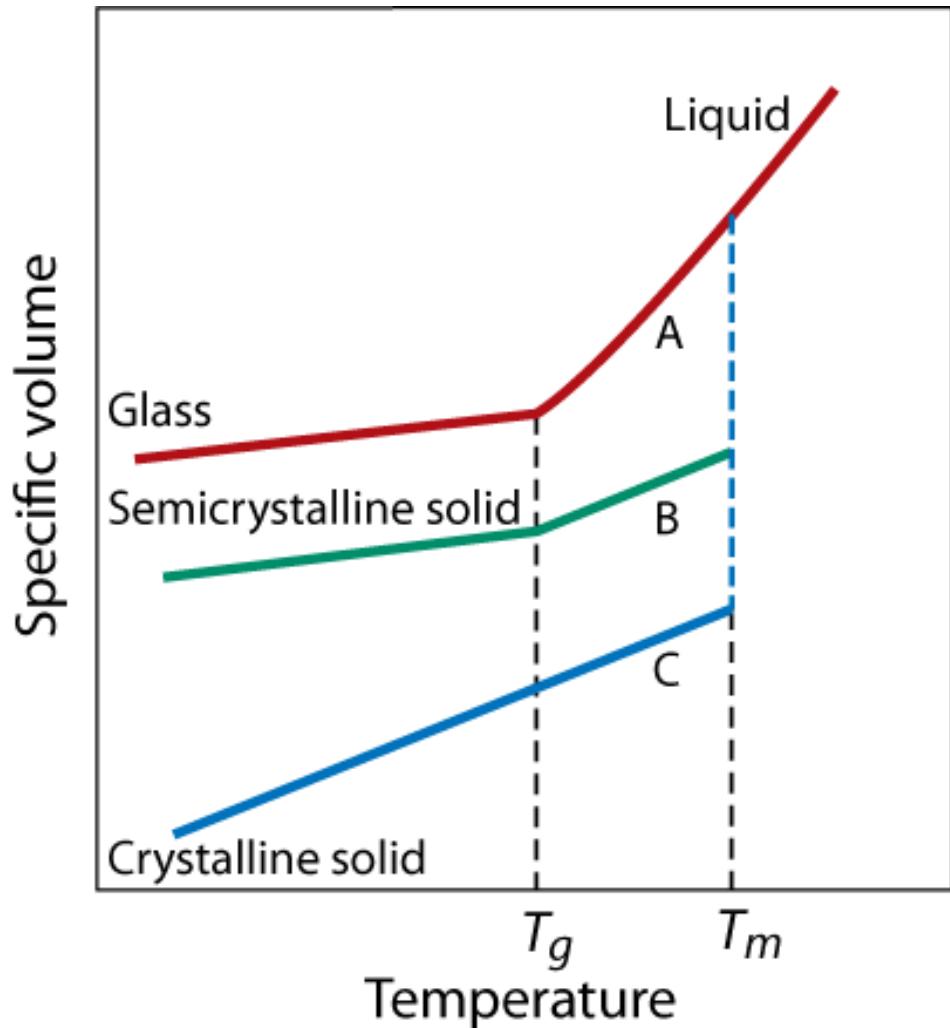


Schematic representations of the molecular structures in both melt and solid states for (a) semicrystalline, (b) amorphous, and (c) liquid crystal polymers.

Melting vs. Glass Transition Temperature

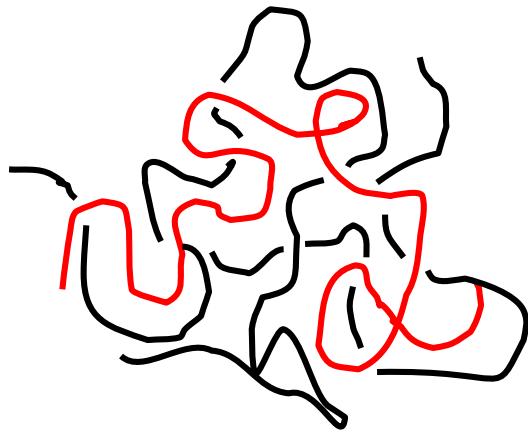
What factors affect T_m and T_g ?

- Both T_m and T_g increase with increasing chain stiffness
- Chain stiffness increased by
 1. Bulky sidegroups
 2. Polar groups or sidegroups
 3. Double bonds or aromatic chain groups
- Regularity (tacticity) – affects T_m only

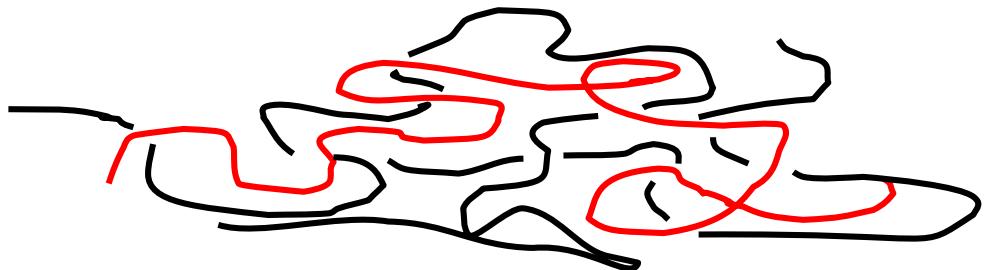


Elasticity of Polymers

Random arrangement = High Entropy

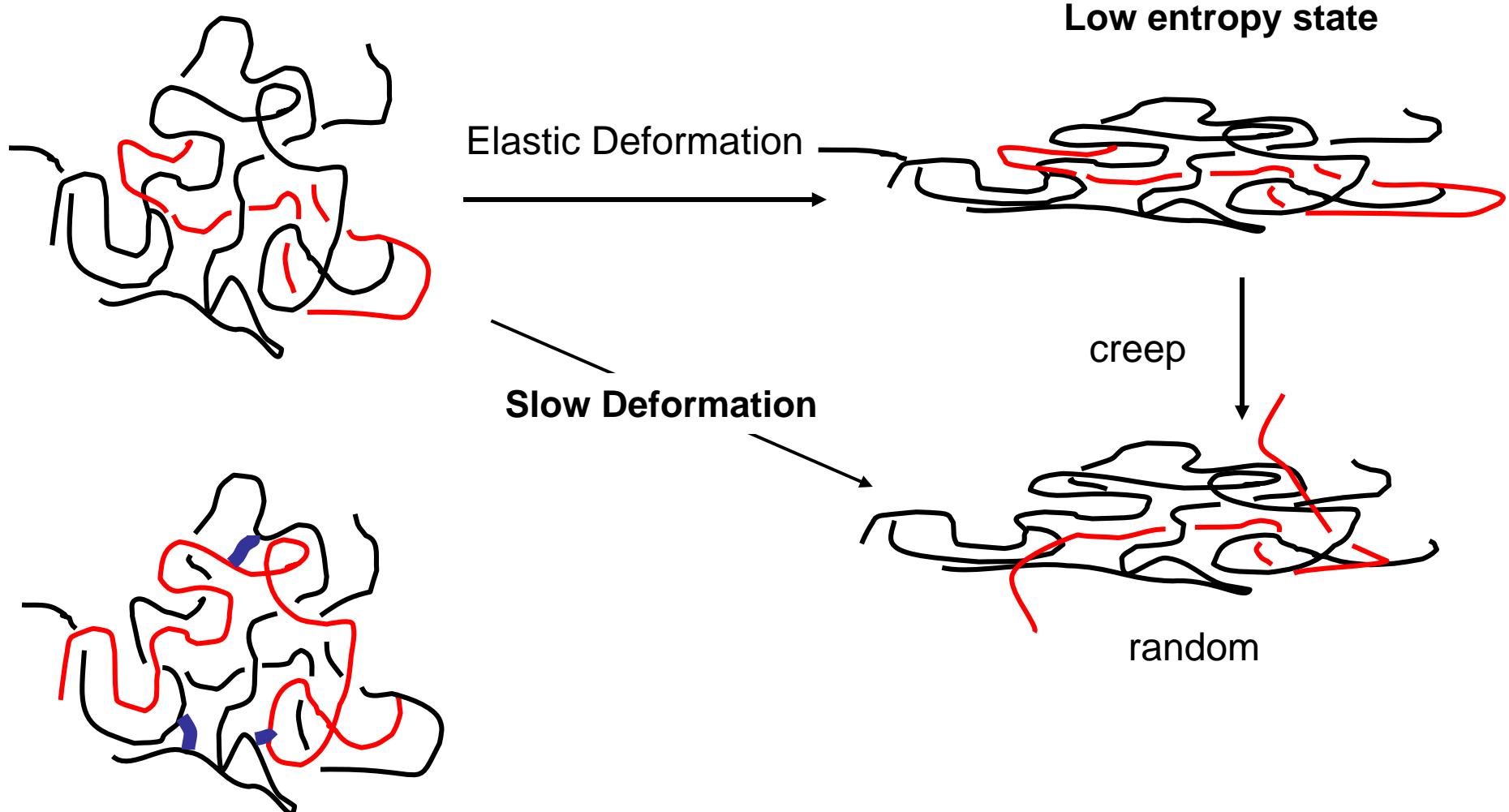


Stretched = Low Entropy



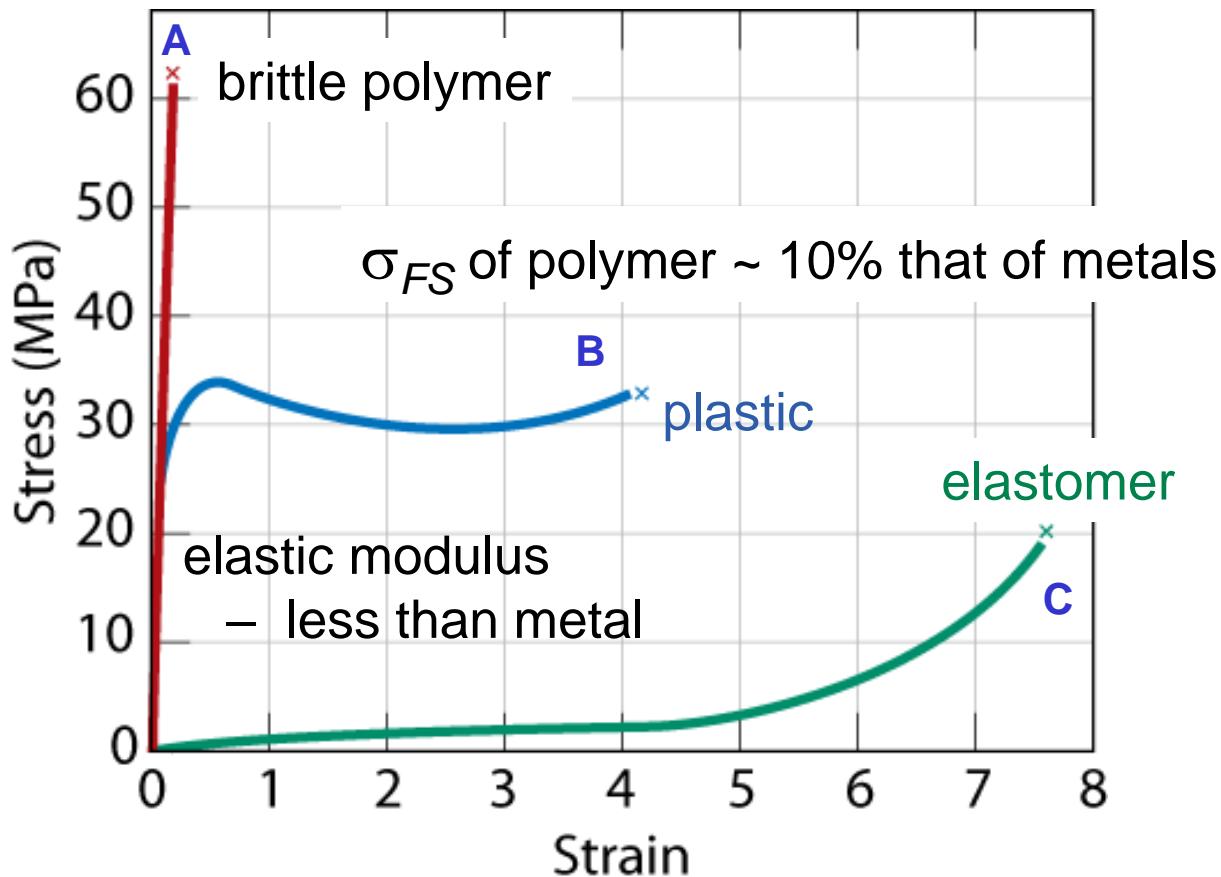
Entropy is a measure of randomness: The more ordered the chains are, the lower is the entropy. Spontaneous processes always tend to increase the entropy, which means that after stretching, the chains will tend to return to a high-entropy state

Viscosity of Polymers



Cross-linking stops the sliding of chains

Stress – Strain Behavior of Polymers

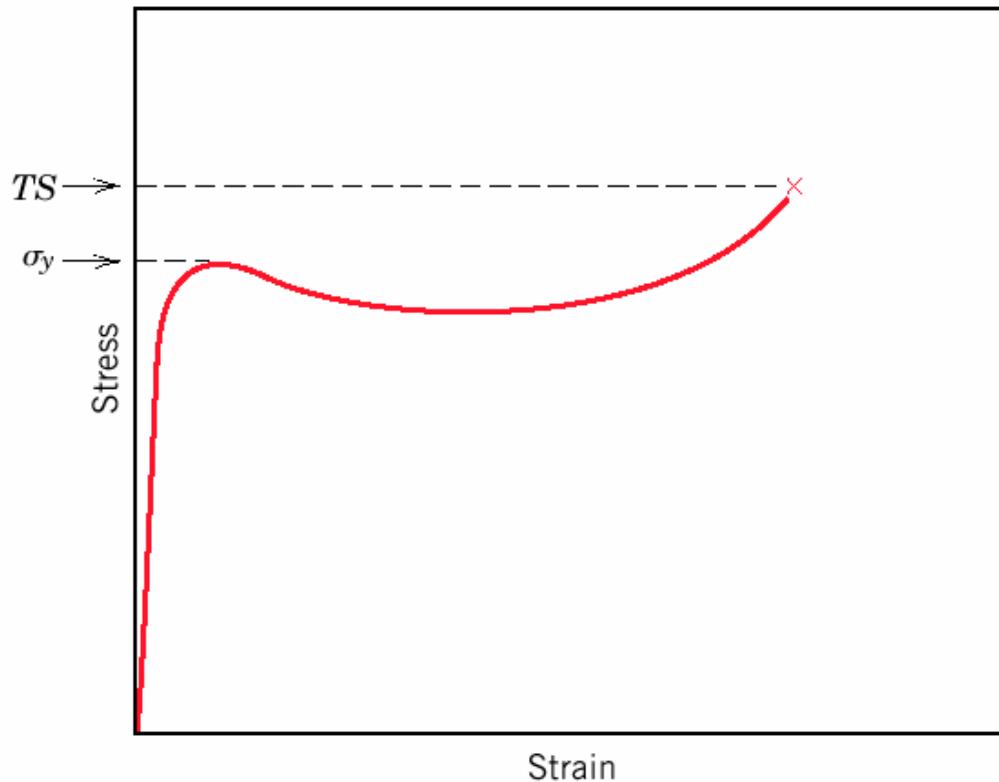


The description of stress-strain behavior is (somewhat) similar to that of metals

Strains – deformations > 1000% possible (for metals, maximum strain $\sim 100\%$ or less)

Polymers can be brittle (A), plastic (B), or highly elastic (C). Deformation shown by curve C is totally elastic (rubber-like elasticity, large recoverable strain at low stress levels). This class of polymers – **elastomers**.

Stress – Strain Behavior of Polymers



- Moduli of elasticity for polymers are ~ 10 MPa – 4 GPa (compare to metals ~ 50 - 400 GPa)
- Tensile strengths are ~ 10 - 100 MPa (compare to metals, hundreds of MPa to several GPa)
- Elongation can be up to 1000 % in some cases (< 100% for metals)

Characteristics of stress-strain behavior:

Modulus of elasticity – defined as for metals

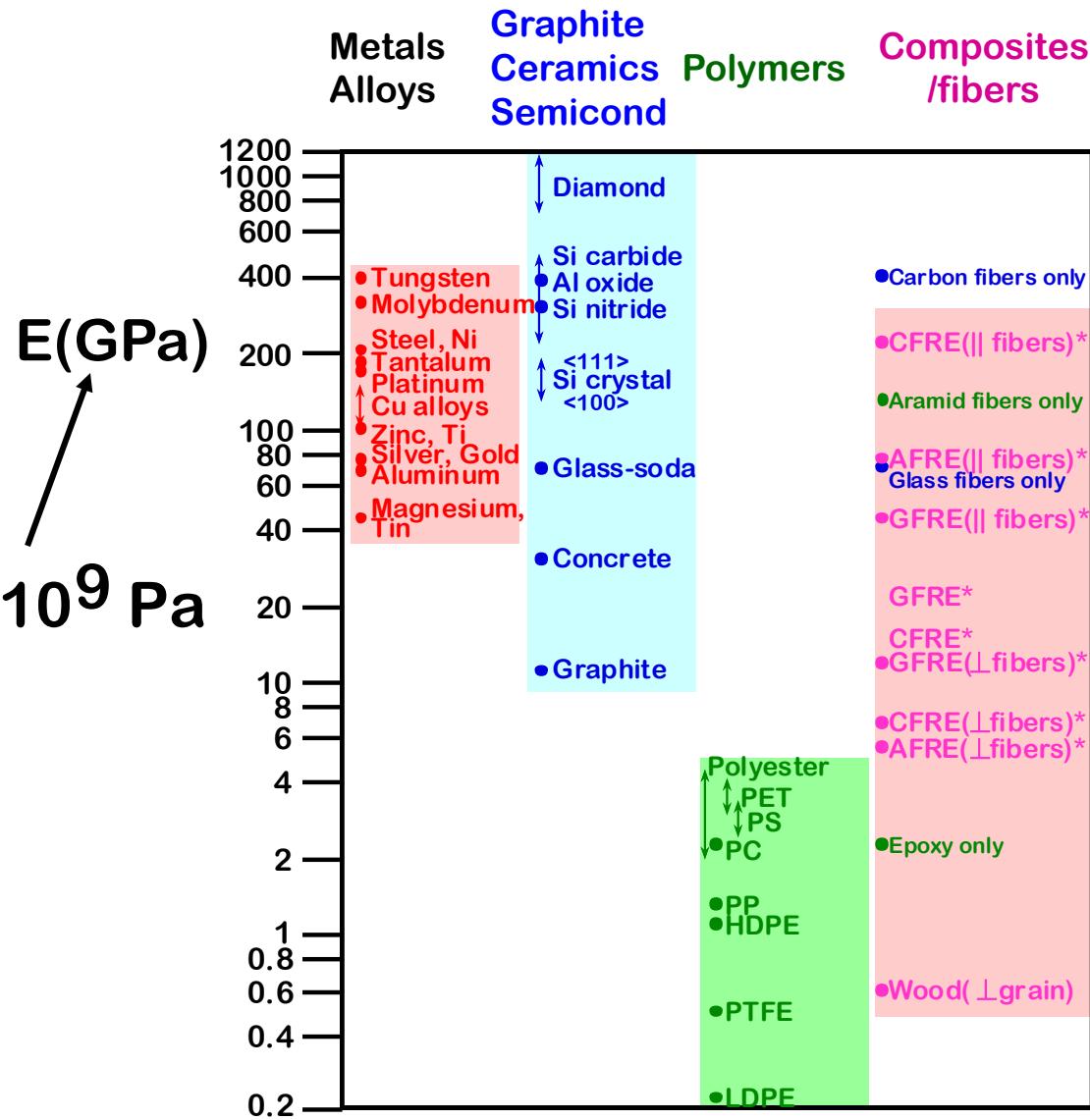
Ductility (%EL) – defined as for metals

Yield strength - For plastic polymers (B), yield strength is defined by the maximum on curve just after the elastic region (different from metals)

Tensile strength is defined at the fracture point and can be lower than the yield strength (different from metals)

$$TS = TS_{\infty} - \frac{A}{M_n}$$

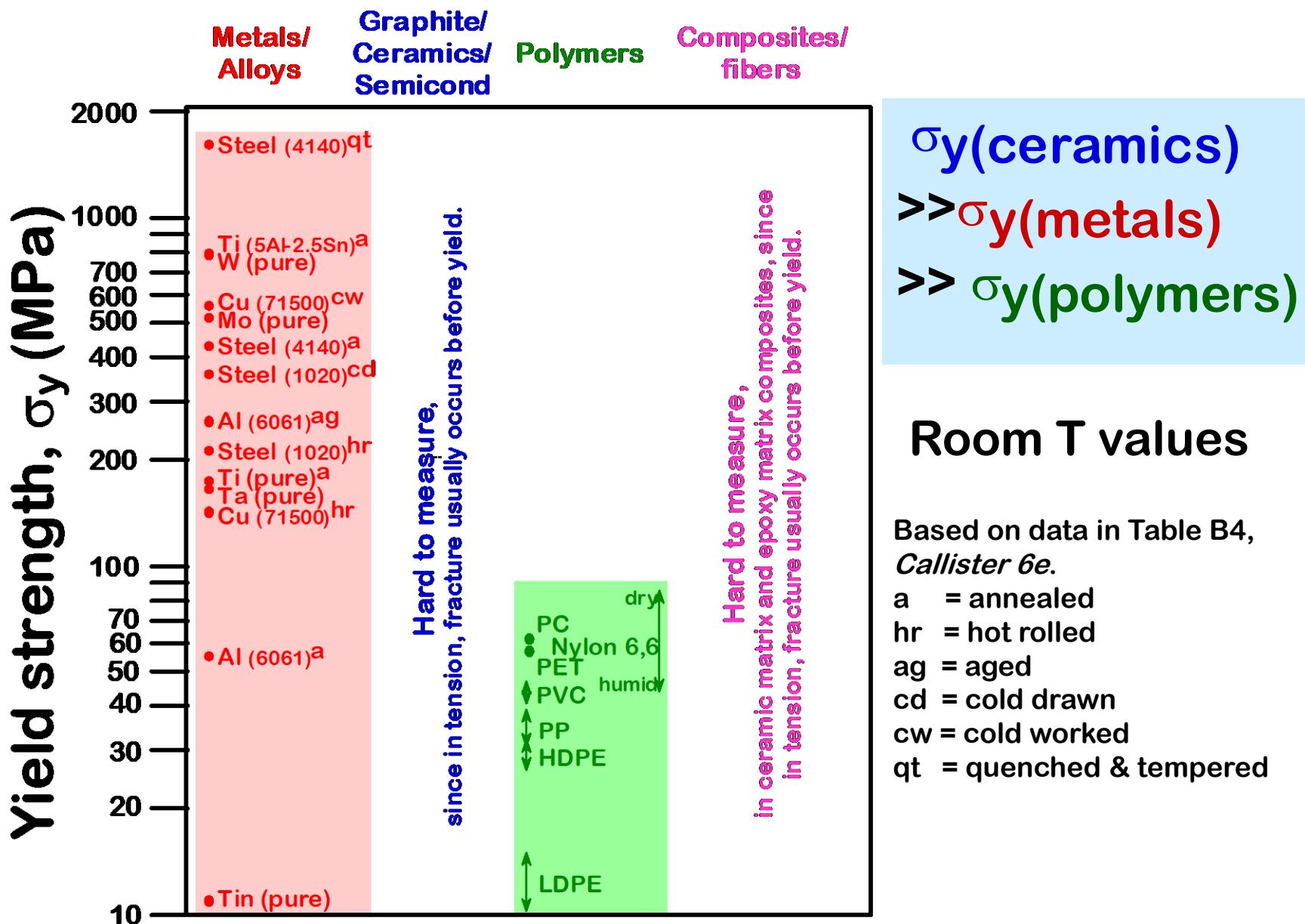
YOUNG'S MODULI: COMPARISON



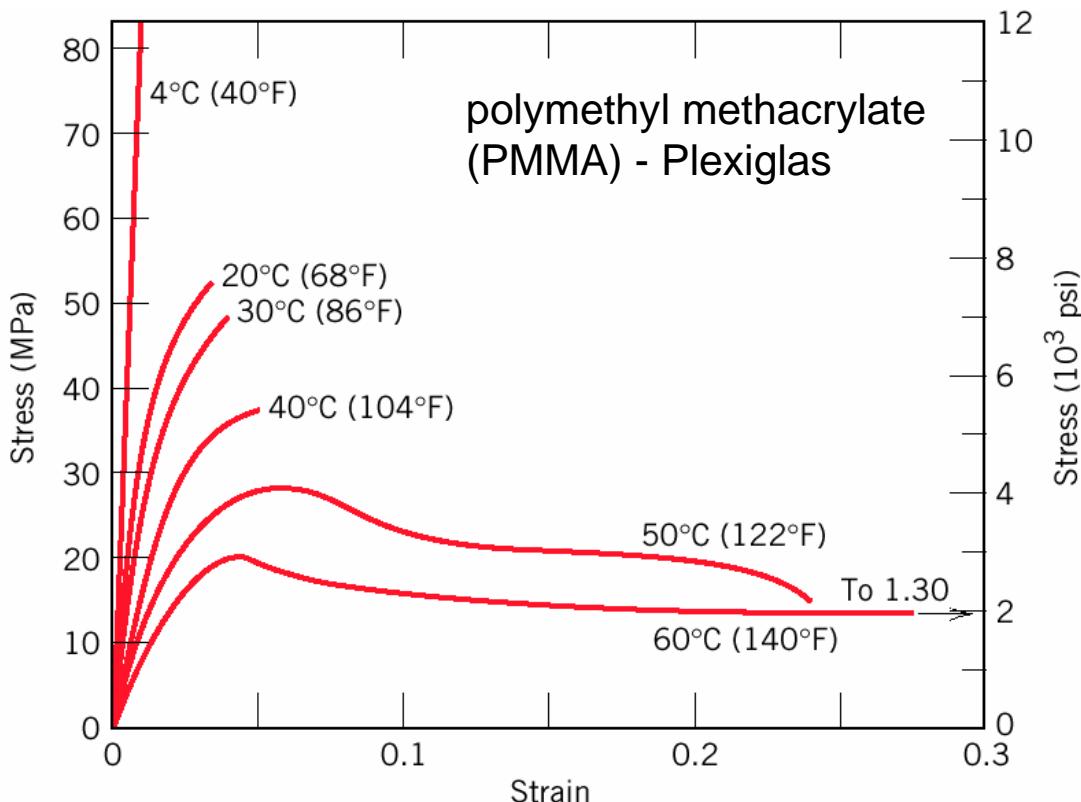
Eceramics
> Emetals
>> Epolymers

Based on data in Table B2,
Callister 6e.
 Composite data based on
 reinforced epoxy with 60 vol%
 of aligned
 carbon (CFRE),
 aramid (AFRE), or
 glass (GFRE)
 fibers.

YIELD STRENGTH: COMPARISON



Stress – Strain Temperature Dependence



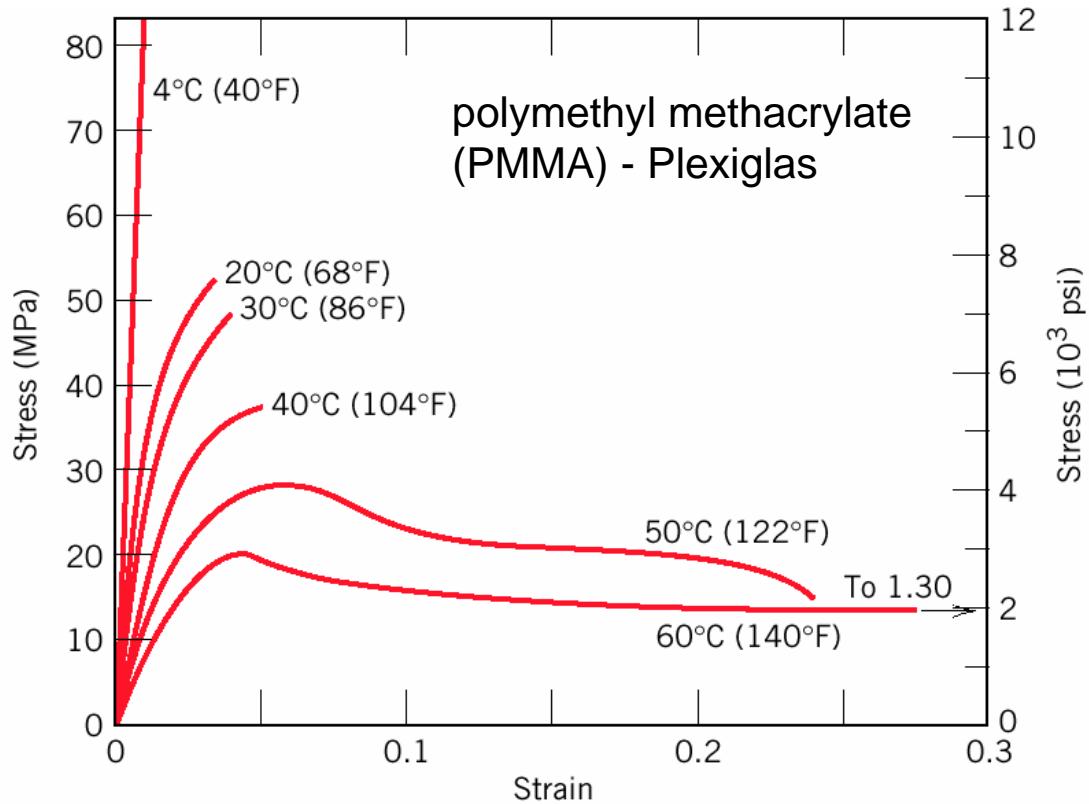
Temperature increase leads to:

- Decrease in elastic modulus
- Reduction in tensile strength
- Increase in ductility

The glass transition temperature (T_g) of PMMA ranges from 85 to 165 °C – all of the above curves are for temperatures below T_g .

- Mechanical properties of polymers change dramatically with temperature, going from glass-like *brittle* behavior at low temperatures to a *rubber*-like behavior at high temperatures.
- Polymers are also very sensitive to the *rate of deformation* (strain rate). *Decreasing rate of deformation has the same effect as increasing temperature (T).*

Quiz: Stress – Strain Temperature Dependence

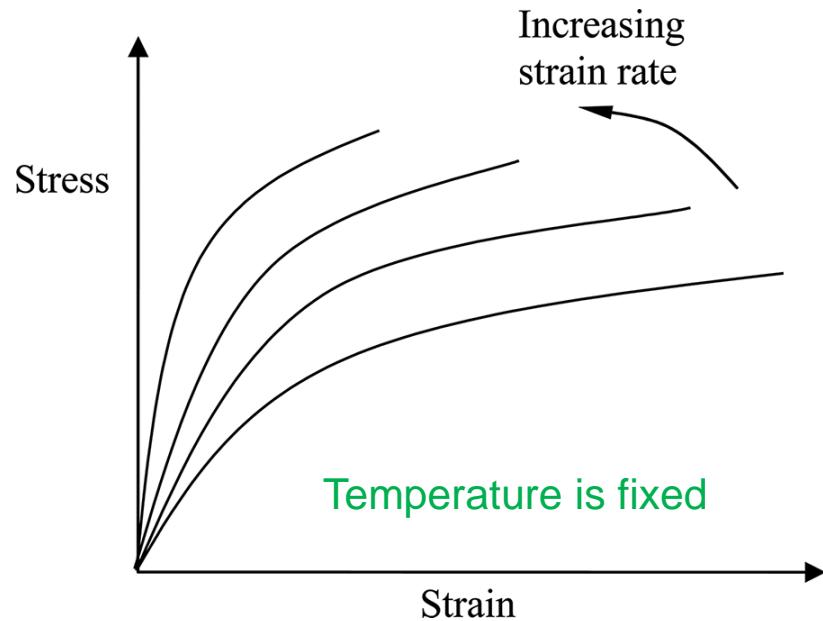
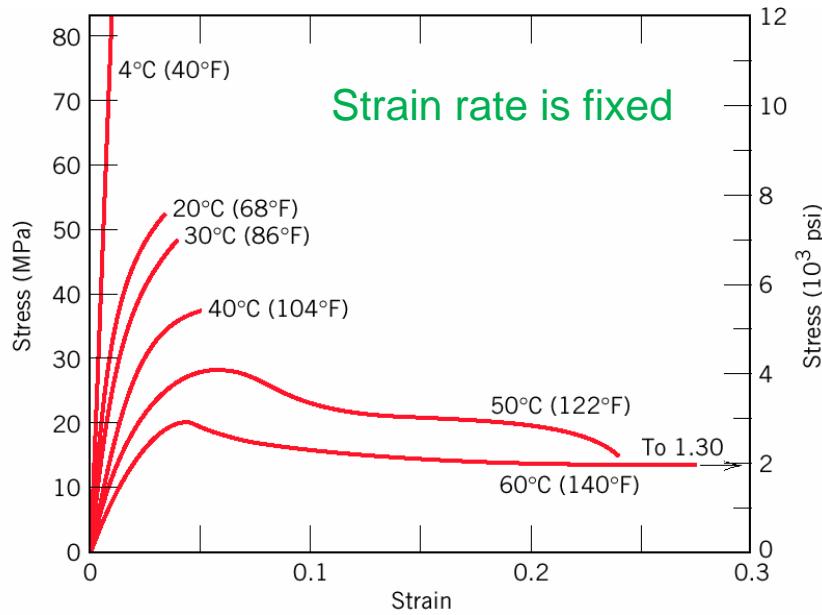


From the stress–strain data for poly(methyl methacrylate) shown in Figure estimate the modulus of elasticity and tensile strength at room temperature 20C.

$$E = \frac{\Delta \text{ (stress)}}{\Delta \text{ (strain)}} = \frac{30 \text{ MPa} - 0 \text{ MPa}}{9 \times 10^{-3} - 0} = 3.3 \text{ GPa} \quad (483,000 \text{ psi})$$

The tensile strength corresponds to the stress at which the curve ends, which is 52 MPa

Stress – Strain Temperature and Rate Dependence



Temperature increase leads to:

- Decrease in elastic modulus
- Reduction in tensile strength
- Increase in ductility

- Mechanical properties of polymers change dramatically with temperature, going from glass-like *brittle* behavior at low temperatures to a *rubber*-like behavior at high temperatures.
- Polymers are also very sensitive to the *rate of deformation* (strain rate). Decreasing rate of deformation has the same effect as increasing temperature (T).

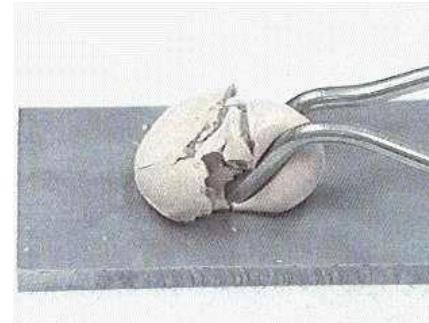
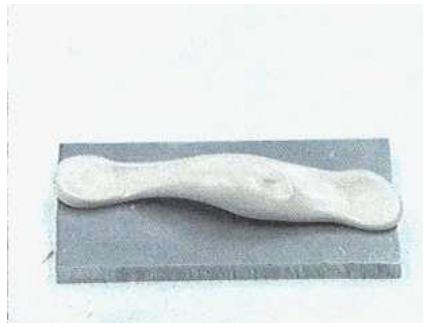
Time dependence of viscoelastic (polymeric) materials showing the changes in stress-strain with strain rate

Viscoelasticity

Amorphous polymer: glass at low temperatures, rubber at intermediate temperatures, viscous liquid at high T.

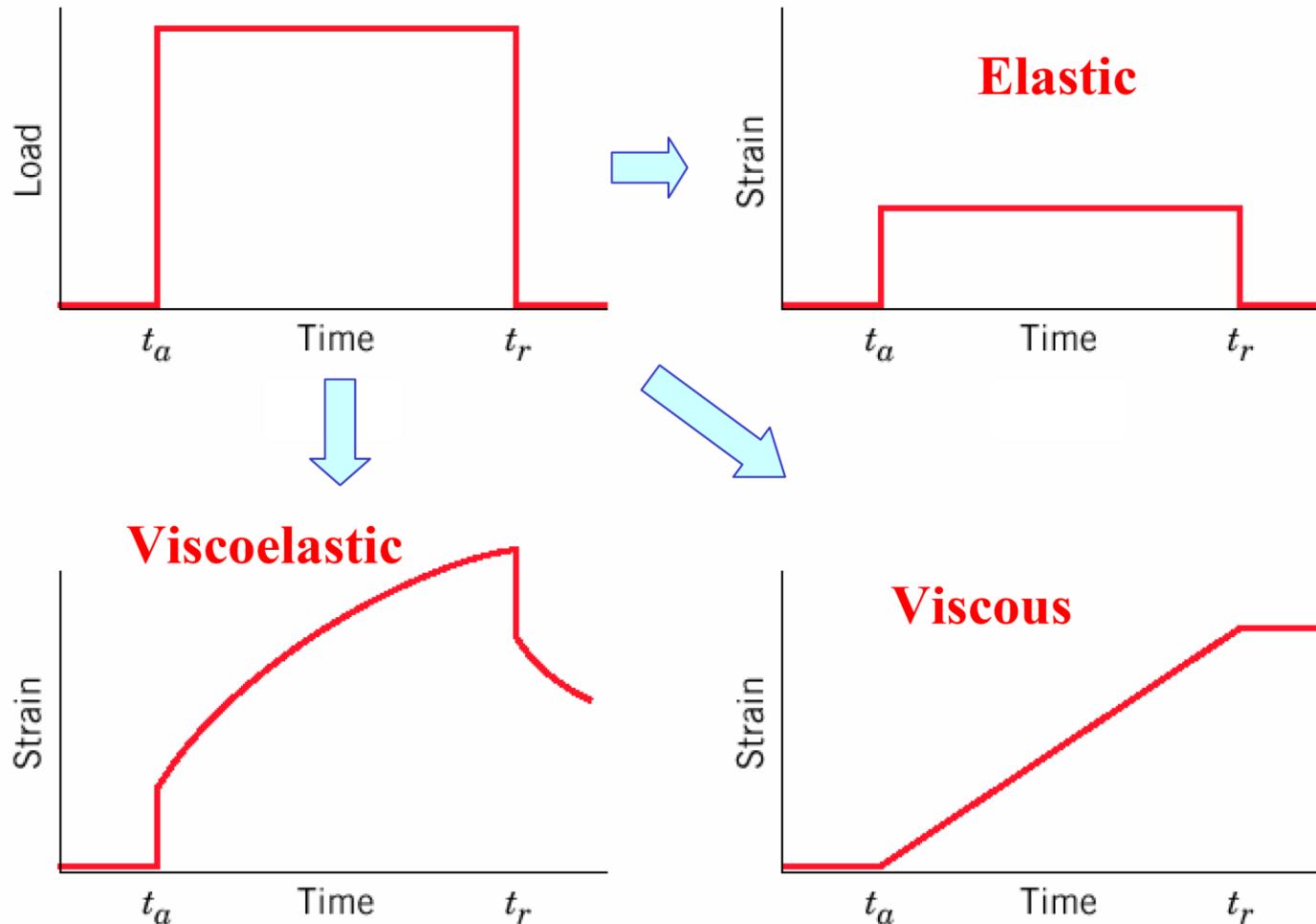
- Low temperatures: **elastic** deformation at small strains ($\sigma = E\epsilon$). Deformation is instantaneous when load is applied. Deformation is reversible.
- High temperatures: **viscous** behavior. Deformation is time dependent and not reversible.
- Intermediate temperatures: **viscoelastic** behavior. Instantaneous elastic strain followed by viscous time dependent strain.

Viscoelastic behavior is determined by rate of strain (elastic for rapidly applied stress, viscous for slowly applied stress).



Rate dependence of viscoelastic properties in a silicone polymer (Silly Putty).

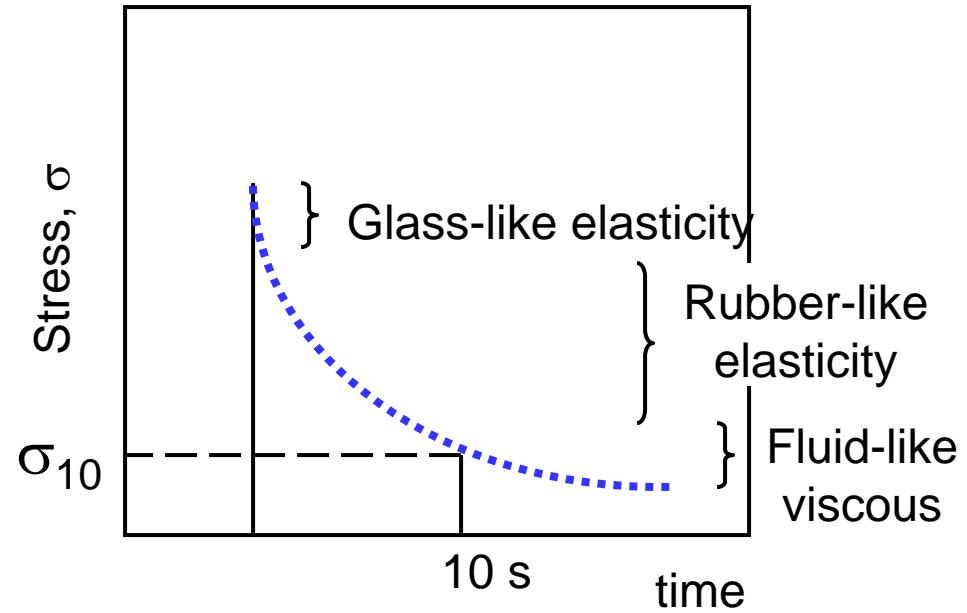
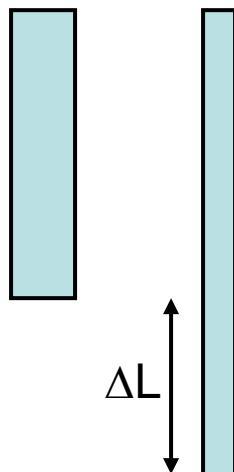
Viscoelasticity



Load is applied at t_a and released at t_r

Definition of the Relaxation Modulus

- Stress relaxation test:
 - strain to ε_o and hold.
 - observe decrease in stress with time.



Viscoelastic Modulus
Modulus of Elasticity
Relaxation Modulus

$$E_r(10s) = \frac{\sigma(10)}{\varepsilon_{fixed}}$$

$$\varepsilon_{fixed} = \frac{\Delta L}{L_o}$$

$$\begin{aligned} E_r(0) &= E, \text{ Young's Modulus} \\ E_r(\infty) &= 0 \end{aligned}$$

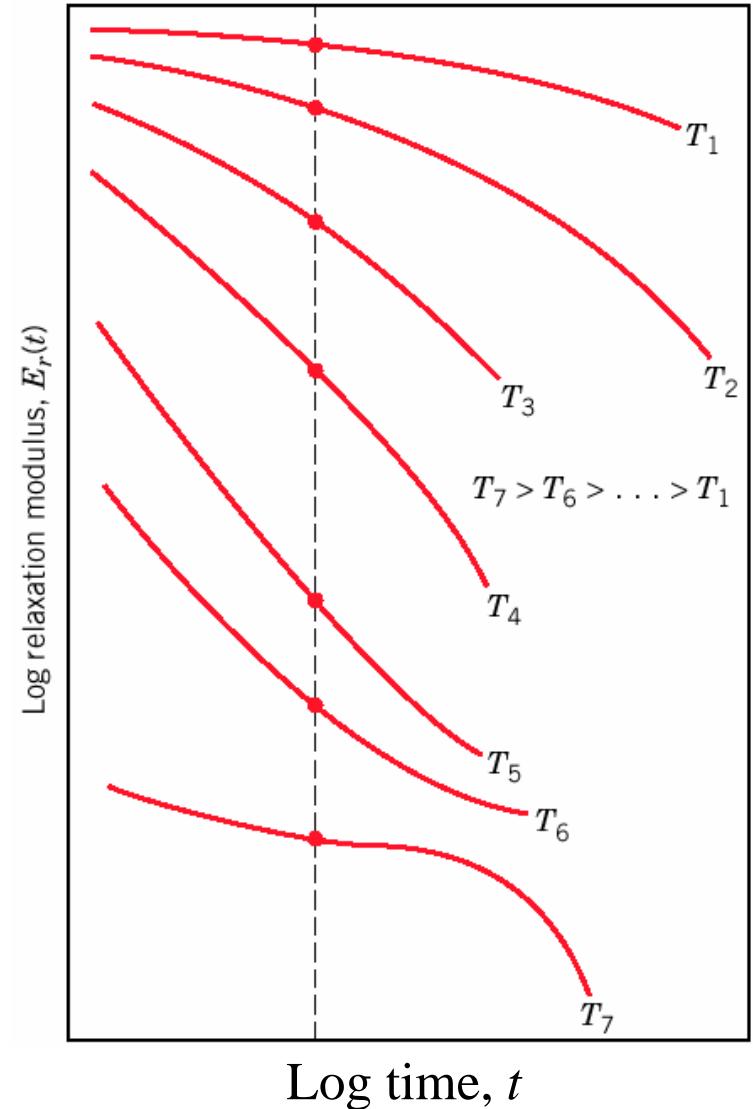
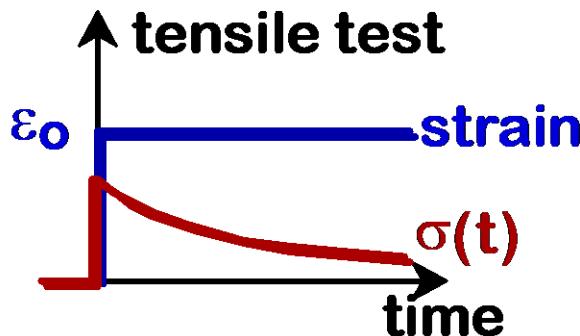
Viscoelasticity: Relaxation Modulus

Viscoelasticity can be characterized by the **viscoelastic relaxation modulus**:

- Sample is strained rapidly to pre-determined strain.
- Stress required to maintain this strain ε_0 over time is measured at constant T.
- Stress decreases with time due to molecular relaxation processes.
- Relaxation modulus can be defined as:

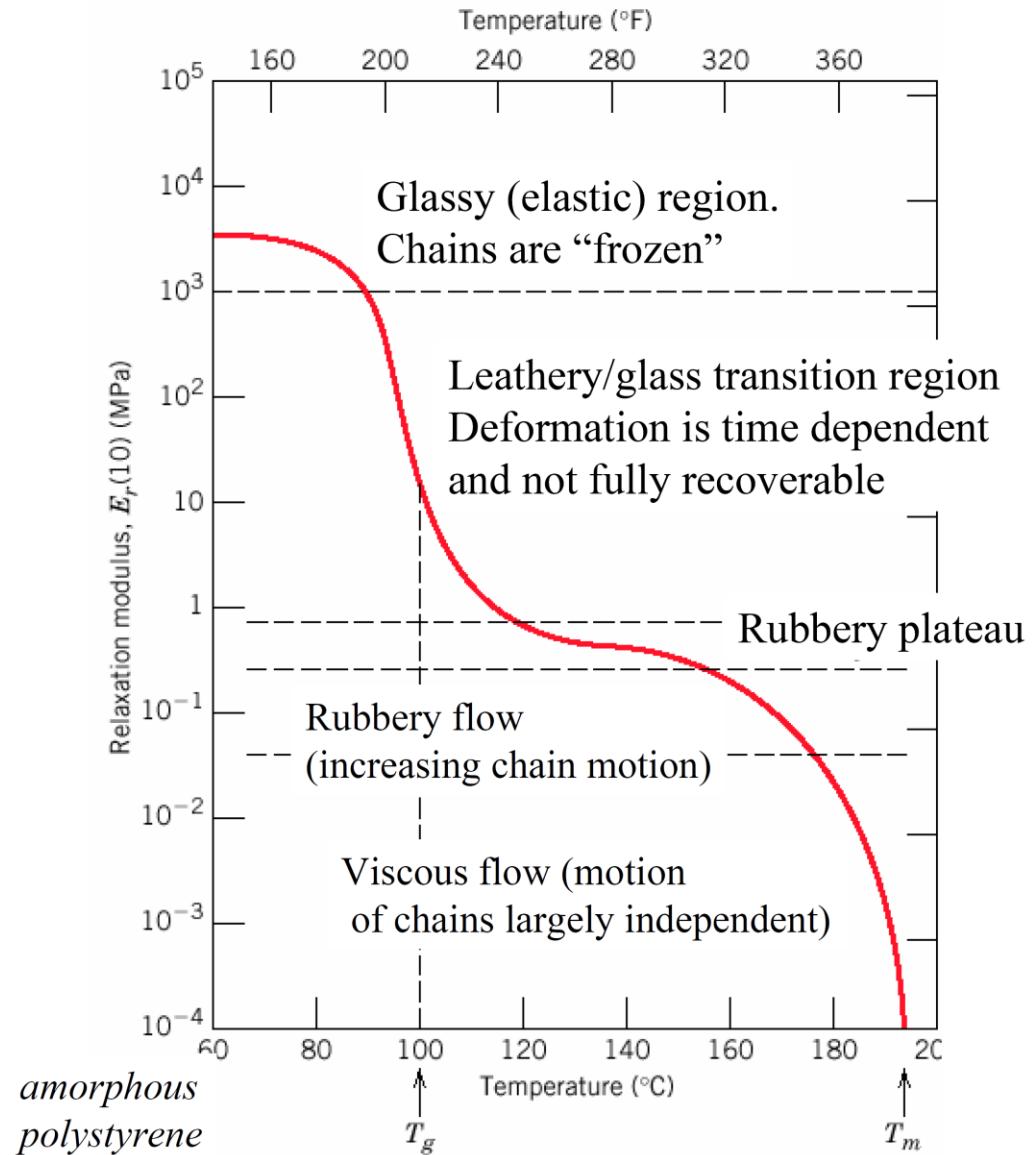
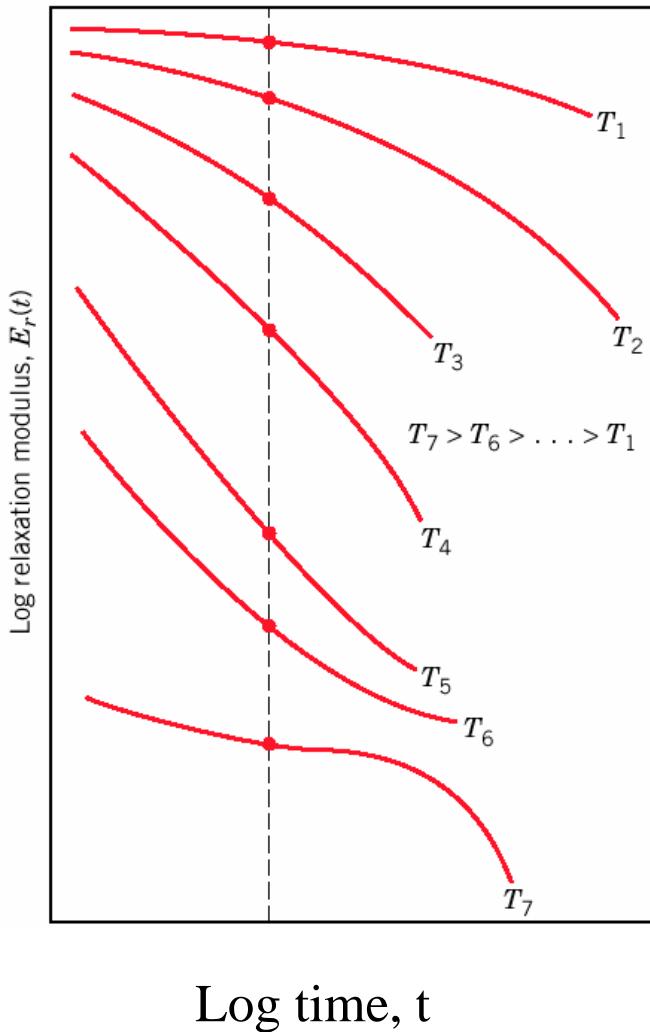
$$E_r(t) = \frac{\sigma(t)}{\varepsilon_0}$$

- $E_r(t)$ is also a function of temperature.



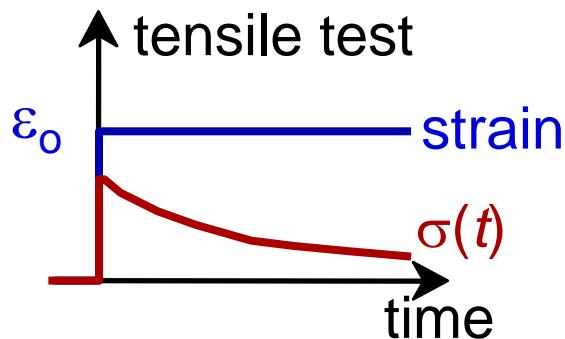
Viscoelasticity: Relaxation Modulus

To show the influence of temperature, the relaxation modulus can be plotted at a fixed time for different T:



Time-Dependent Deformation

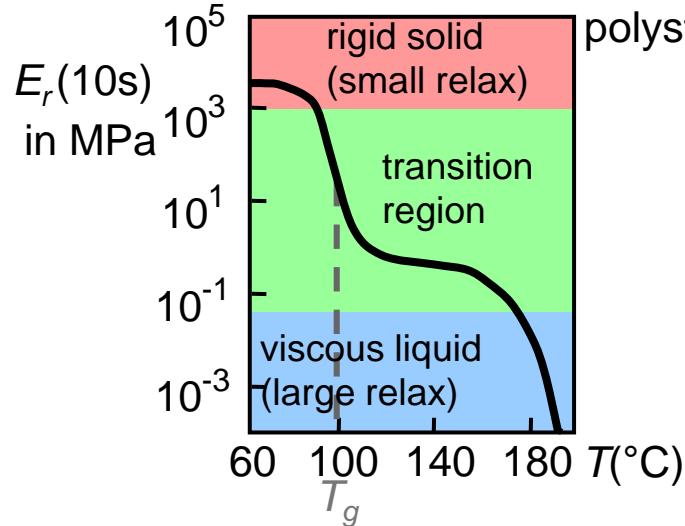
- Stress relaxation test:
 - strain to ε_o and hold.
 - observe decrease in stress with time.



- Relaxation modulus:

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_o}$$

- Data: Large drop in E_r for $T > T_g$ (amorphous polystyrene)



- Sample T_g (°C) values:

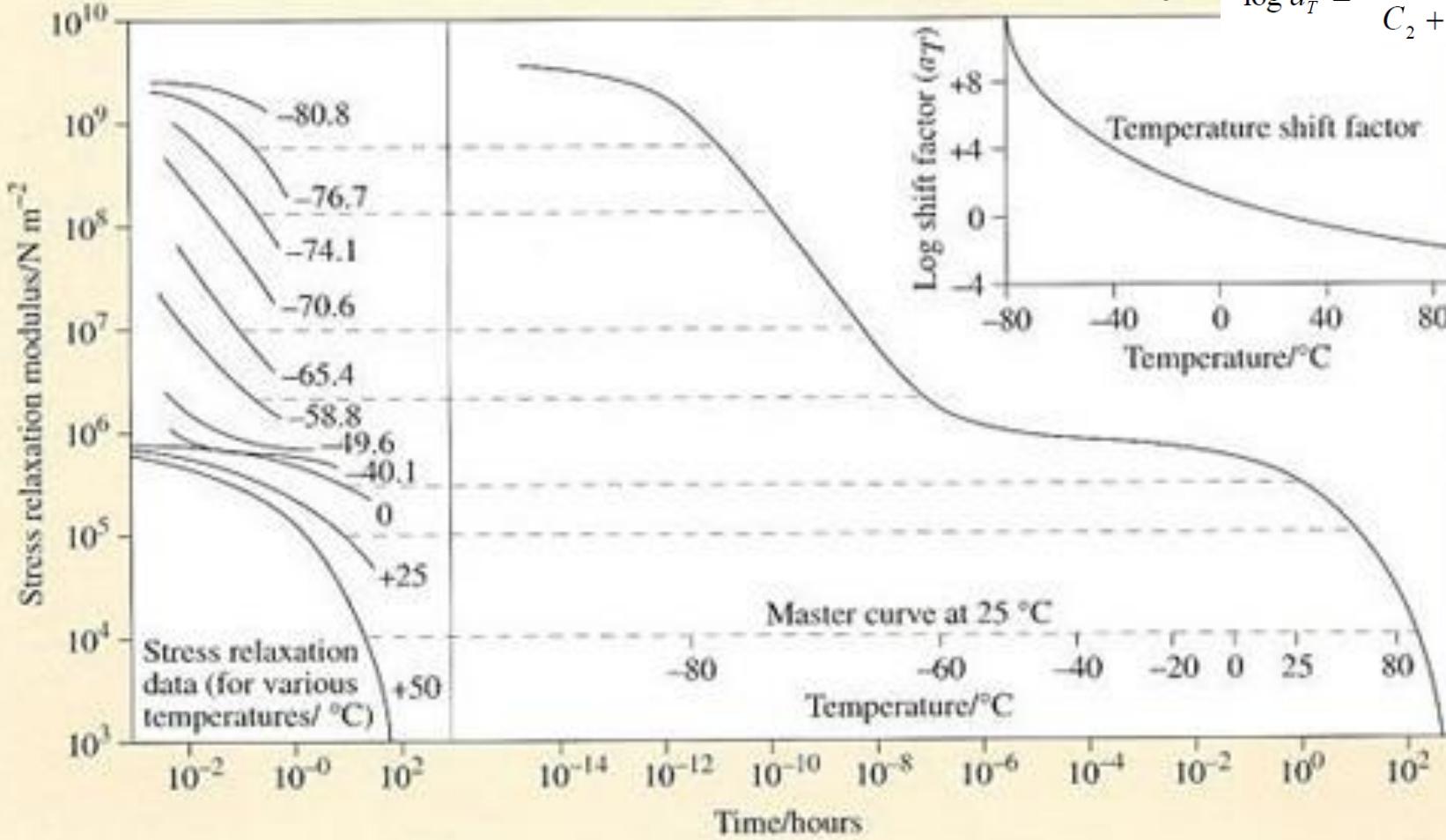
PE (low density)	- 110
PE (high density)	- 90
PVC	+ 87
PS	+100
PC	+150

Selected values from
Table 15.2, Callister
7e.

Time-Temperature Superposition

$$G(t, T) = G(a_T t, T_{ref})$$

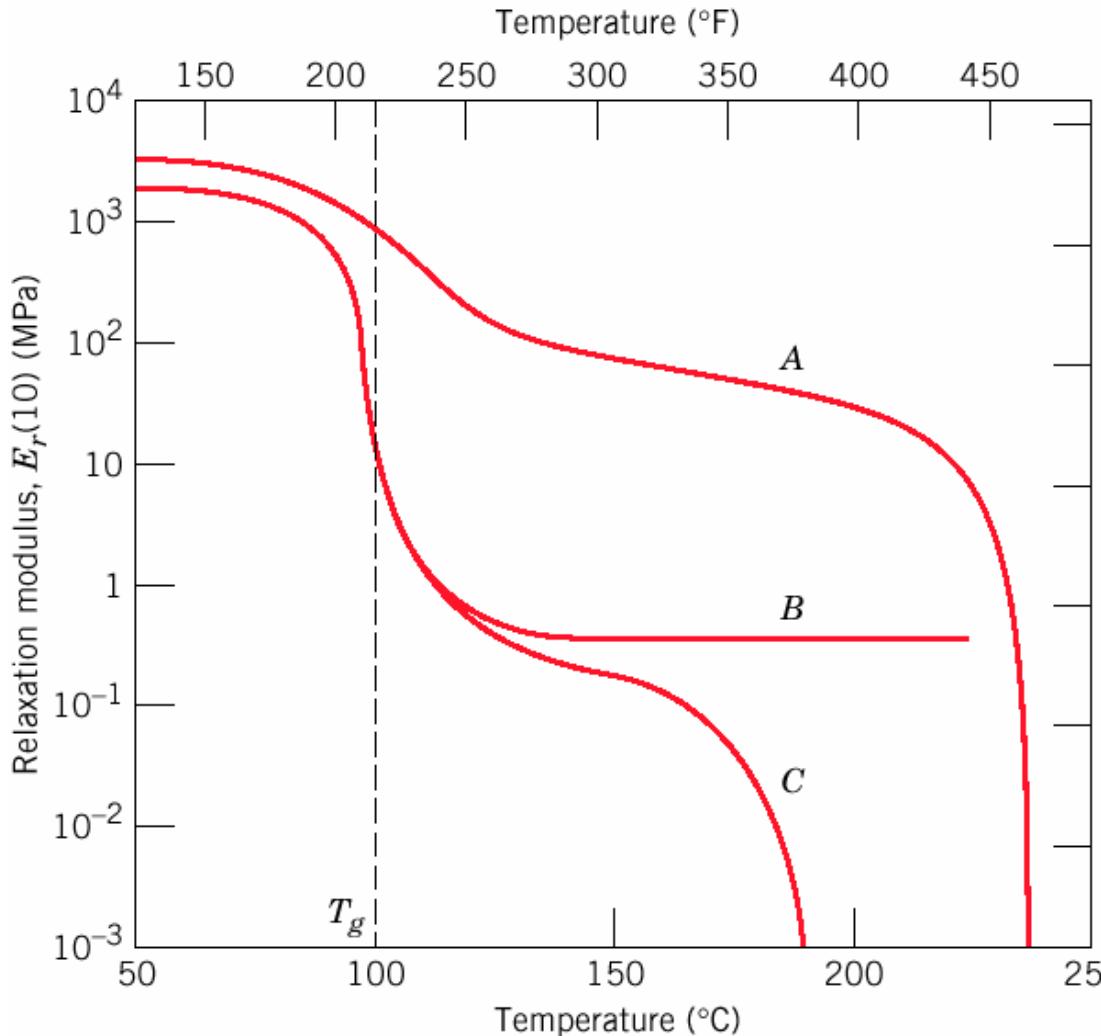
$$\log a_T = -\frac{C_1(T - T_{ref})}{C_2 + (T - T_{ref})}$$



Construction of the viscoelastic master curve for PIB (Polyisobutylene) at 25 °C reference temperature by shifting stress relaxation curves obtained at different temperatures horizontally along the time axis. The shift factor, a_T varies with temperature as shown in the inset.

Viscoelasticity

Temperature dependence of the relaxation modulus for different **polymer structures**



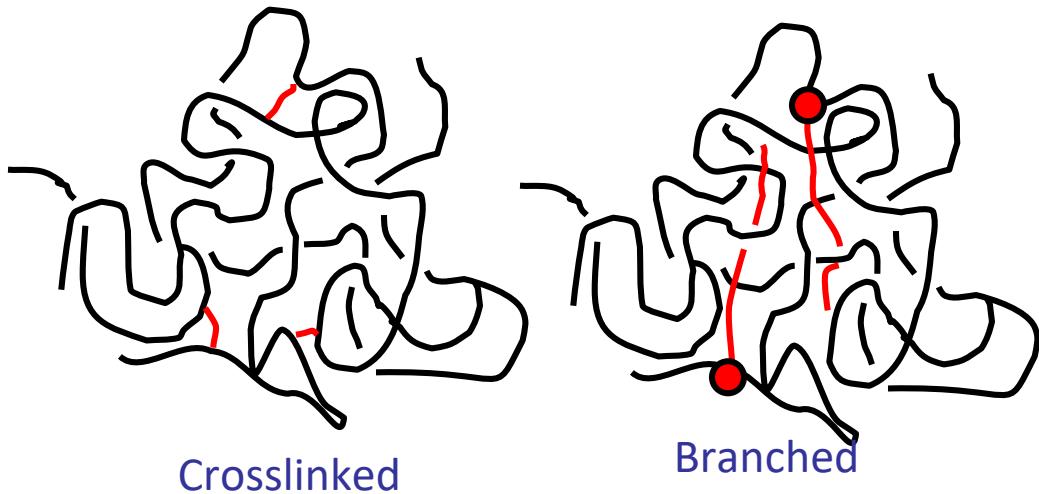
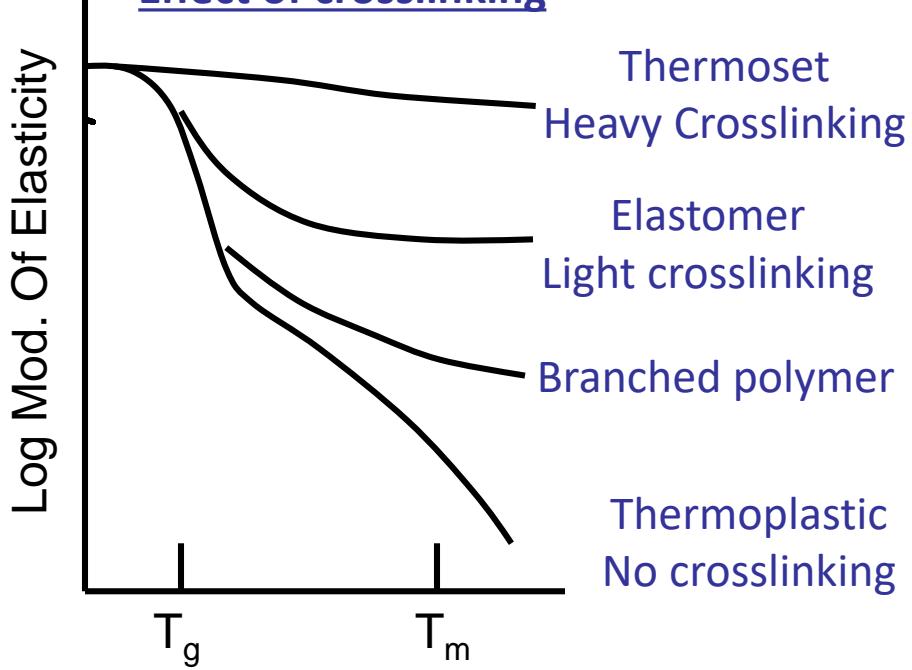
A : Largely **crystalline** isotactic polystyrene. Glass transition region limited – small amount of amorphous material

B: Lightly **cross-linked** atactic polystyrene – leathery region extends to decomposition temperature: no melting

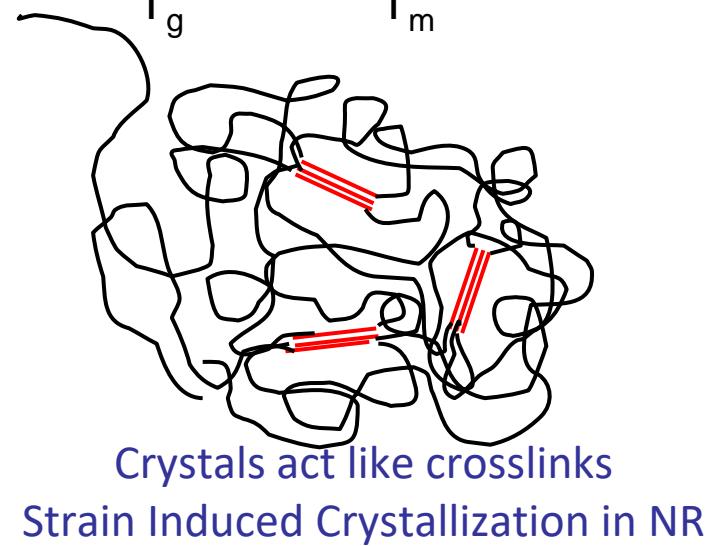
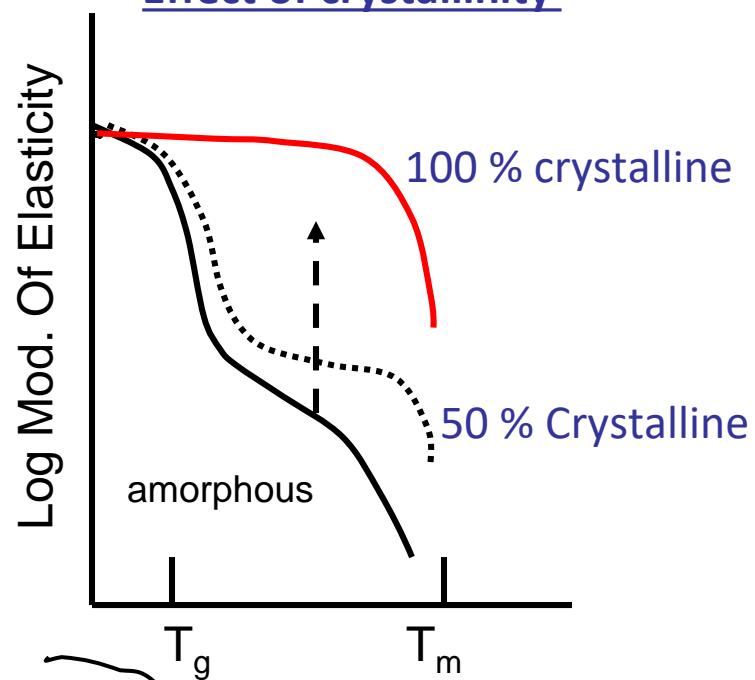
C: **Amorphous** polystyrene

Viscoelasticity: Structure Dependence

Effect of crosslinking

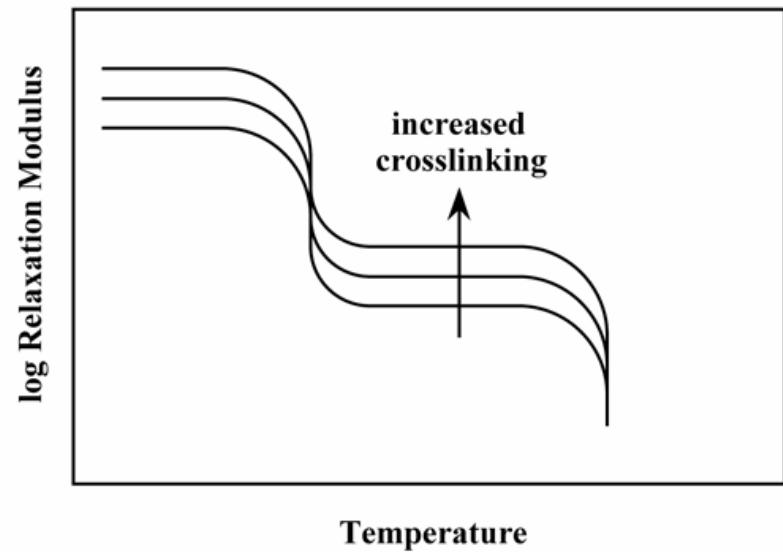
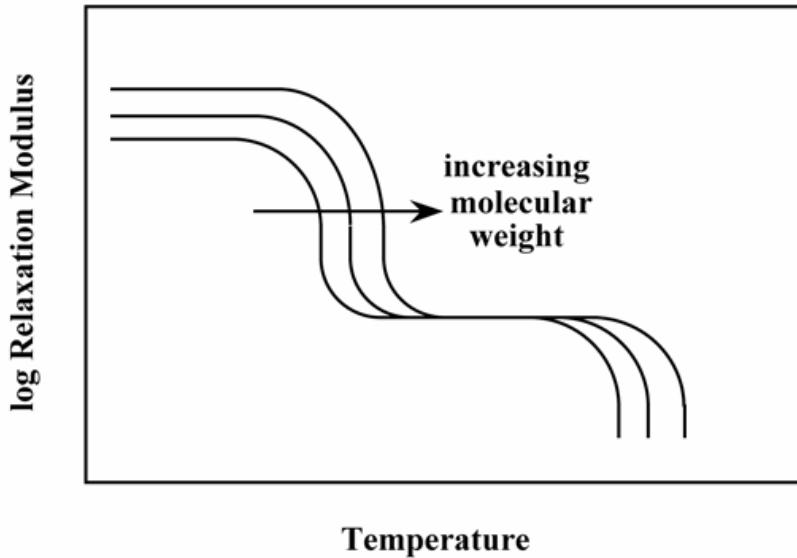


Effect of crystallinity



Viscoelasticity: Structure Dependence

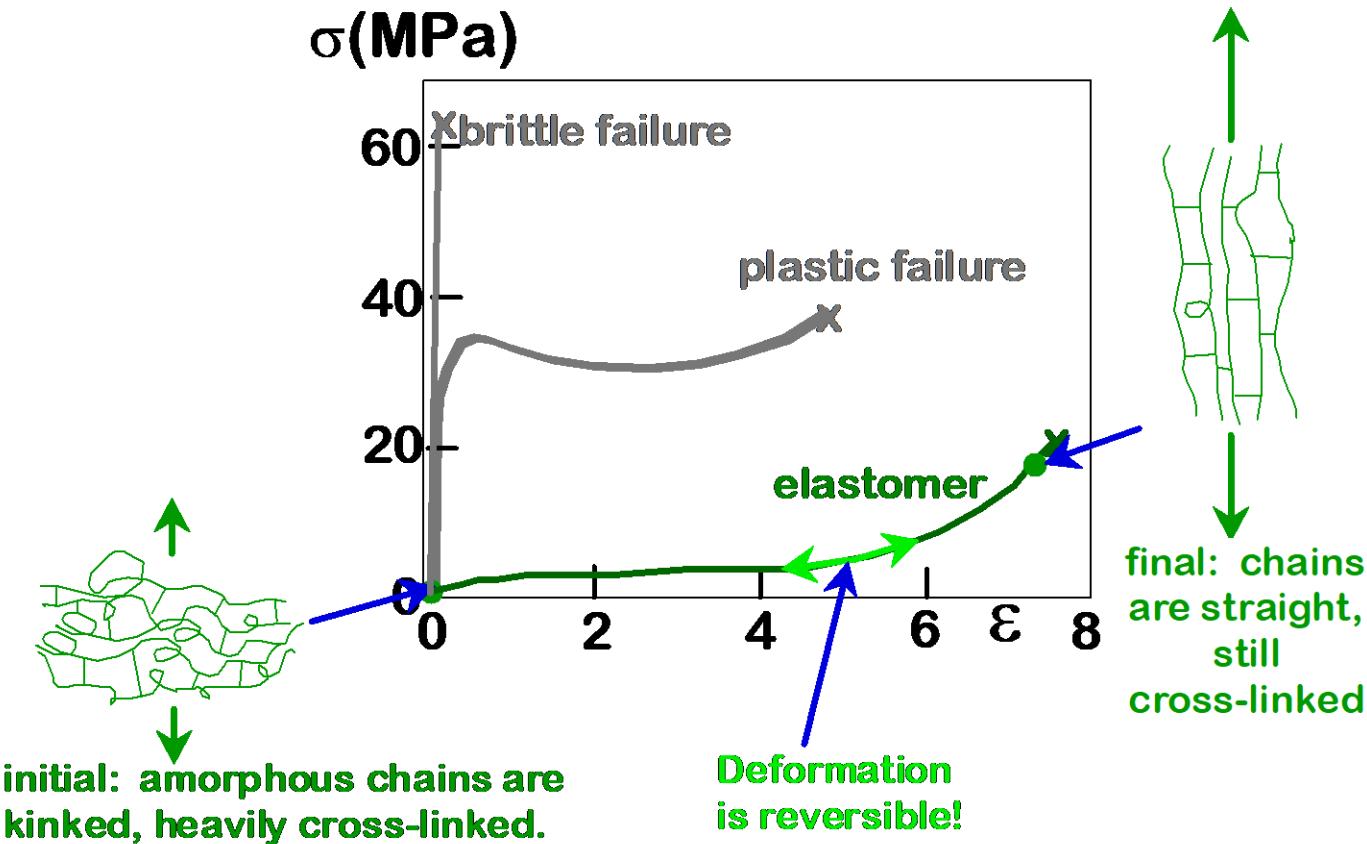
Make two schematic plots of the logarithm of relaxation modulus versus temperature for an amorphous polymer (a) how the behavior changes with increasing molecular weight and (b) change in behavior with increasing crosslinking.



Increasing molecular weight increases both glass-transition and melting temperatures.

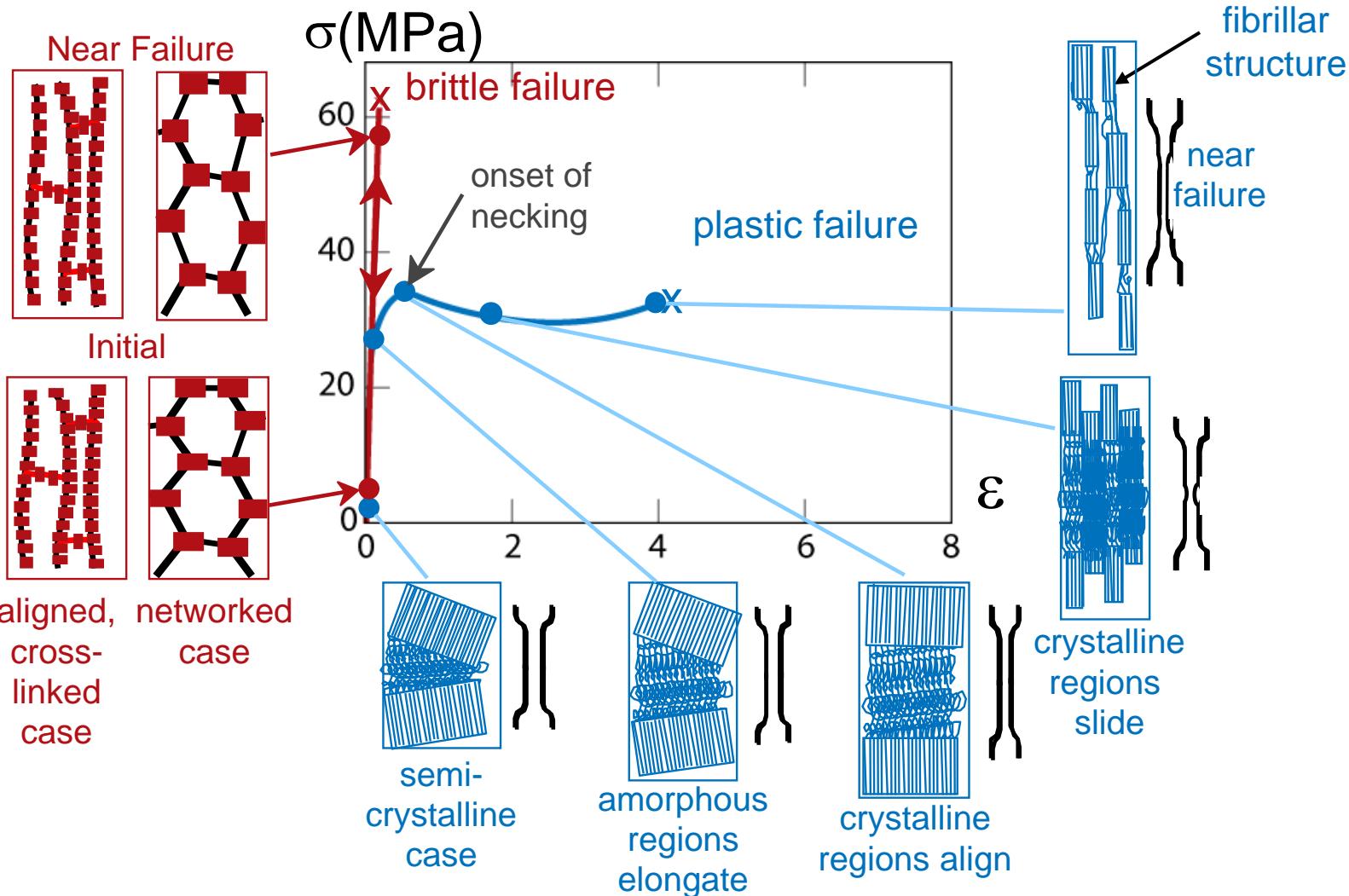
Increasing the degree of crosslinking will increase the modulus in both glassy and rubbery regions.

TENSILE RESPONSE: ELASTOMER (ex: rubberband)



- Compare to responses of other polymers:
 - brittle response (aligned, cross-linked & networked case)
 - plastic response (semi-crystalline case)

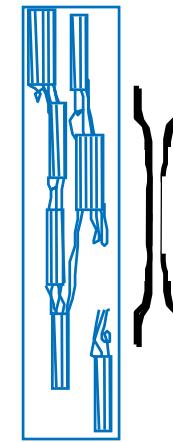
TENSILE RESPONSE: BRITTLE & PLASTIC



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.)

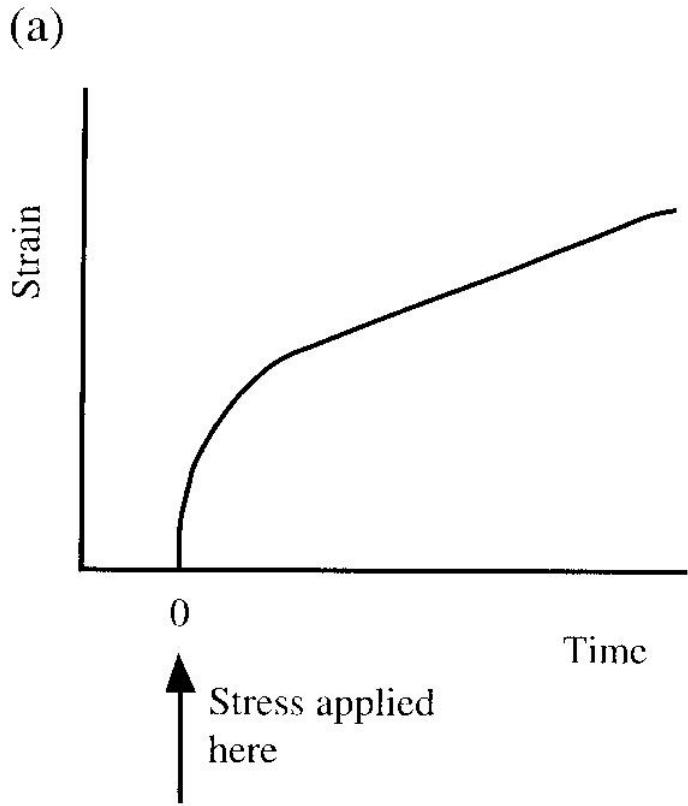
Predeformation by Drawing

- Drawing...(ex: monofilament fishline)
 - stretches the polymer prior to use
 - aligns chains in the stretching direction
- Results of drawing:
 - increases the elastic modulus (E) in the stretching direction
 - increases the tensile strength (TS) in the stretching direction
 - decreases ductility (% EL)
- Annealing after drawing ...
 - decreases alignment
 - reverses effects of drawing.
- Comparable to cold working in metals (change of defects, metal becomes more resistant to further deformation)!



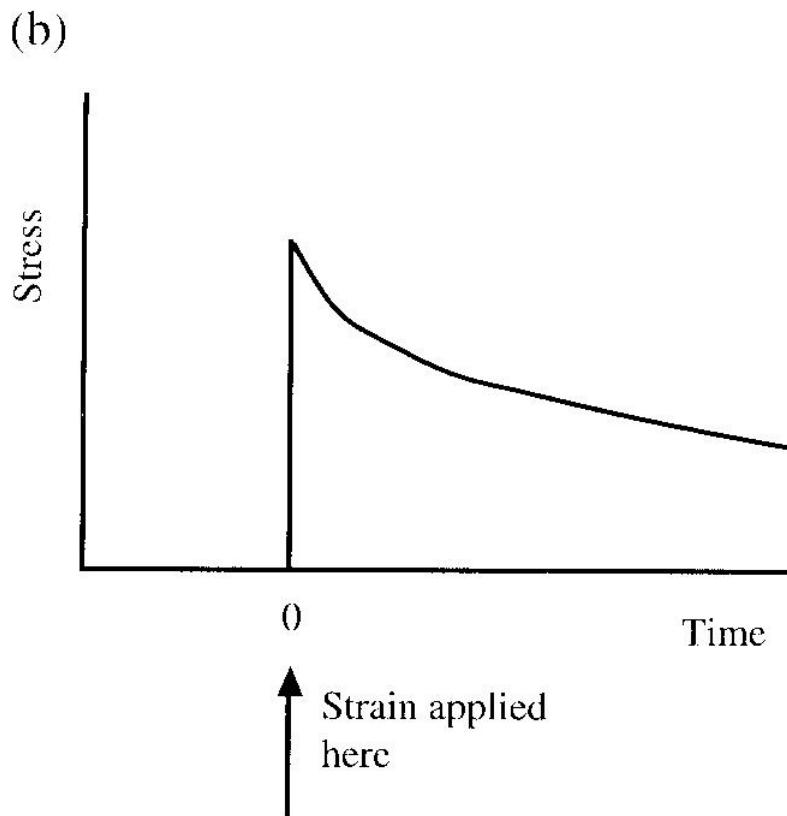
Adapted from Fig. 15.13, *Callister* 7e. (Fig. 15.13 is from J.M. Schultz, *Polymer Materials Science*, Prentice-Hall, Inc., 1974, pp. 500-501.)

Viscoelastic properties in polymers



A stress σ_0 is applied at time $t=0$ and held constant. The strain $\varepsilon(t)$ is followed over time. The **creep compliance** $J(t)$ is given by:

$$\varepsilon(t) = \sigma_0 J(t)$$



A strain ε_0 is applied at $t=0$ and held constant. The stress $\sigma(t)$ is followed over time. The **stress relaxation modulus** $G(t)$ is given by:

$$\sigma(t) = \varepsilon_0 G(t)$$

The complex modulus G^*

If a sinusoidal strain is applied: $\varepsilon(t) = \varepsilon_0 \cos(\omega t)$
the resulting stress is given by:

$$\sigma(t) = \varepsilon_0 [G'(\omega) \cos(\omega t) - G''(\omega) \sin(\omega t)]$$

The complex modulus, $G^* = G'(\omega) + iG''(\omega)$ is given by a Fourier transform of $G(t)$.

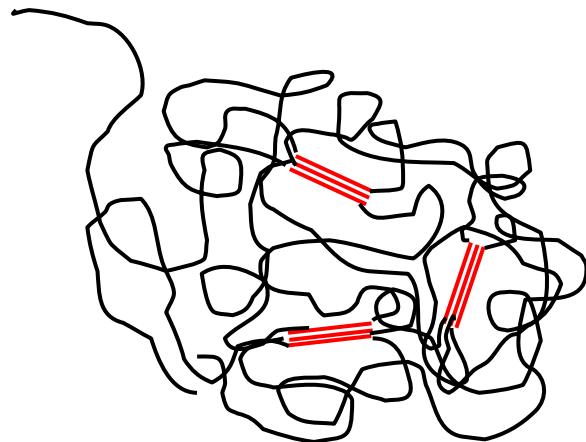
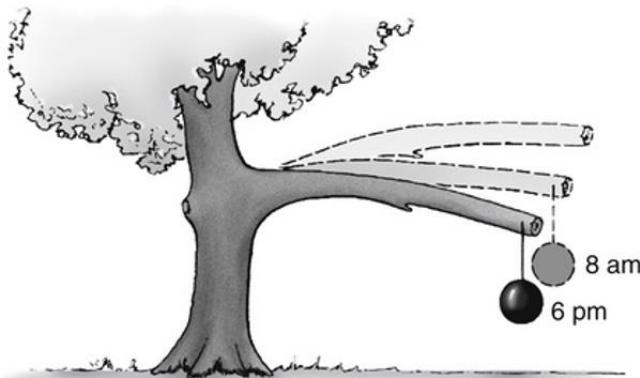
G' gives the elastic response, G'' the viscous response

Viscoelastic Creep

- Many polymers susceptible to time-dependent deformation under **constant load** – viscoelastic creep.
- Creep may be significant even at room temperature and under moderately low stresses (below yield strength).
- Results of creep tests are described by time dependent creep modulus:

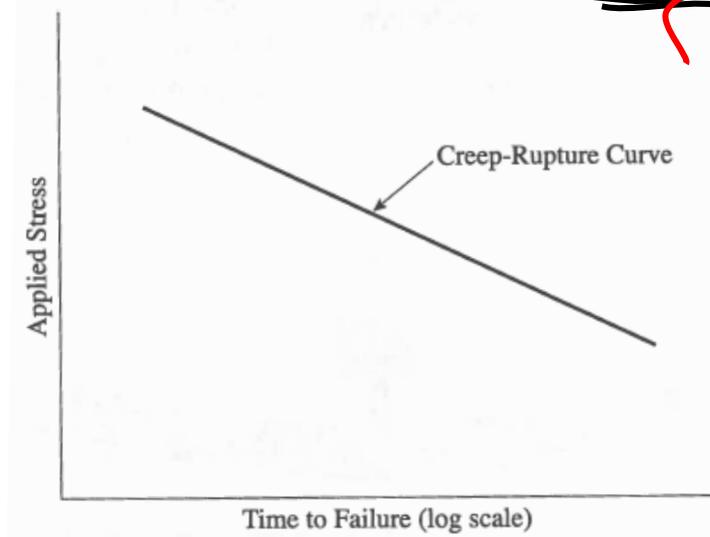
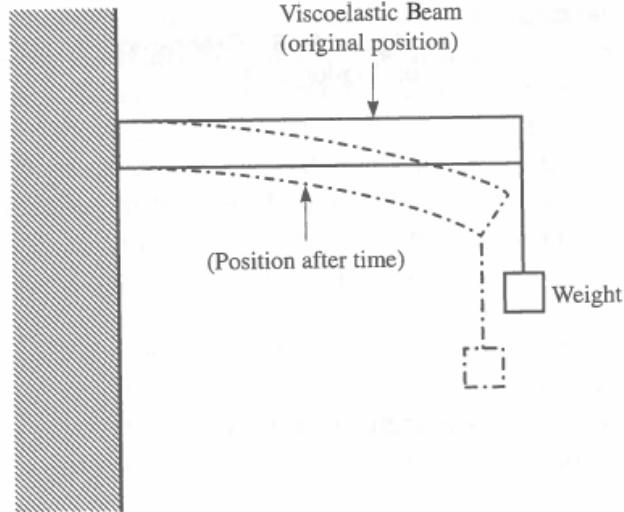
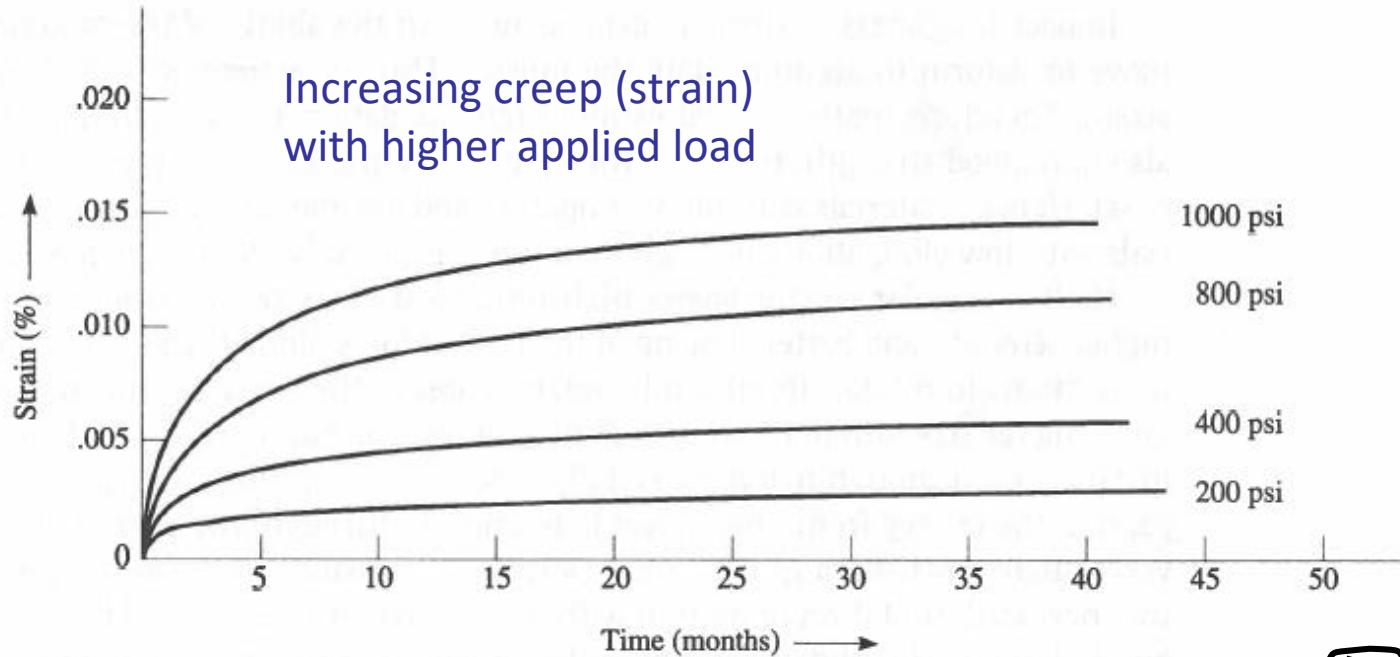
$$E_c(t) = \sigma_0 / \varepsilon(t)$$

- Amount of creep decreases as crystallinity increases.



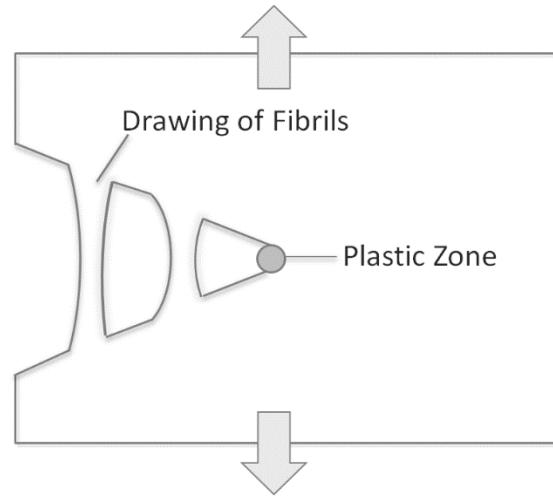
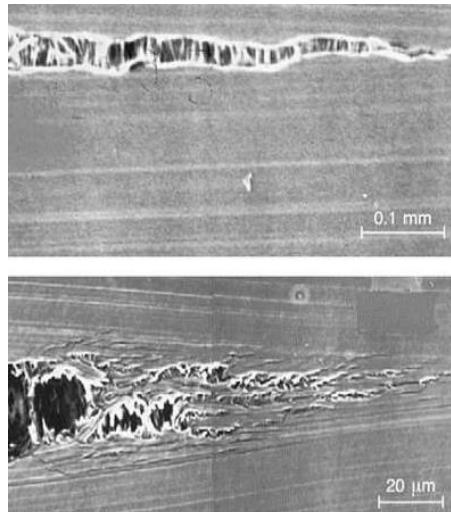
Crystals act like crosslinks

Viscoelastic Creep



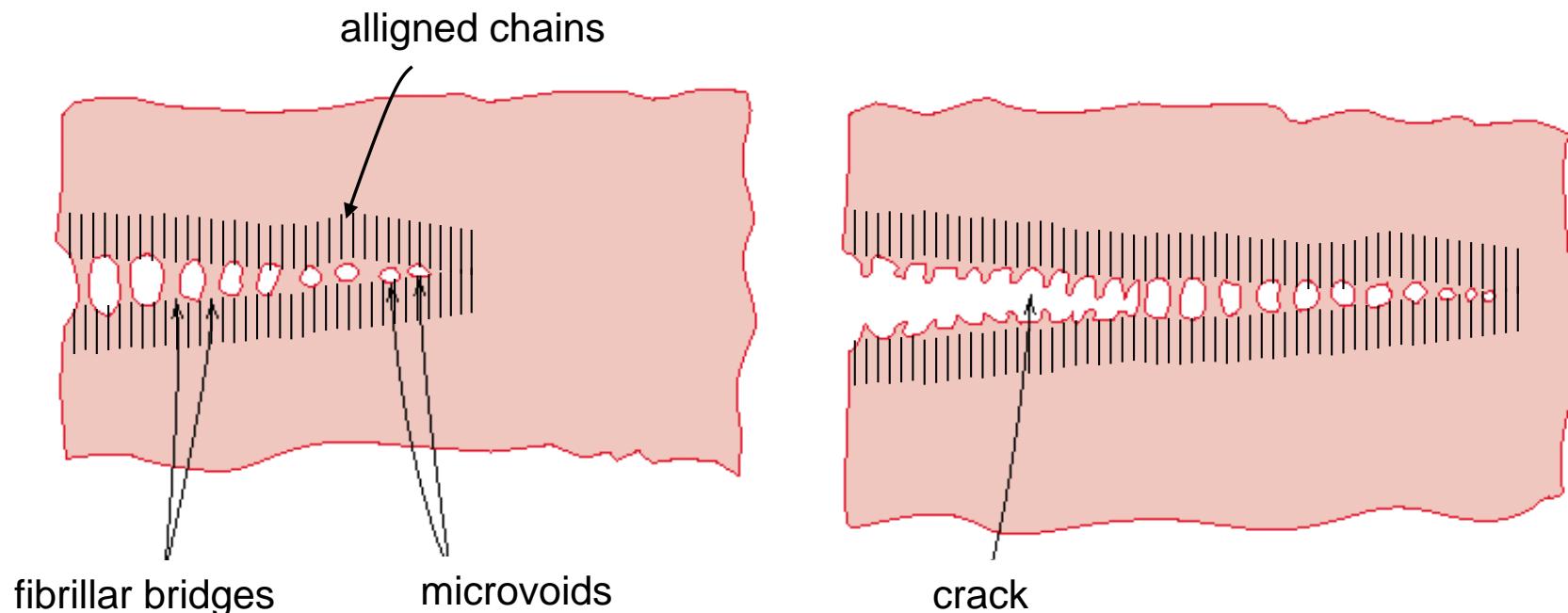
Fracture of Polymers

- Fracture strengths of polymers are low compared to metals and ceramics.
- Brittle fracture occurs in **thermosetting polymers**. Fracture is initiated at stress concentrators (scratches, notches, etc). Covalent bonds are severed during fracture.
- In **thermoplastic polymers**, both ductile and brittle fracture are possible. Brittle fracture is favored at lower temperatures, higher strain rates, and at stress concentrators (sharp notches).
- Brittle to ductile transition often occurs with increasing temperature.

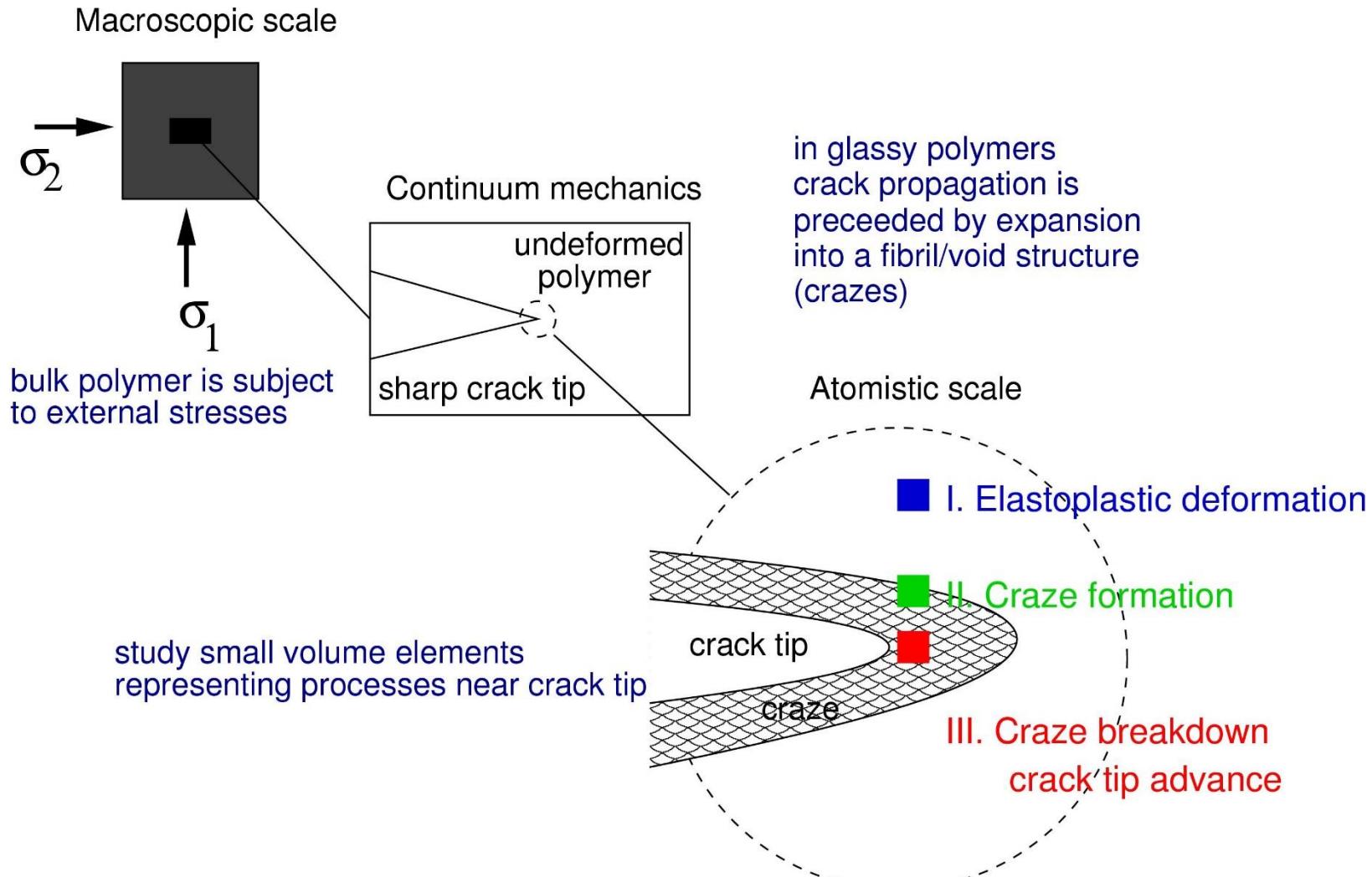


Crazing During Fracture of Thermoplastic Polymers

- Fracture of glassy **thermoplastic polymers** often proceeds through **crazing**. Crazing occurs when localized regions yield, forming an interconnected array of microvoids. **Fibrillar bridges** of oriented molecular chains form between voids.
- At high enough tensile loads, these bridges elongate and break, enabling crack propagation.
- Crazing absorbs fracture energy and increases fracture toughness.

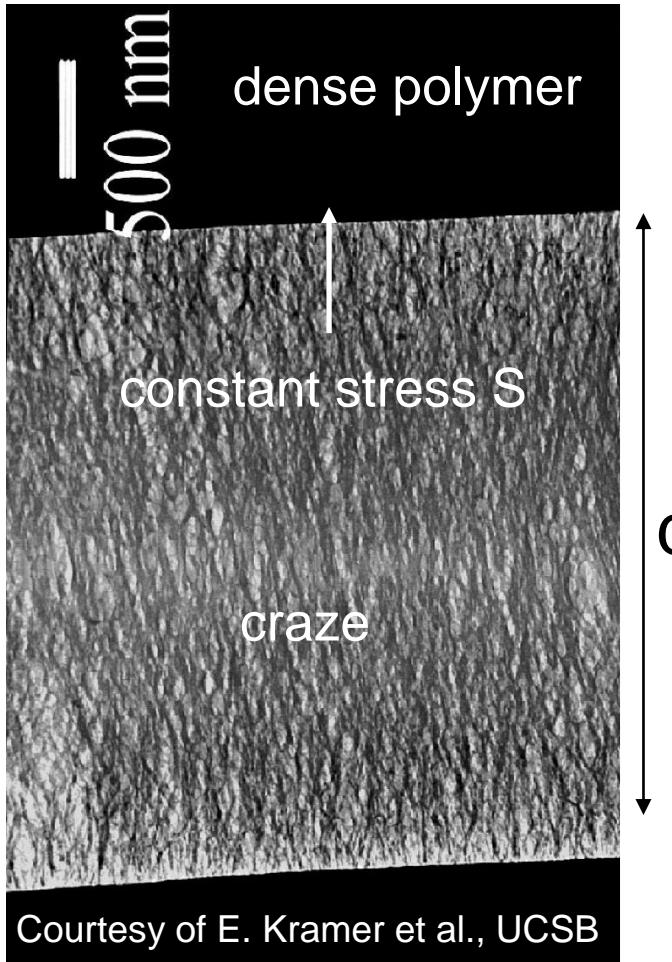


Deformation and Failure in Glassy Polymers

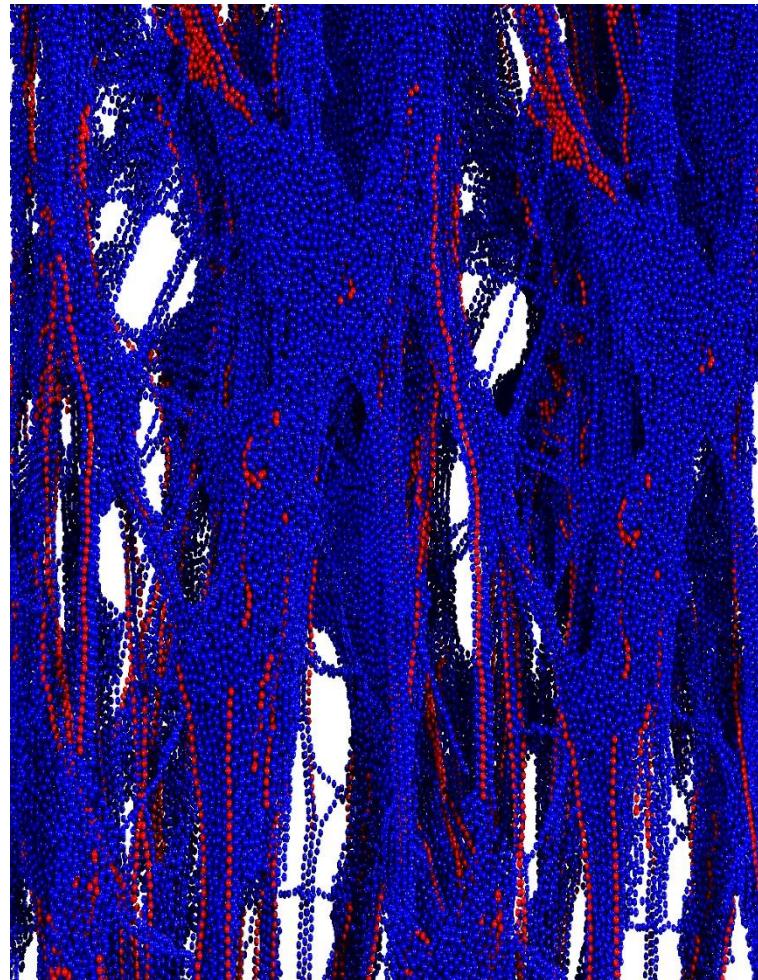


Craze Formation and Fracture in Glassy Polymers

Experiment:



Simulation:

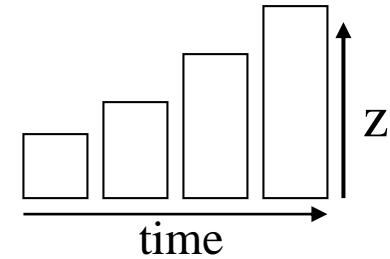
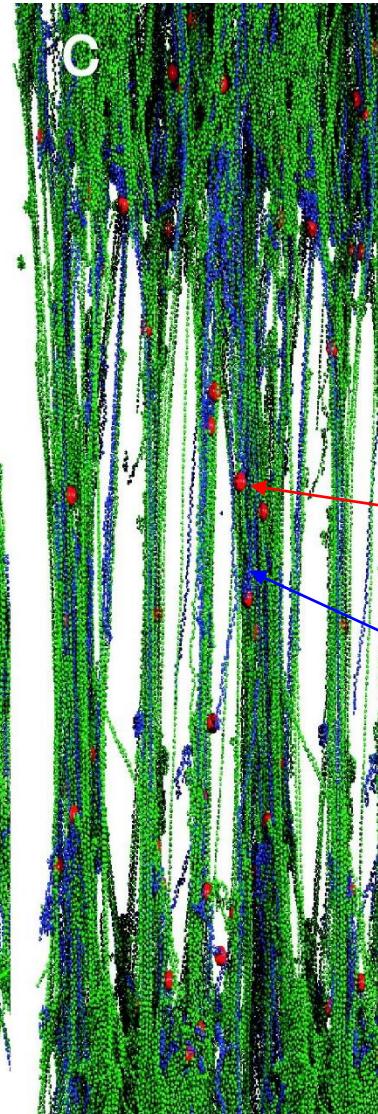
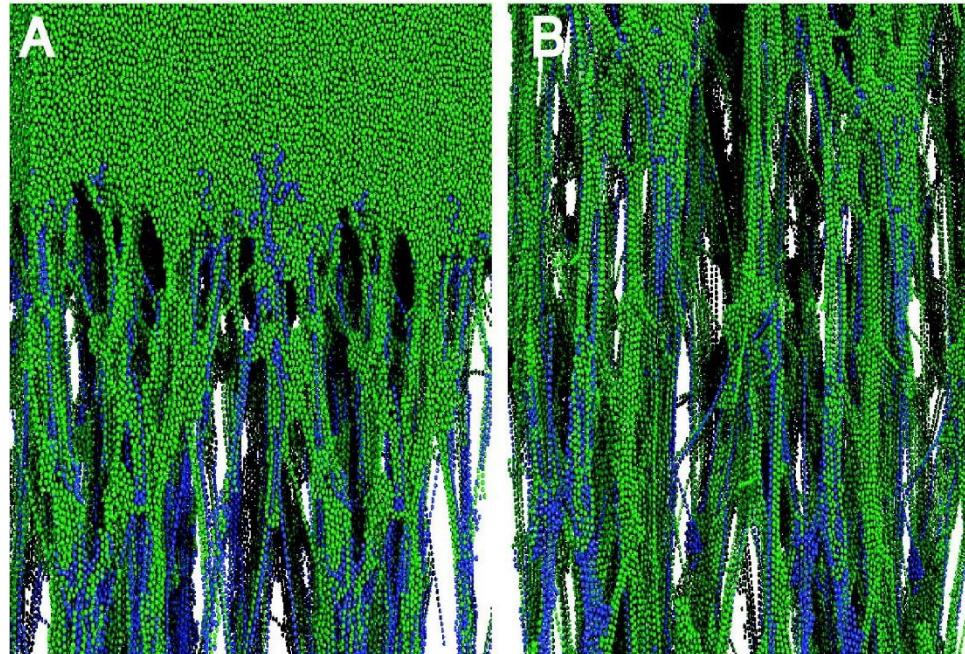
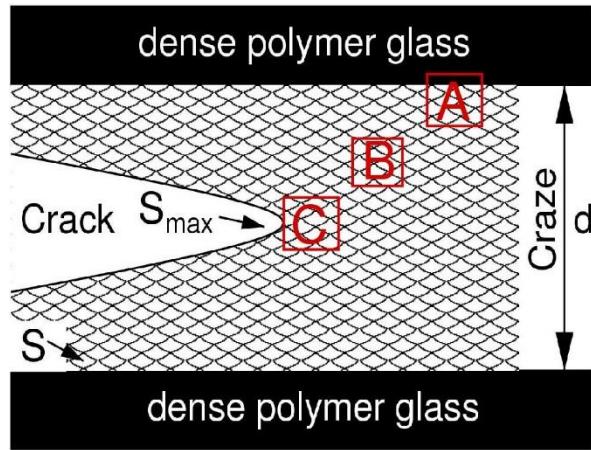


Experimental craze growth parameters:

- extension ratio $\lambda = \rho_i/\rho_f \sim 2-6$
- drawing stress $S \sim 40-70\text{ MPa}$
- fibril diameter $D \sim 5-30\text{ nm}$
- craze width $d \sim 3-20\mu\text{m}$

Craze Formation and Fracture in Glassy Polymers

cm crack \leftrightarrow μm craze \leftrightarrow 10nm fibril \leftrightarrow nm polymer

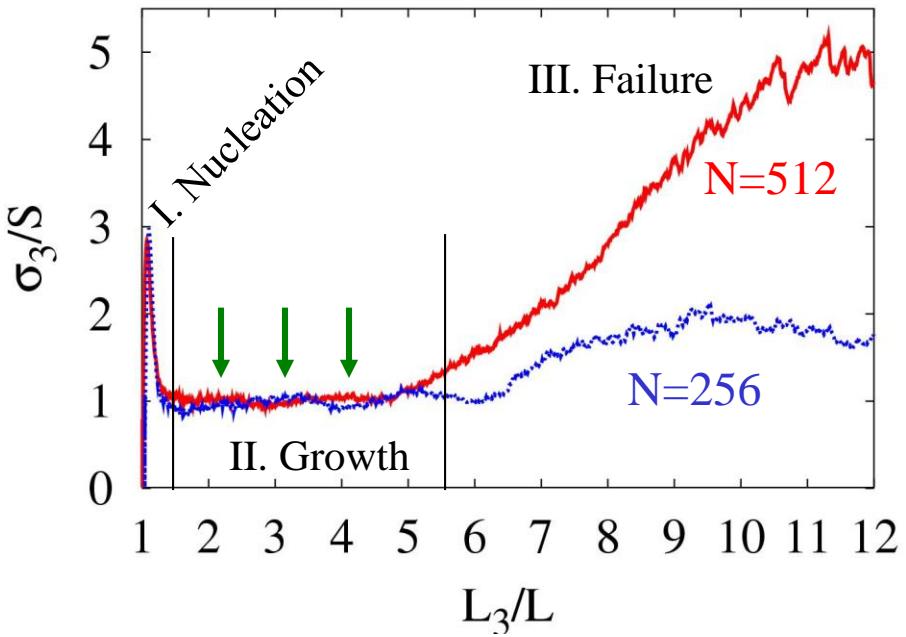


broken bonds are
marker by red

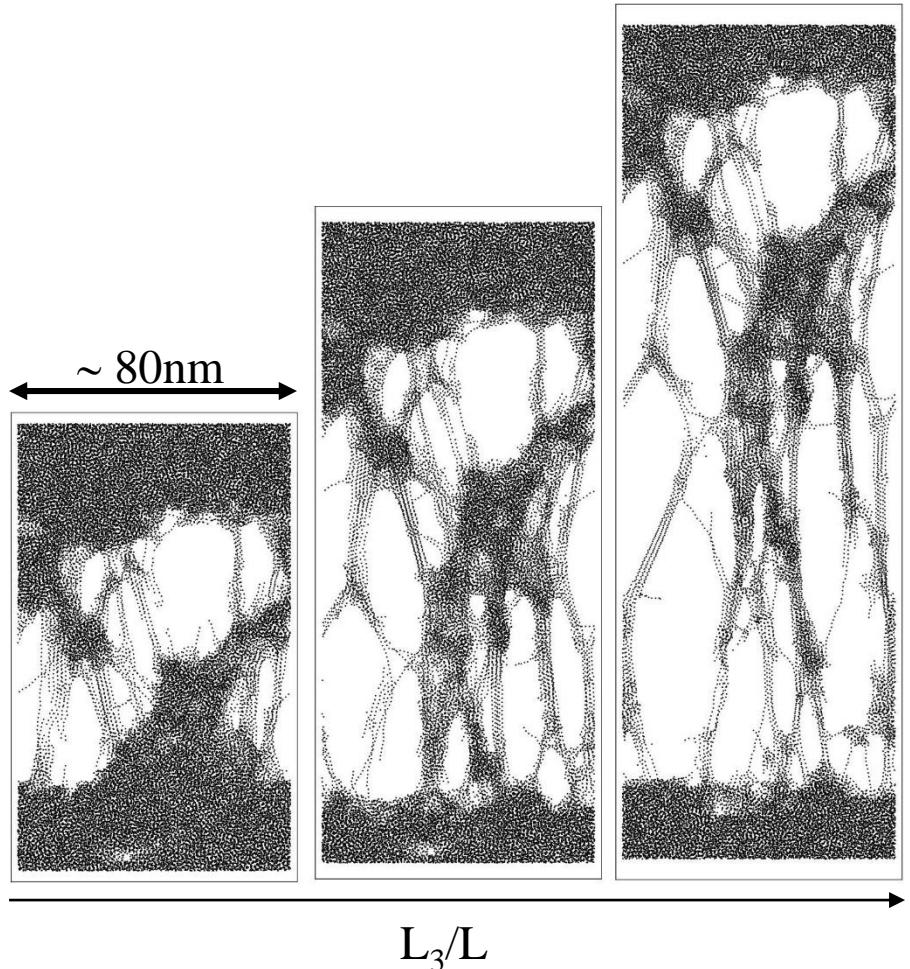
Chains that
carry maximum
load indicated
by blue color

Craze Formation and Fracture in Glassy Polymers

Stress-strain curves



- Growth (fibril drawing) in II at constant stress S
- I and II independent of N , not so III



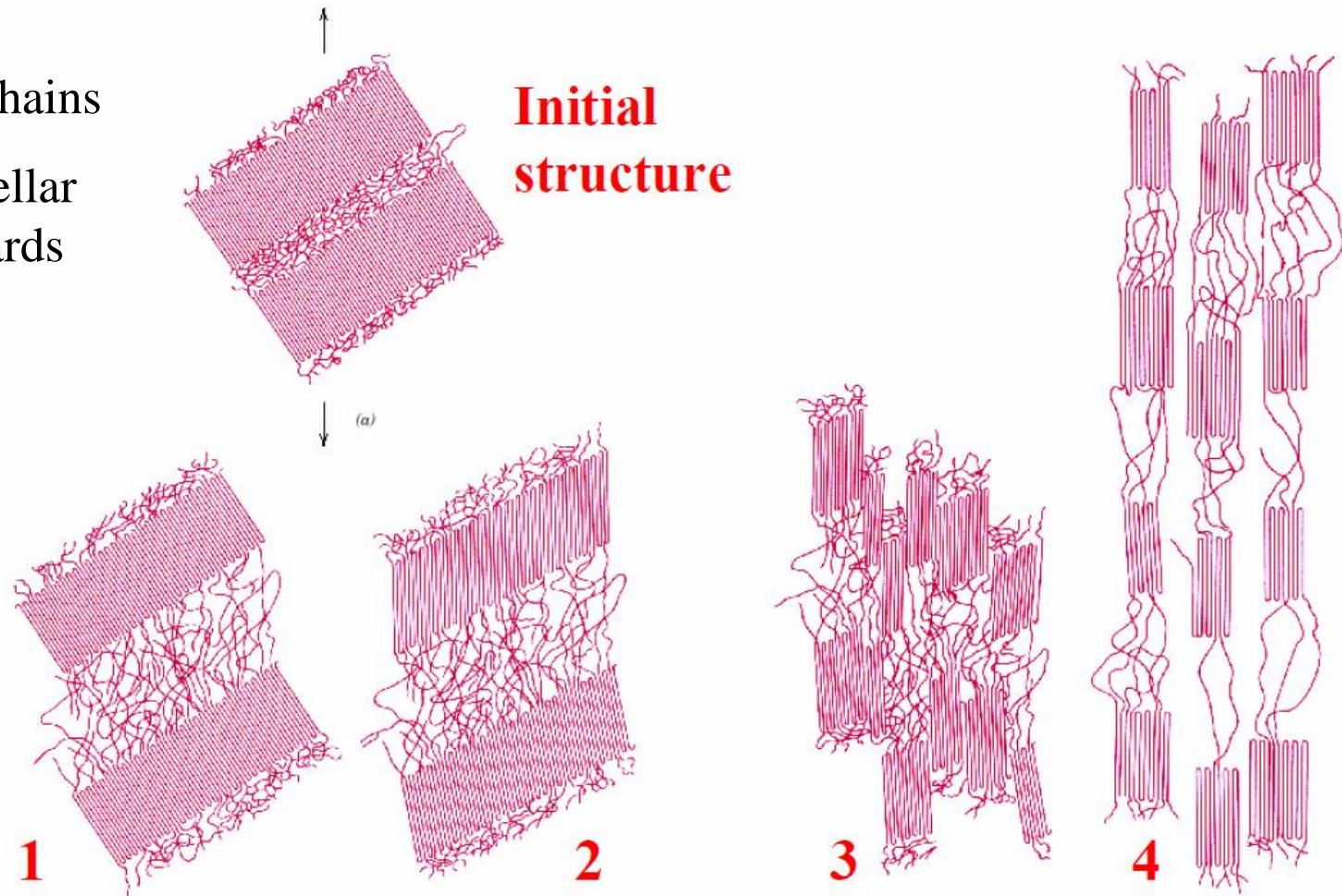
- Two phases coexist at constant normal stress S

Plastic Deformation of Semicrystalline Polymers

Plastic deformation is defined by the interaction between crystalline and amorphous regions and is *partially reversible*.

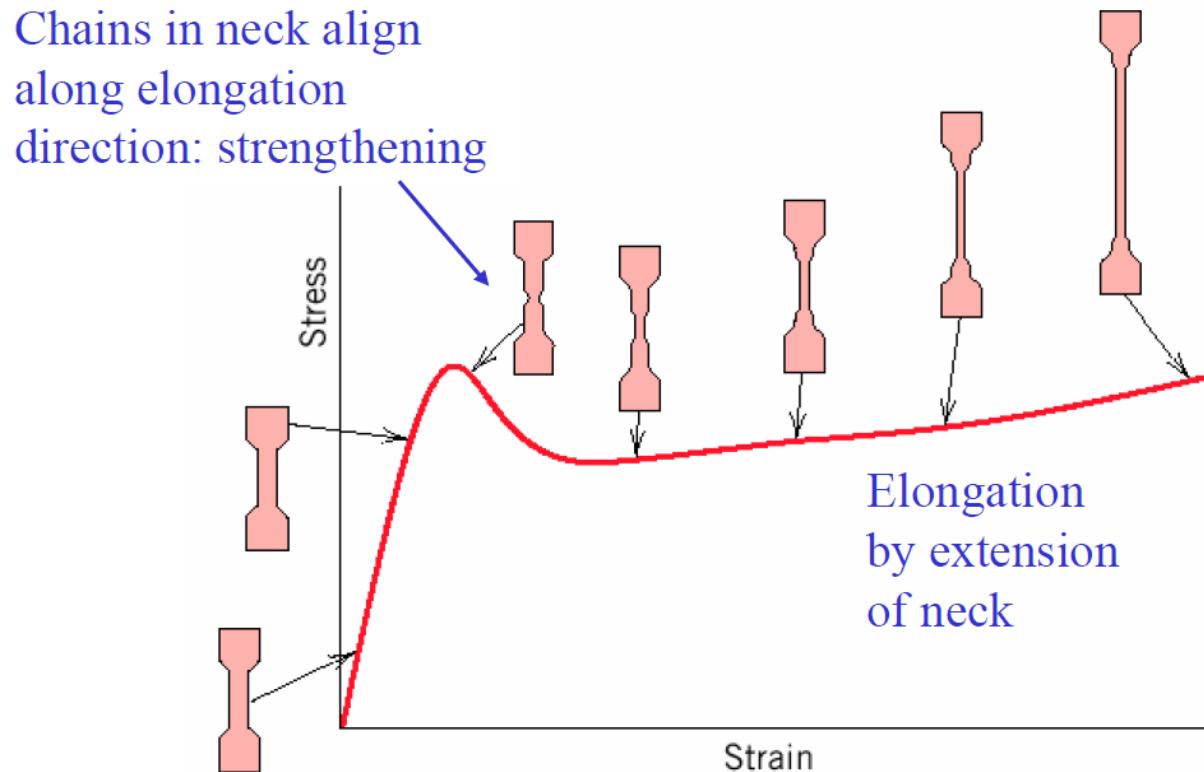
Stages of plastic deformation:

1. elongation of amorphous tie chains
2. tilting of lamellar crystallites towards the tensile axis
3. separation of crystalline block segments
4. stretching of crystallites and amorphous regions along tensile axis



Plastic Deformation of Semicrystalline Polymers

The macroscopic deformation involves **necking**. Neck gets stronger since the deformation aligns the chains and increases local strength in the neck region (up to 2-5 times) \Rightarrow neck is expanding along the specimen.



Different from ductile metals where the deformation is confined in the initial neck region.

Factors that Influence Mechanical Properties

Temperature and strain rate (already discussed)

Chain entanglement, strong intermolecular bonding

(van der Waals, cross-links) increase strength

Drawing, analog of work hardening in metals, corresponds to the neck extension. Is used in production of fibers and films. Molecular chains become highly oriented ⇒ properties of drawn material are **anisotropic** (perpendicular to the chain alignment direction strength is reduced)

Heat treatment - changes in crystallite size and order

- **undrawn material**: Increasing annealing temperature leads to
 - increase in elastic modulus
 - increase in yield/tensile strength
 - decrease in ductility

Note that these changes are opposite from metals

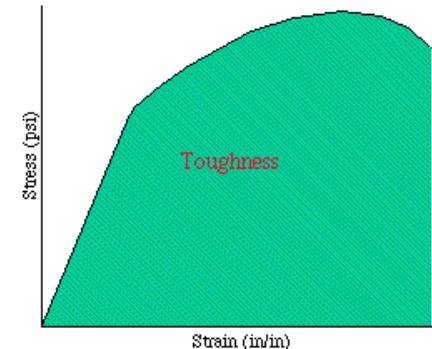
- **drawn material**: opposite changes (due to recrystallization and loss of chain orientation)

Equilibrium Toughness (long deformation times)

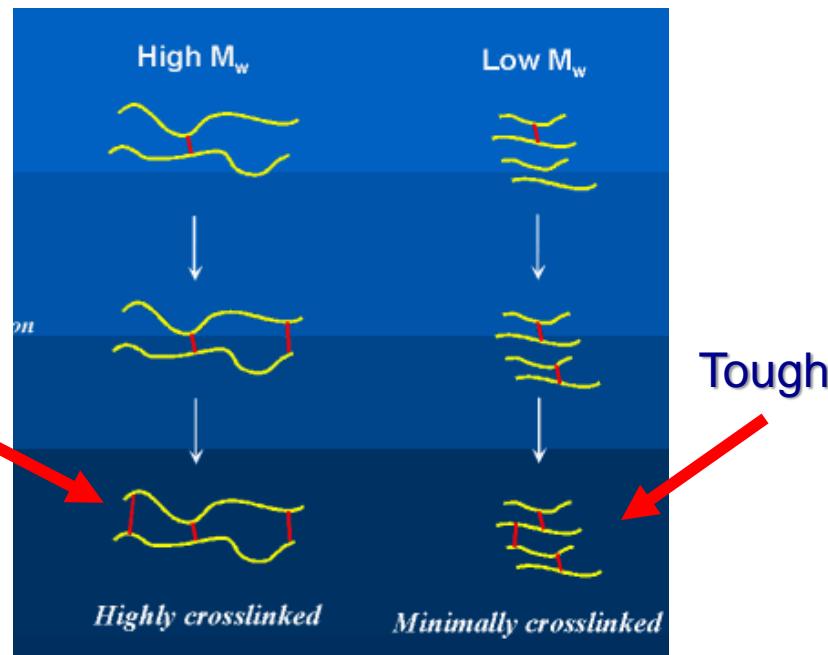
- The total area under the true stress-strain curve which measures the energy absorbed by the specimen in the process of breaking.

Toughness is not Strength:

$$\text{Toughness} = \int \sigma d\varepsilon$$



- Tough: High elongation, low modulus.
 - High M_w
 - Low Intermolecular strength
 - Rubber, slight cross linking
- Brittle: Low elongation, high modulus
 - Crystalline
 - High degree of Xlinked rigid
 - High Intermolecular strength

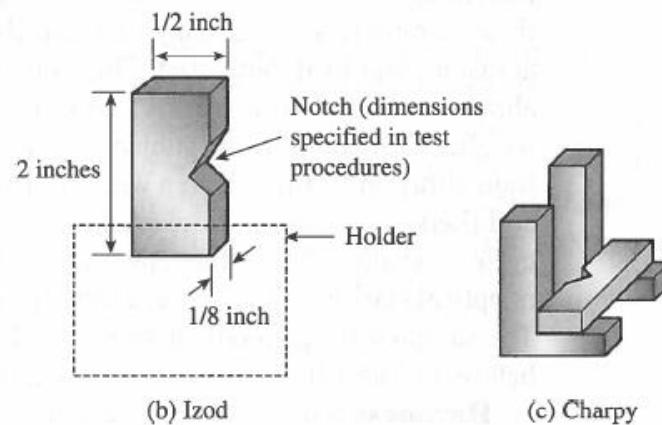
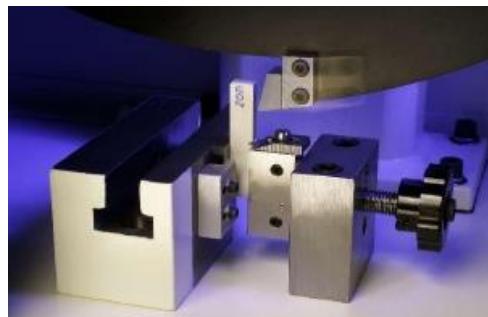
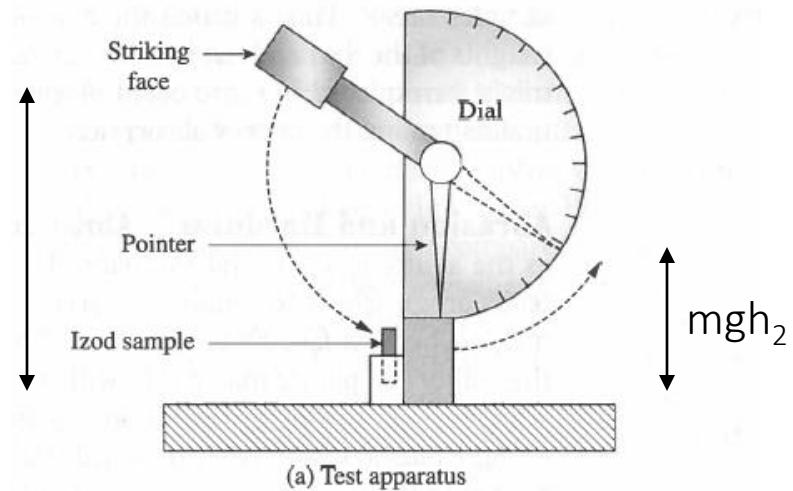
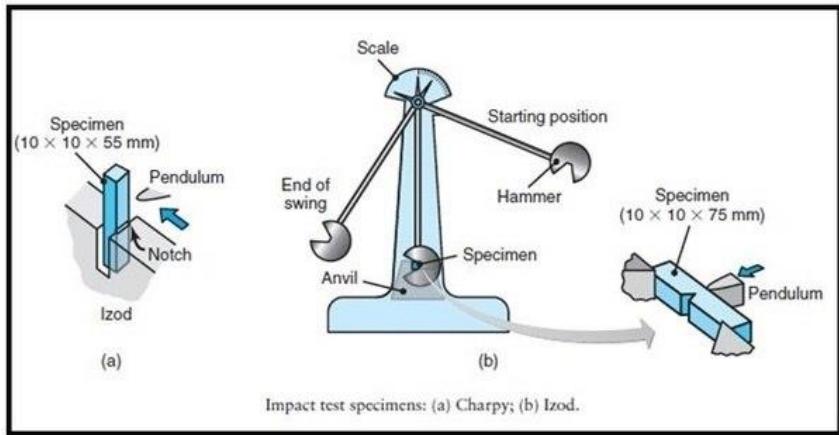


To be tough, a material should withstand both high stresses and high strains. **Strength** indicates how much force the material can support, while toughness indicates how much energy a material can absorb before rupturing. Brittle materials (like *ceramics*) that are strong but with limited ductility are not tough.

Impact Toughness or Impact Strength

Impact toughness is the energy adsorbed by material upon *sudden impact*.

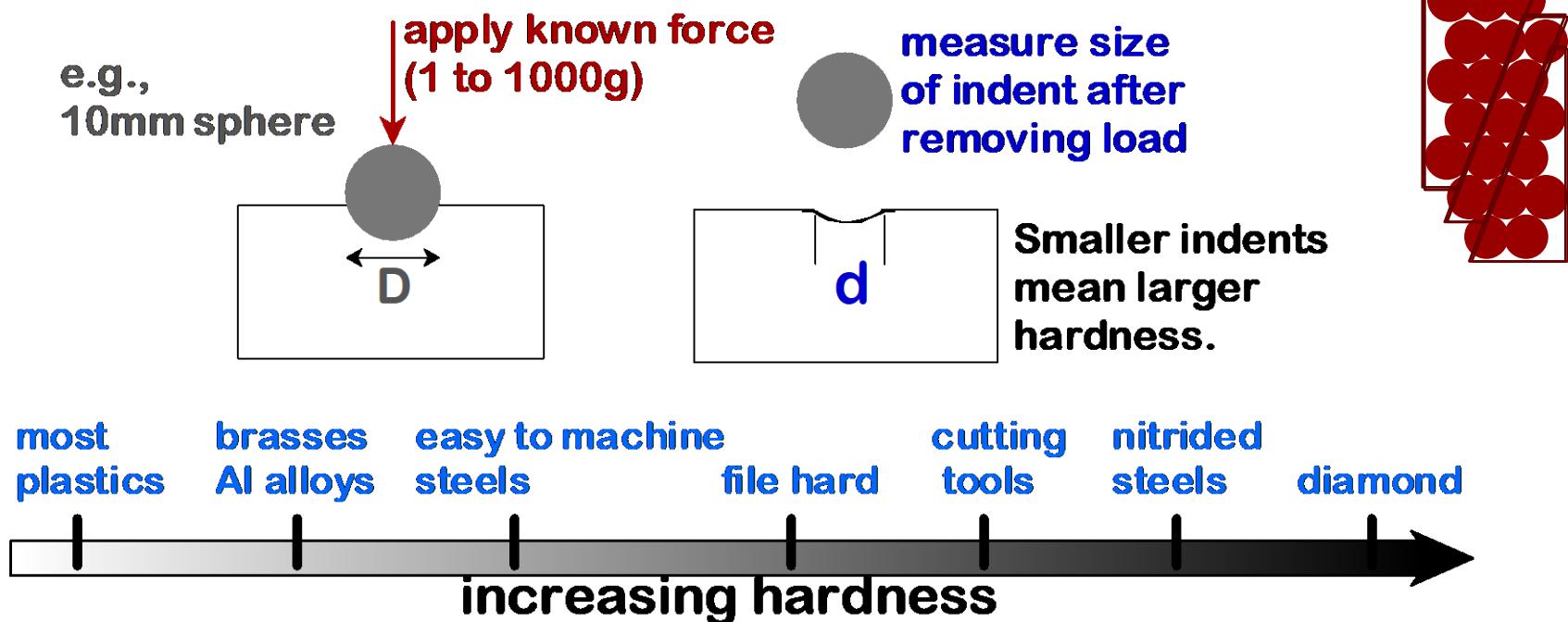
Tough: high elongation and low modulus; Brittle: low elongation and high modulus



Charpy/Izon impact toughness tests

HARDNESS

- Resistance to permanently indenting the surface.
- Large hardness means:
 - resistance to plastic deformation or cracking in compression.
 - better wear properties.

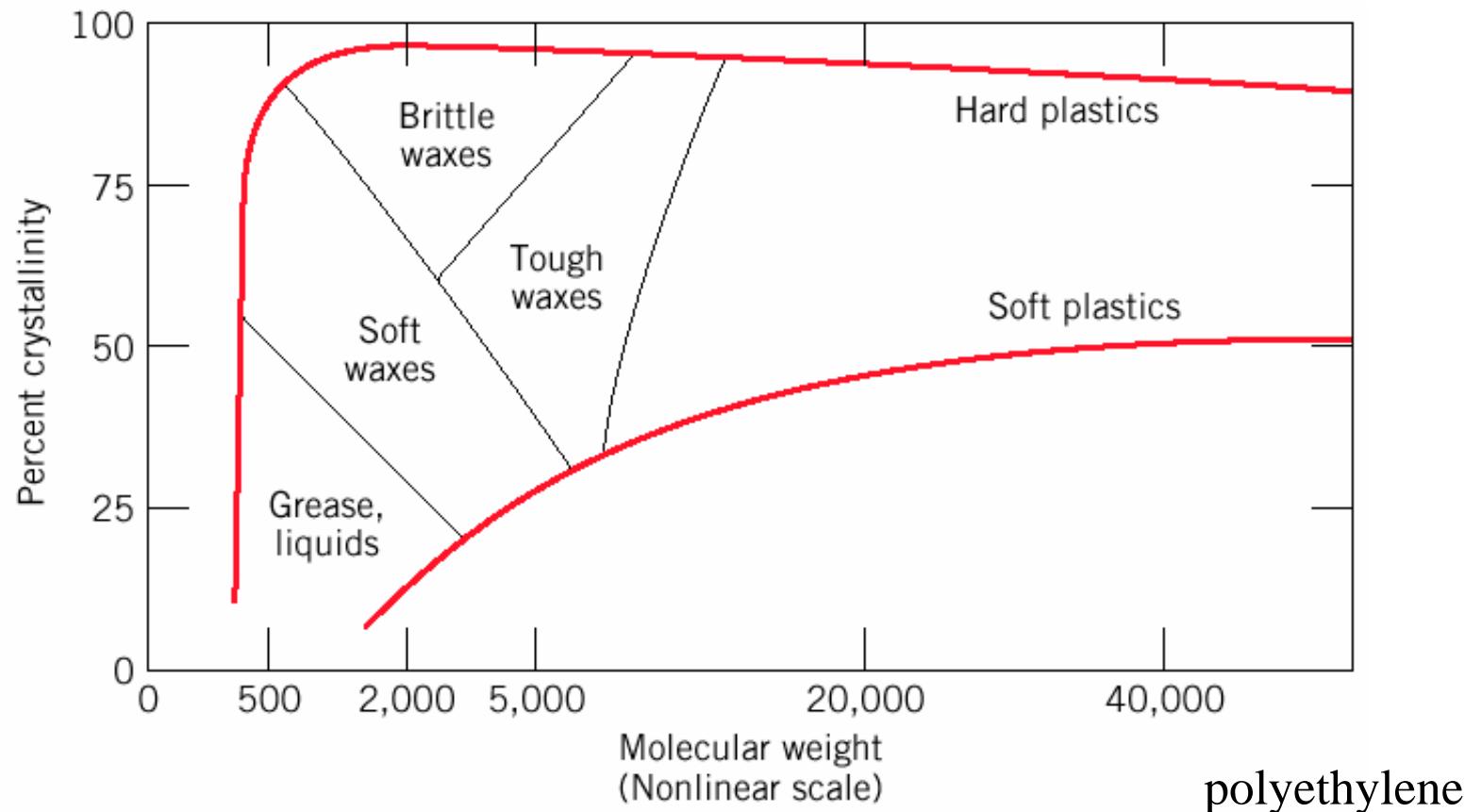


Adapted from Fig. 6.18, *Callister 6e*. (Fig. 6.18 is adapted from G.F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202, John Wiley and Sons, 1957.)

Factors that Influence Mechanical Properties

Tensile strength increases with **molecular weight** – effect of entanglement

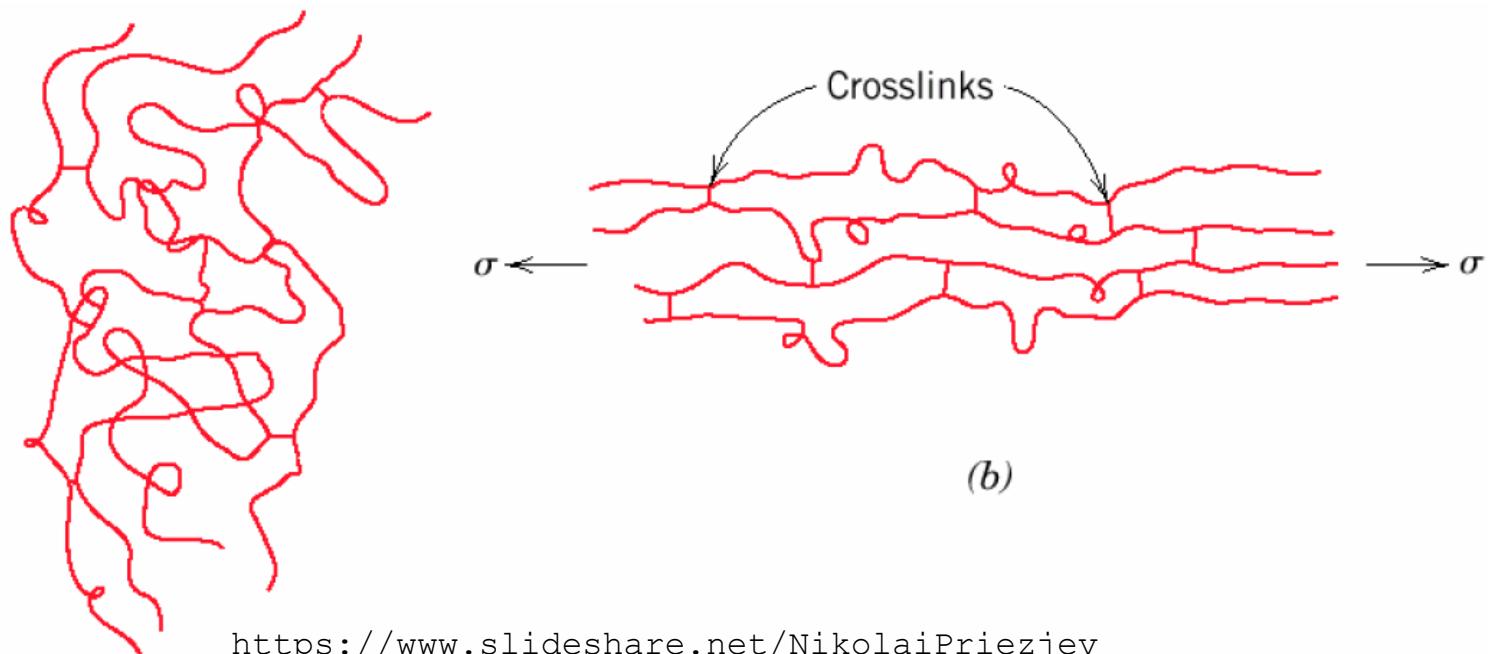
Higher **degree of crystallinity** – stronger secondary bonding - stronger and more brittle material



Elastomers

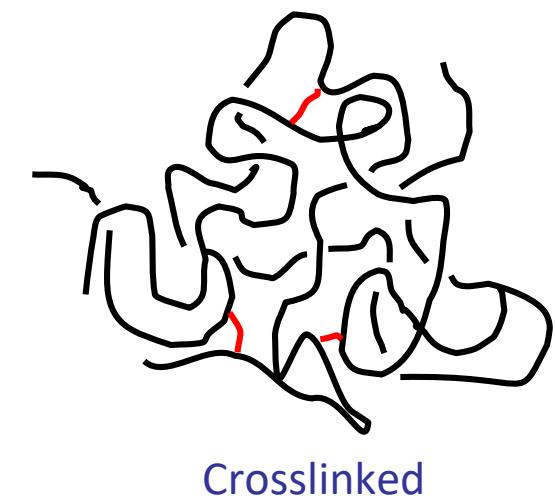
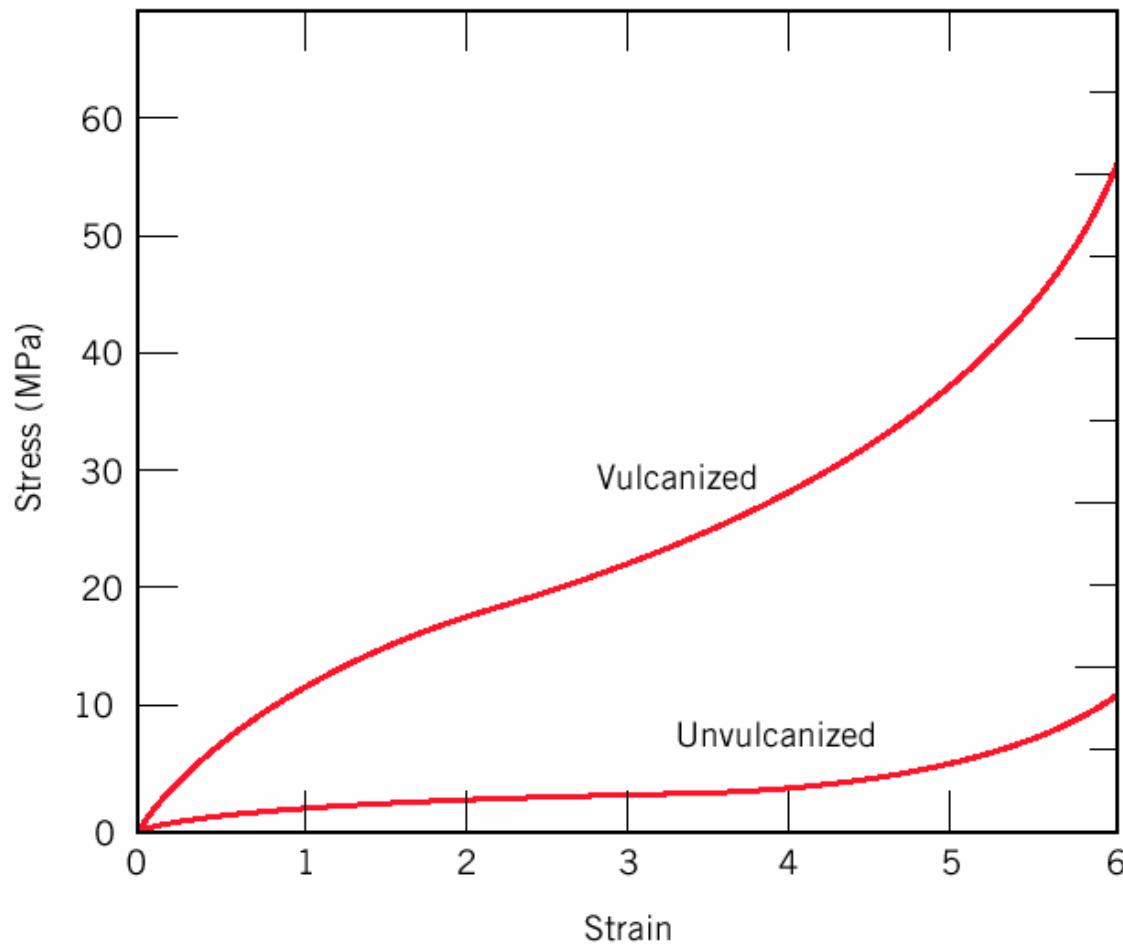
Elastomers can be deformed to **very large strains** and then spring back elastically to the original length, a behavior first observed in natural rubber. To be elastomeric, the polymer needs to meet several criteria:

- Resistance to crystallization (elastomers are amorphous).
- Relatively free chain rotations (unstressed elastomers have coiled/twisted structure – uncoil during deformation).
- Certain degree of cross-linking (achieved by vulcanization) that increases resistance to plastic deformation.
- Temperature is above the glass transition temperature (below T_g elastomer becomes brittle).



Elastomers: Vulcanization

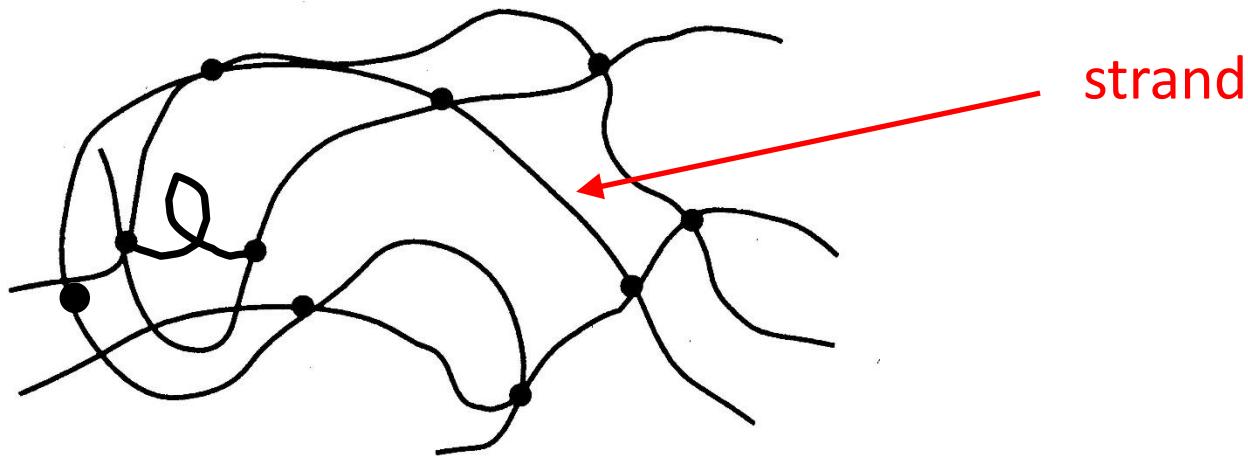
Because they are cross-linked, elastomeric materials are **thermosetting polymers**. Elastic modulus, tensile strength, oxidation resistance increased by vulcanization – magnitude of E is proportional to number of cross-links. Too many cross-links reduces extensibility.



Crosslinked

Rubber Elasticity

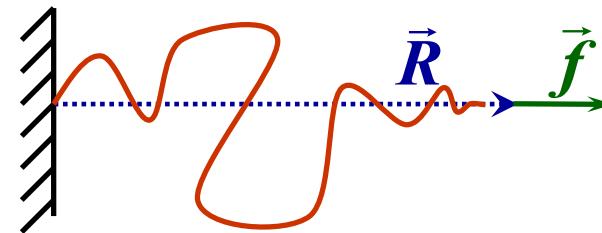
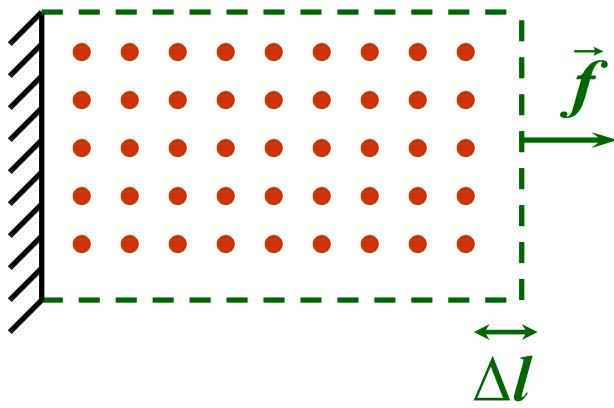
A rubber (or elastomer) can be created by linking together linear polymer molecules into a 3-D network. **n** is the number of strands per unit volume.



Chemical bonds between polymer molecules are called “crosslinks”. Sulphur can crosslink natural rubber.

To observe “stretchiness”, the temperature should be $> T_g$ for the polymer.

Elasticity of a Single Ideal Chain



$$\vec{f} = \frac{\partial F}{\partial \vec{R}} = \frac{3kT}{Ll} \vec{R}$$

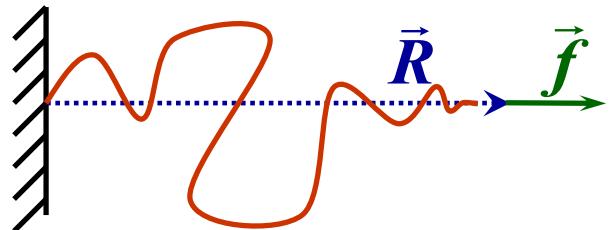
For crystalline solids the elastic response appears, because external stress changes the equilibrium interatomic distances and increases the **internal energy** of the crystal (**energetic elasticity**).

Since the energy of ideal polymer chain is equal to zero, the elastic response appears by purely entropic reasons (**entropic elasticity**). Due to the stretching the chain adopts the less probable conformation \Rightarrow **its entropy decreases**.

$$L = \text{total unfolded length} = lN$$

Elasticity of a Single Ideal Chain

- The chain is elongated in the direction of \vec{f} and $\vec{f} \propto \vec{R}$ (kind of a Hooke law).



- “Elastic modulus” $\frac{3kT}{Ll}$:

1) is proportional to $1/L$, i.e. very small
for large values of L . Long polymer chains
are very susceptible to external actions.

2) is proportional to kT which is the
indication to *entropic nature of elasticity*.

$$\vec{f} = \frac{\partial F}{\partial \vec{R}} = \frac{3kT}{Ll} \vec{R}$$

$$L = \text{total unfolded length} = lN$$

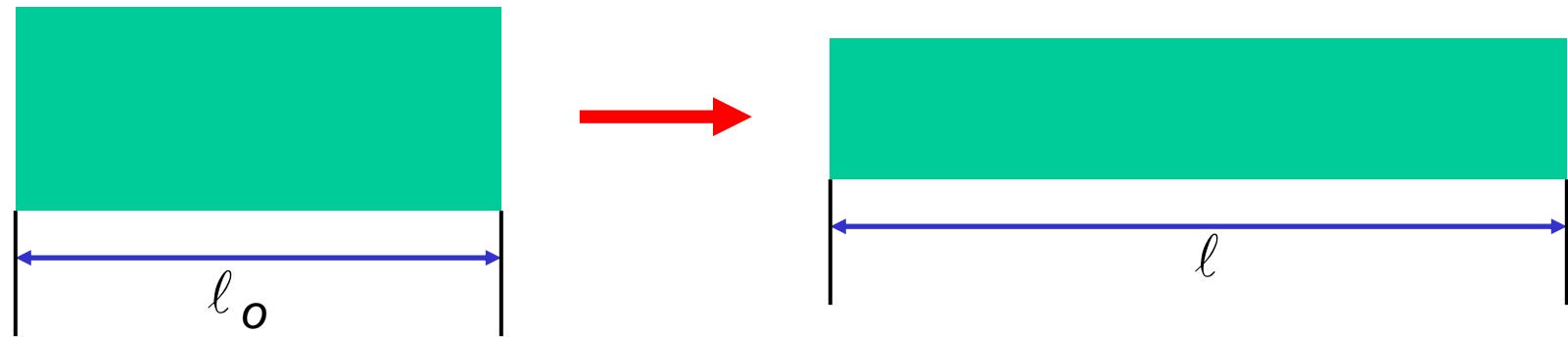
Affine Deformation

With an *affine* deformation, the macroscopic change in dimension is mirrored at the molecular level.

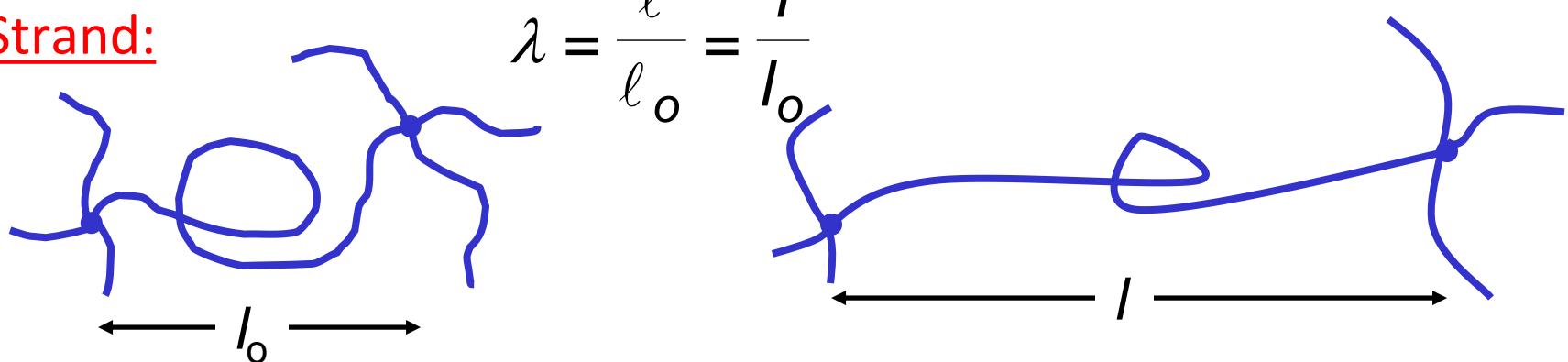
We define an extension ratio, λ , as the dimension *after* a deformation divided by the *initial* dimension:

$$\lambda = \frac{\ell}{\ell_0}$$

Bulk:

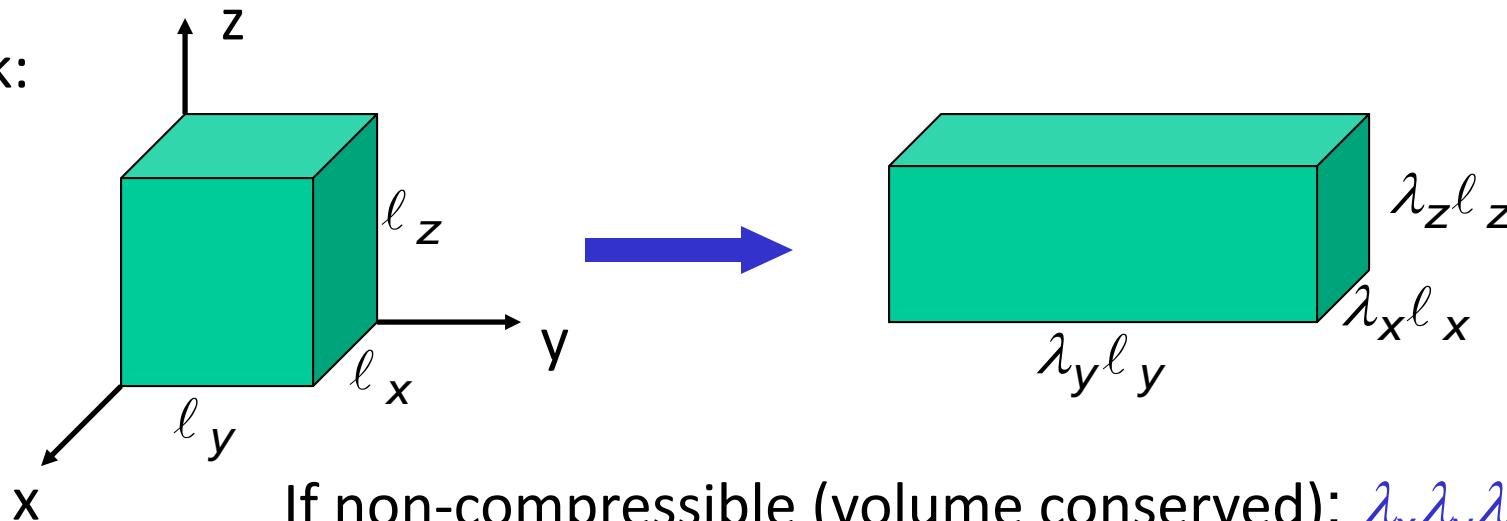


Strand:

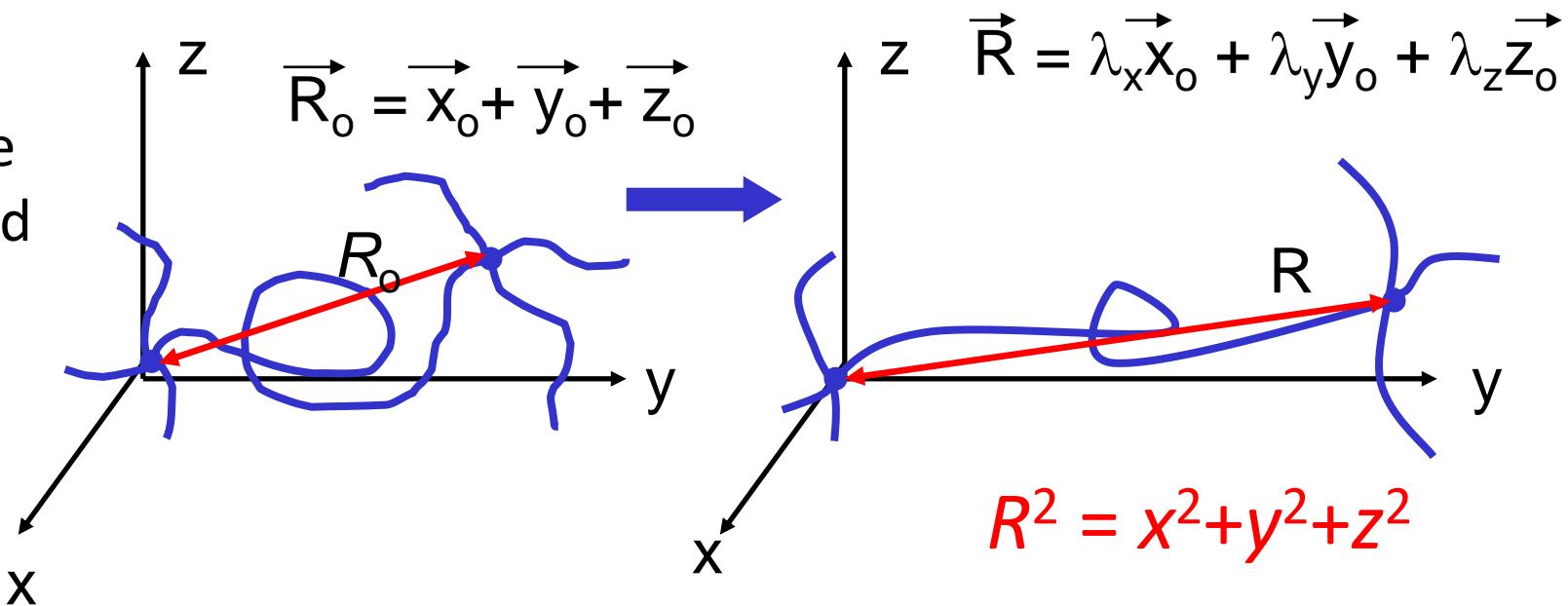


Transformation with Affine Deformation

Bulk:



Single
Strand



Force for Rubber Deformation

At the macro-scale, if the initial length is L_0 , then $\lambda = L/L_0$.

$$\Delta F_{bulk} \sim +\frac{nkT}{2} \left(\left(\frac{L}{L_0}\right)^2 + \frac{2L_0}{L} - 3 \right)$$

Tensile stress $\sigma_T = Y\varepsilon$. The strain, ε , for a 1-D tensile deformation is

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} = \frac{L}{L_0} - 1$$

Substituting in $\Delta F_{bulk} \sim +\frac{nkT}{2} \left((\varepsilon + 1)^2 + \frac{2}{(\varepsilon + 1)} - 3 \right)$
 $L/L_0 = \varepsilon + 1$:

Realising that ΔF_{bulk} is an energy of deformation (per unit volume), then $dF/d\varepsilon_T$ is the force, \mathcal{F} (per unit area, A) for the deformation, i.e. the tensile stress, σ_T .

$$\frac{dF}{d\varepsilon} = \frac{\mathcal{F}}{A} = \sigma_T = \frac{nkT}{2} \left[2(\varepsilon + 1) - \frac{2}{(\varepsilon + 1)^2} \right]$$

Young's and Shear Modulus for Rubber

$$\sigma_T = nkT[(\varepsilon + 1) - \frac{1}{(\varepsilon + 1)^2}] = nkT \left[\lambda - \frac{1}{\lambda^2} \right]$$

$$\varepsilon = \frac{\Delta L}{L_o}$$
$$\lambda = L/L_o$$

This is an equation of state, relating together \mathcal{F} , L and T.

In the limit of *small* strain, $\sigma_T \approx 3nkT\varepsilon$, and the Young's modulus is thus $Y = 3nkT$.

The Young's modulus can be related to the shear modulus, G , by a factor of 3 to find a very simple result: $G = nkT$

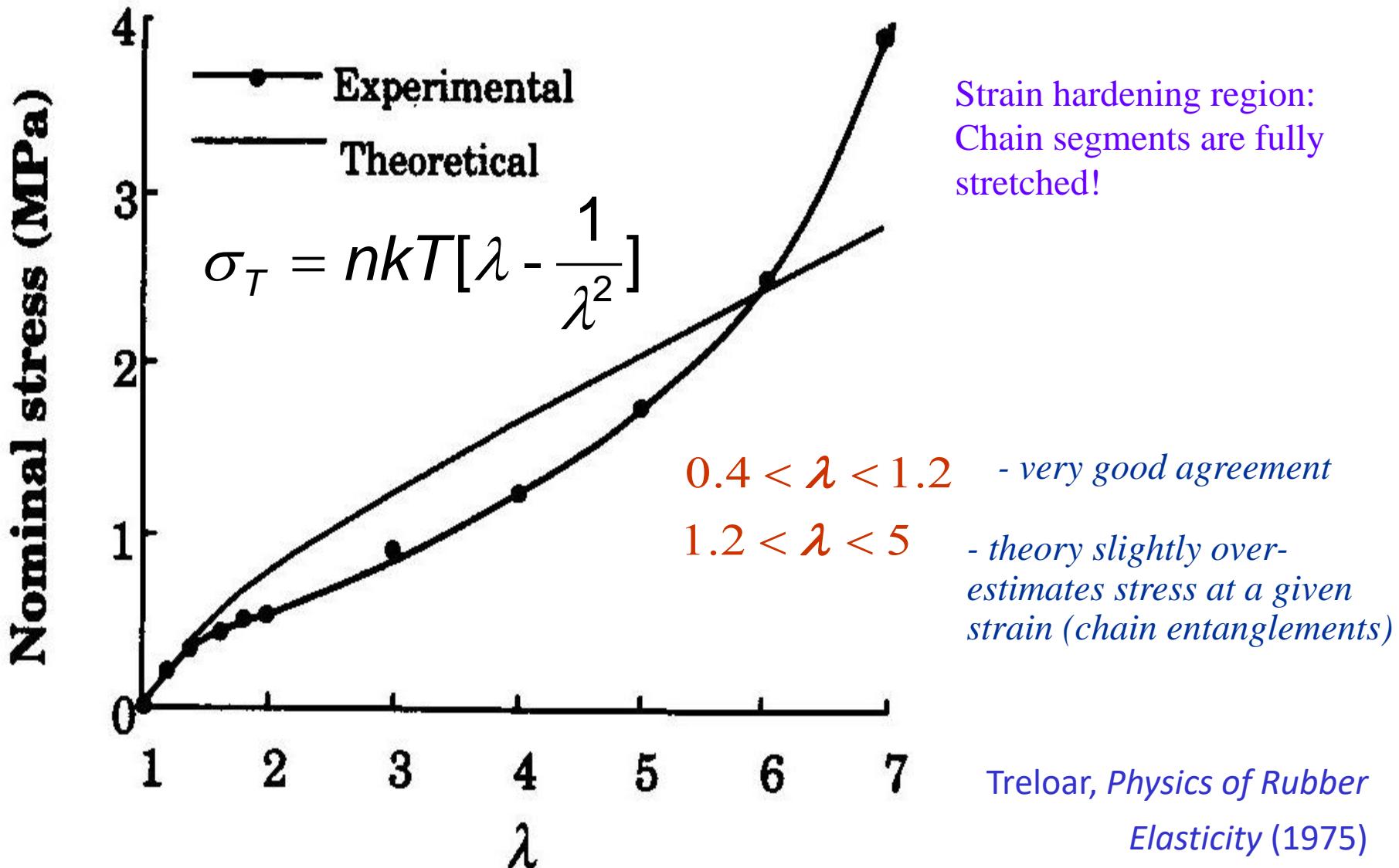
This result tells us something quite fundamental. The elasticity of a rubber does not depend on the chemical make-up of the polymer *nor* on how it is crosslinked.

G does depend on the crosslink **density**. To make a higher modulus, more crosslinks should be added so that the lengths of the segments become shorter.

Experiments on Rubber Elasticity

Rubbers are elastic over a large range of λ !

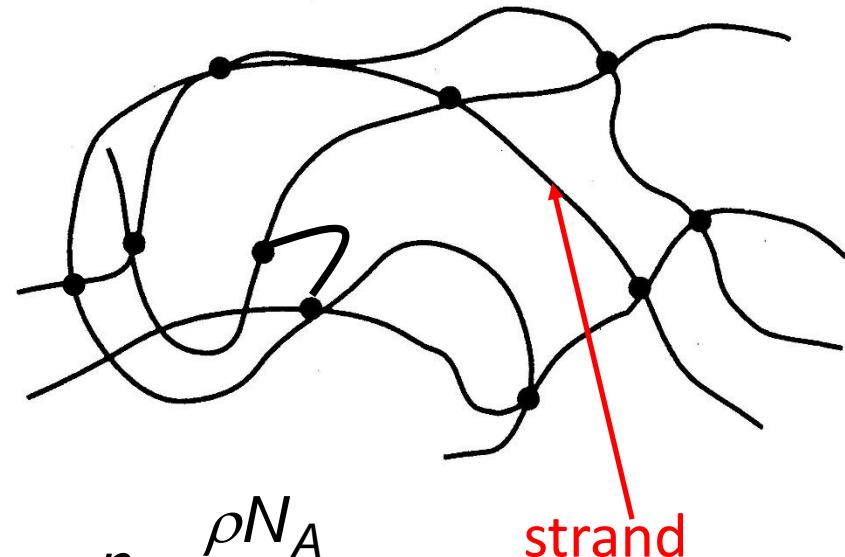
$$\lambda = L/L_0$$



Alternative Equation for a Rubber's G

We have shown that $G = nkT$, where n is the number of strands per unit volume.

For a rubber with a known density, ρ , in which the average molecular mass of a strand is M_x (m.m. between crosslinks), we can write:



$$n = \frac{\rho N_A}{M_x}$$

Looking at the units makes this equation easier to understand:

$$\frac{\# \text{ strands}}{m^3} = \frac{\left(\frac{g}{m^3}\right) \left(\# \text{ strands}/\text{mole}\right)}{\left(\frac{g}{\text{mole}}\right)}$$

Substituting for n :

$$G = nkT = \frac{\rho N_A}{M_x} kT = \frac{\rho RT}{M_x}$$

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. Size: 10nm-macroscopic
- **Plasticizers** (liquids, low vapor pressure, low M_w)
 - Added to reduce the glass transition temperature T_g
 - commonly added to PVC - otherwise it is brittle

Polymer Additives

- Stabilizers (counteract deterioration, mechanical integrity)
 - Antioxidants (consume O₂ before it reaches polymer or block reaction)
 - UV protectants (thin adsorbent layer: sunscreen; material that react with bonds broken by UV)
- Lubricants
 - Added to allow easier processing
 - “slides” through dies easier – ex: Na stearate
- Colorants
 - Dyes (dissolved in polymer) or pigments (separate phase)
- Flame Retardants
 - Cl/F & B

Summary

- Mechanical properties of solids (forces, elastic behavior)
- Mechanical properties of liquids – viscous flows (Newtonian non-Newtonian regimes, viscosity measurements)
- Viscoelastic materials (definitions, time dependence, short-range, long-range interactions)
- Plastic stress-strain behavior definitions, mechanical models
- Creep, toughness, impact strength, hardness
- Reinforcements, fillers, toughness modifiers

Reading: Chapter 4 of *Plastics: Materials and Processing* by A. Brent Strong