Lecture 26

Materials and their structure- Polymers-Part2
Mechanical Behaviour of Materials

Textbooks:
- Introduction to materials science and Engineering: V. Raghavan
- Materials Science and Engineering: Callister and Rethwisch

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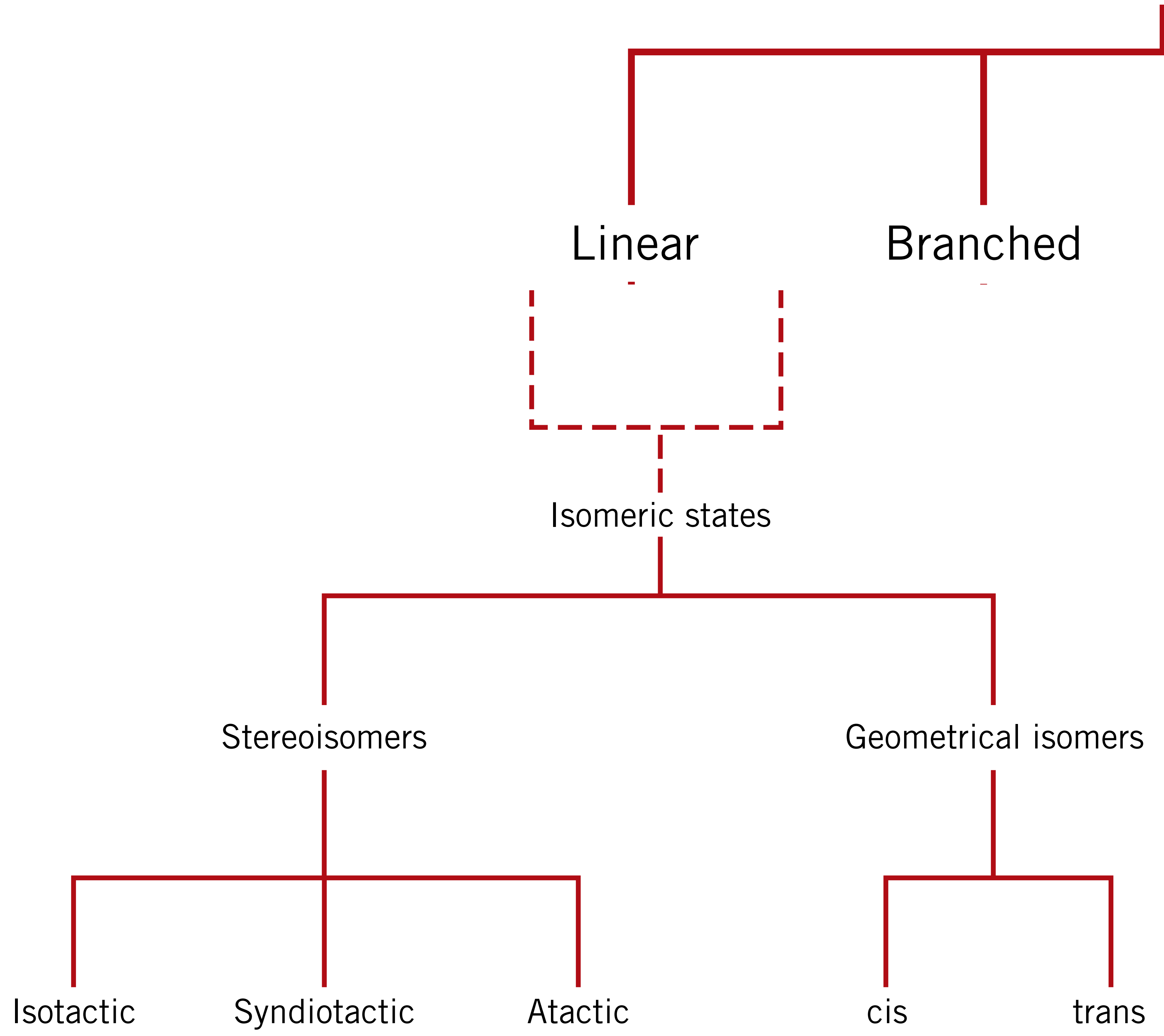
Recap…

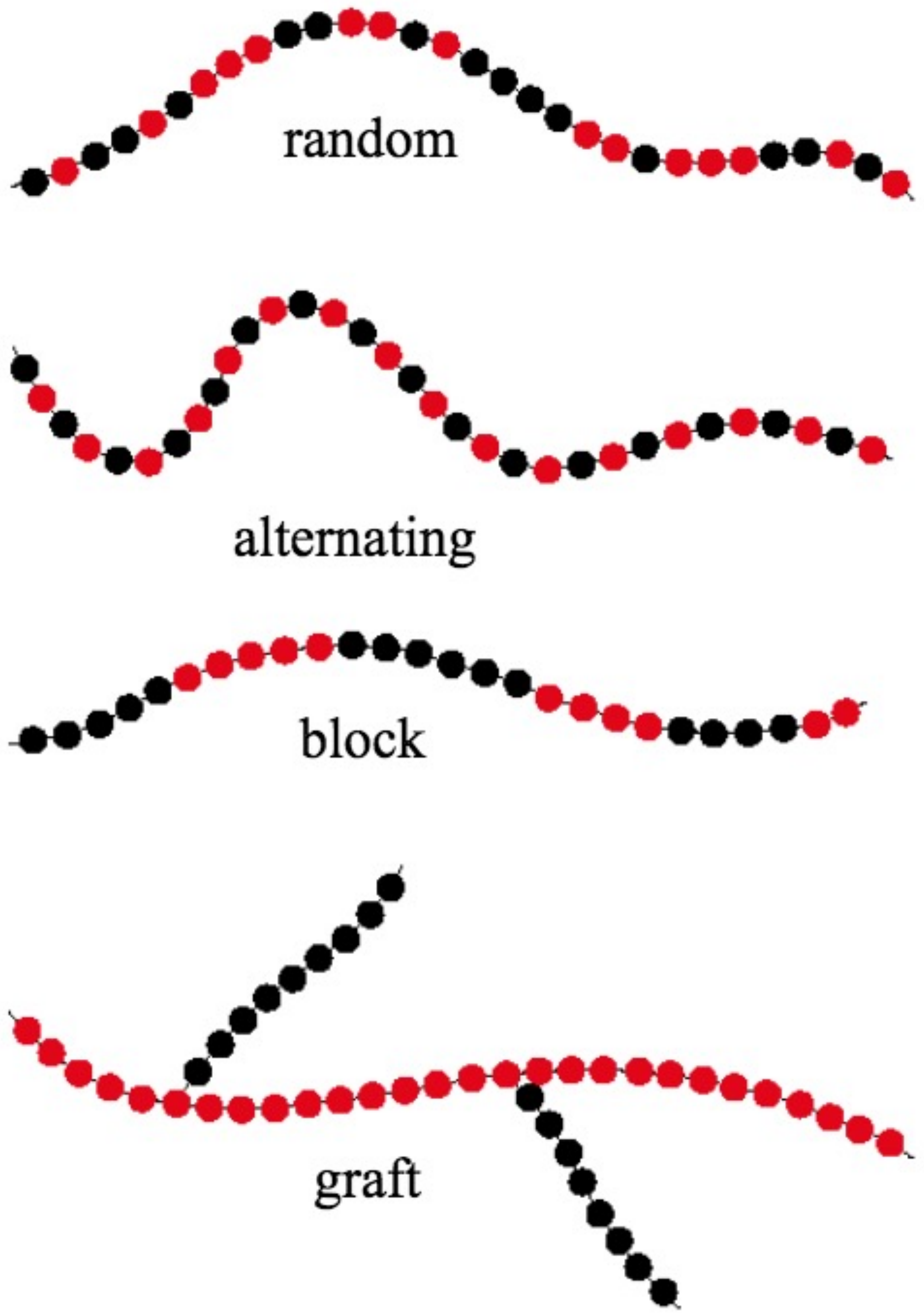
1. Polymers: macromolecules
2. Properties of polymers: chemistry, size, shape, structure
3. Structure of polymers: different categories
4. Linear polymers: tacticity
5. Copolymers
6. Polymer crystallinity

Four main properties

1. Chemistry: monomer
2. Size: molecular Weight and degree of polymerization
3. Shape: chain twisting, entanglement
4. **Structure:** Density and crystallinity



Structure of polymers: Copolymers



Degree of polymerization

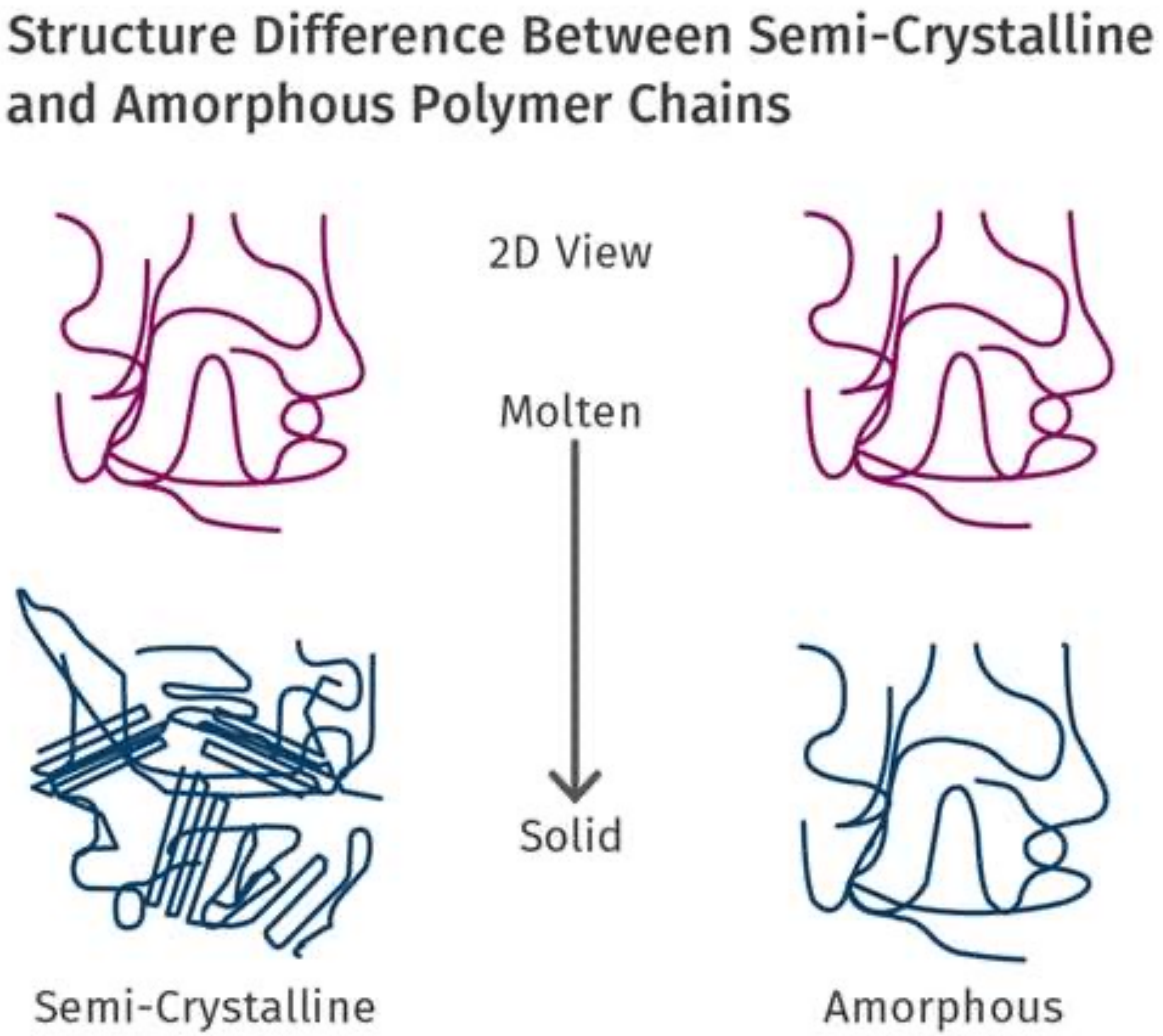
$$DP = \frac{\overline{M}_n}{\overline{m}}$$

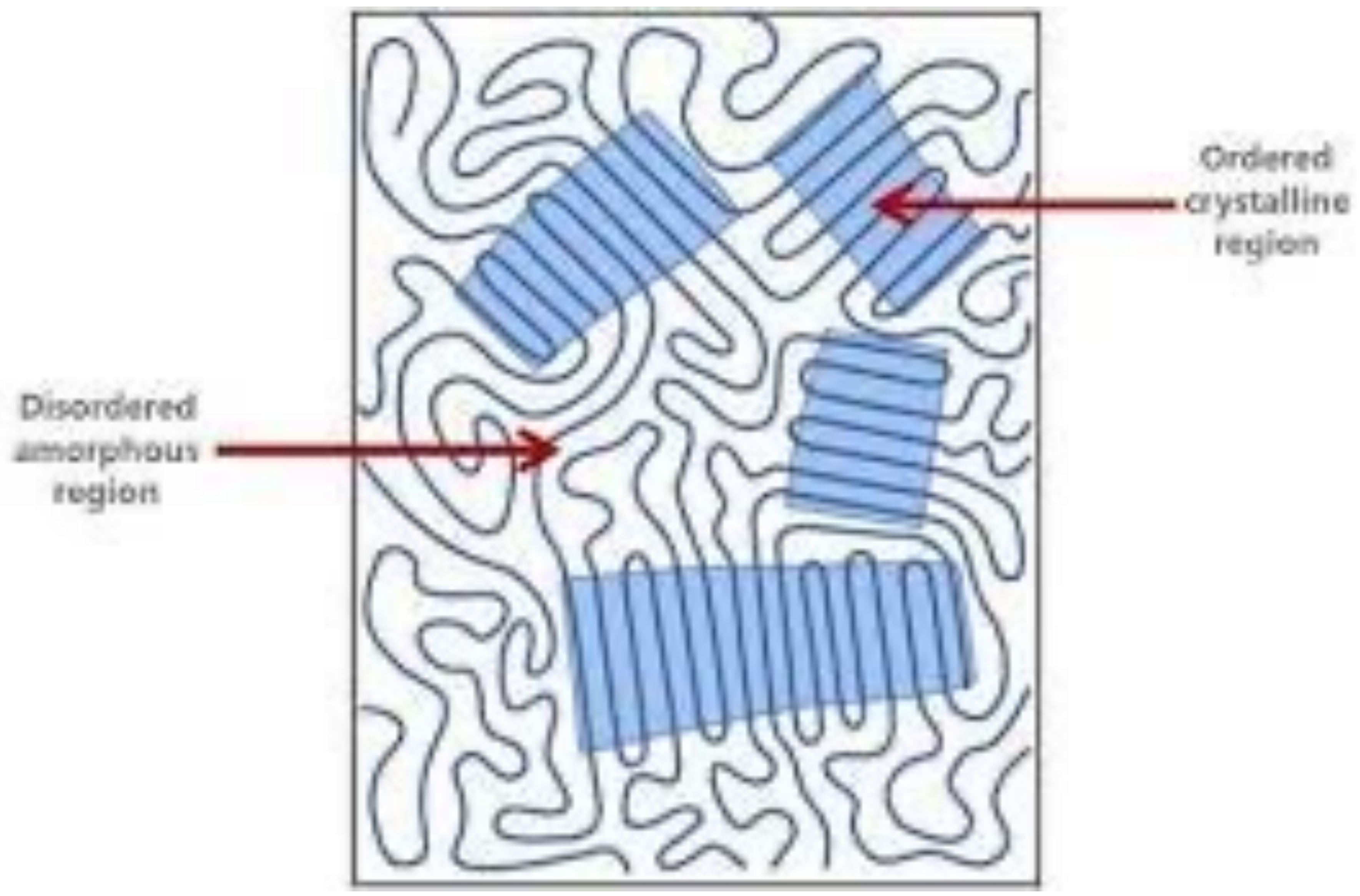
$$\overline{m} = \Sigma f_j m_j$$

fj and *mj* are, respectively, the mole fraction and molecular weight of repeat unit *j* in the polymer chain.

- Random, block and graft polymers form amorphous structures and alternating forms crystalline structure.
- Examples: Styrene–butadiene rubber (SBR) (random copolymer), Nitrile rubber (NBR) (random copolymer)

Polymers are semi-crystalline

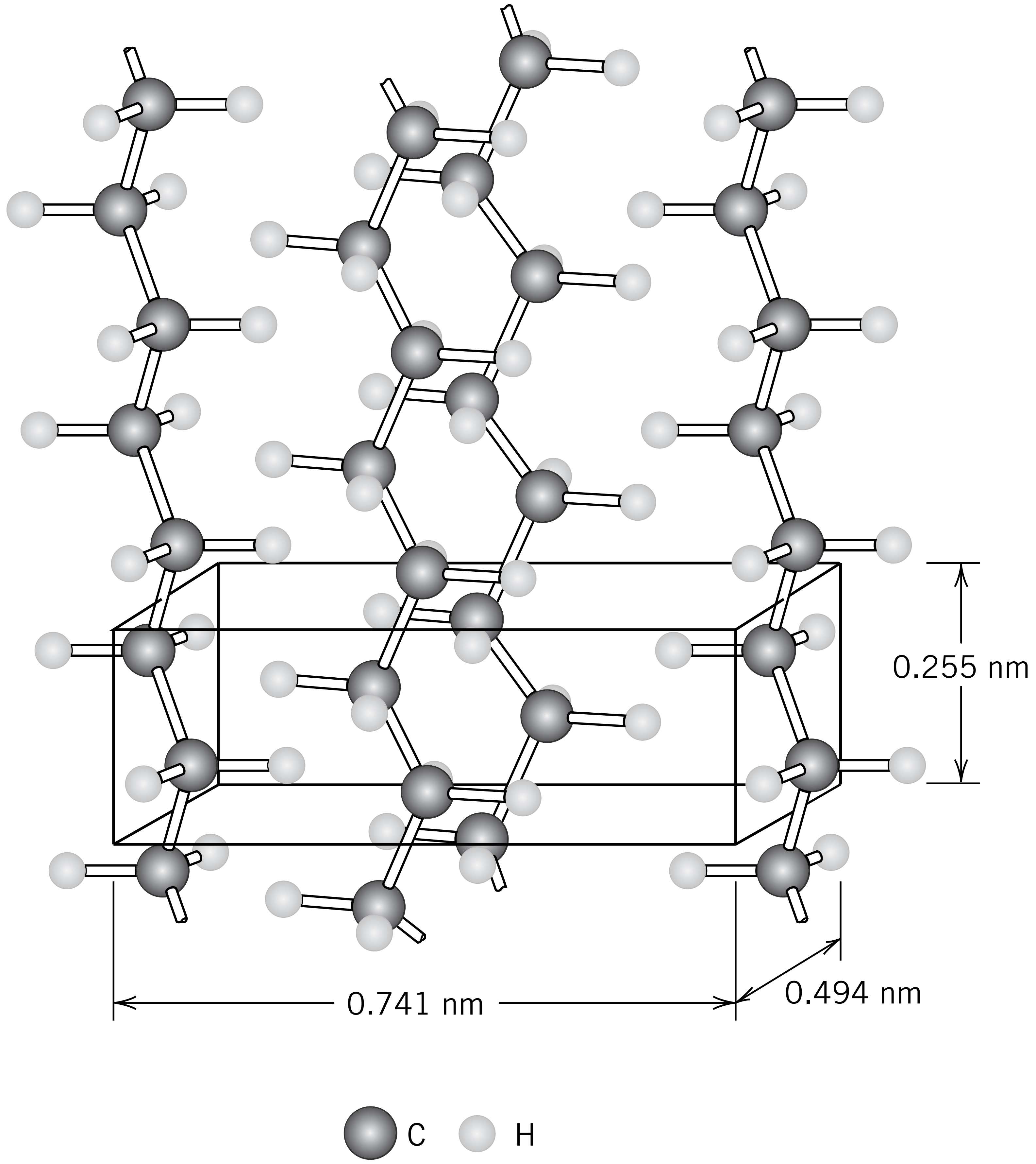




- Crystalline regions dispersed within the remaining amorphous material.
- Long chains fold and form crystalline part
- A given chain may belong to both crystalline and amorphous regions
- A given crystal consists of more than one chains.
- Chain disorder or misalignment (kinking, twisting, coiling) will lead to amorphous region.

Polymer crystallinity

Density and degree of crystallinity



Arrangement of molecular chains in a unit cell for polyethylene

-Polymer crystallinity is the packing of molecular chains to produce an ordered atomic array

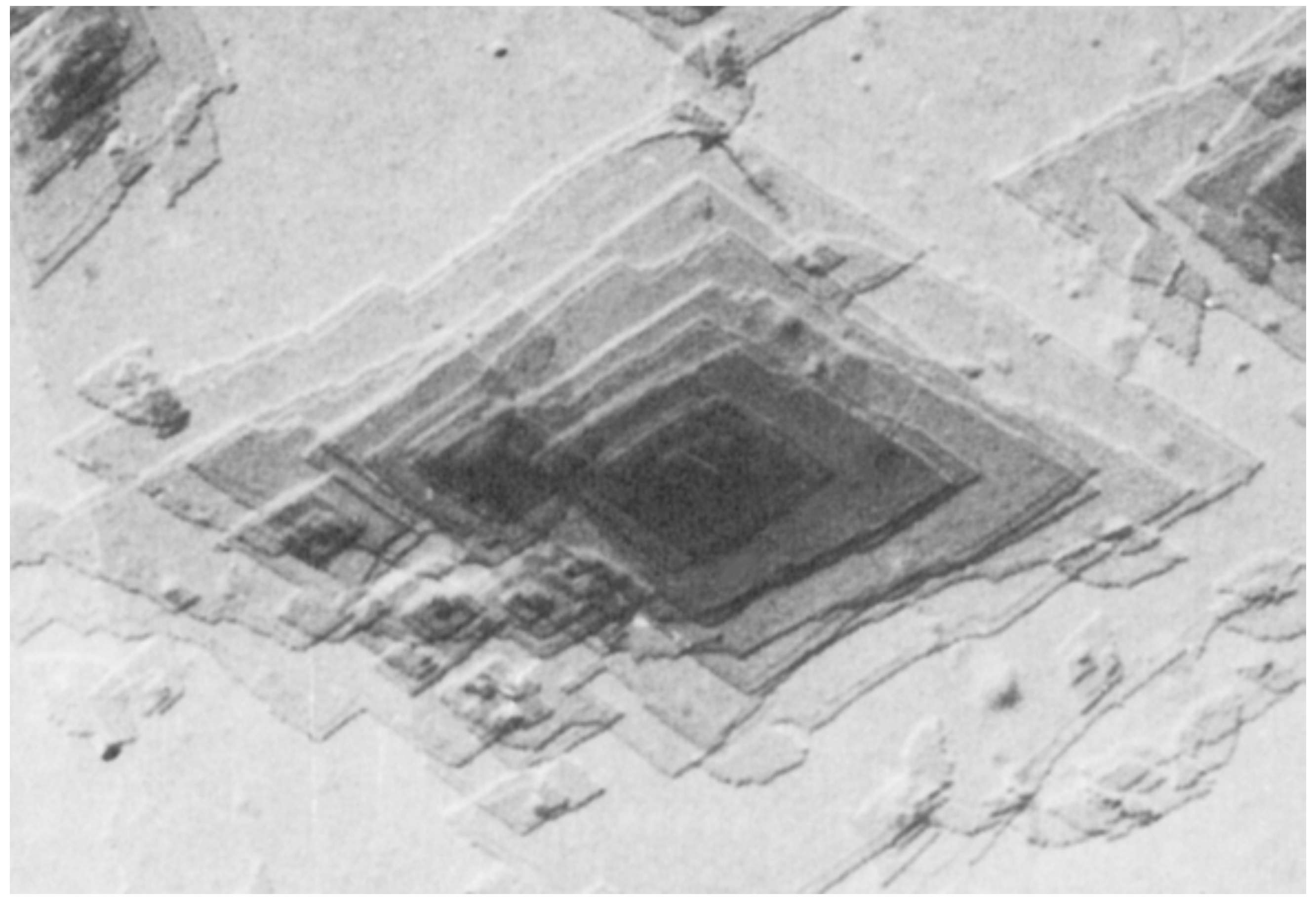
$$\%\,\text{crystallinity} = \frac{\rho_c(\rho_s - \rho_a)}{\rho_s(\rho_c - \rho_a)} \times 100$$

ρ_s : is the density of a specimen for which the percent crystallinity is to be determined

ρ_a : density of the totally amorphous polymer

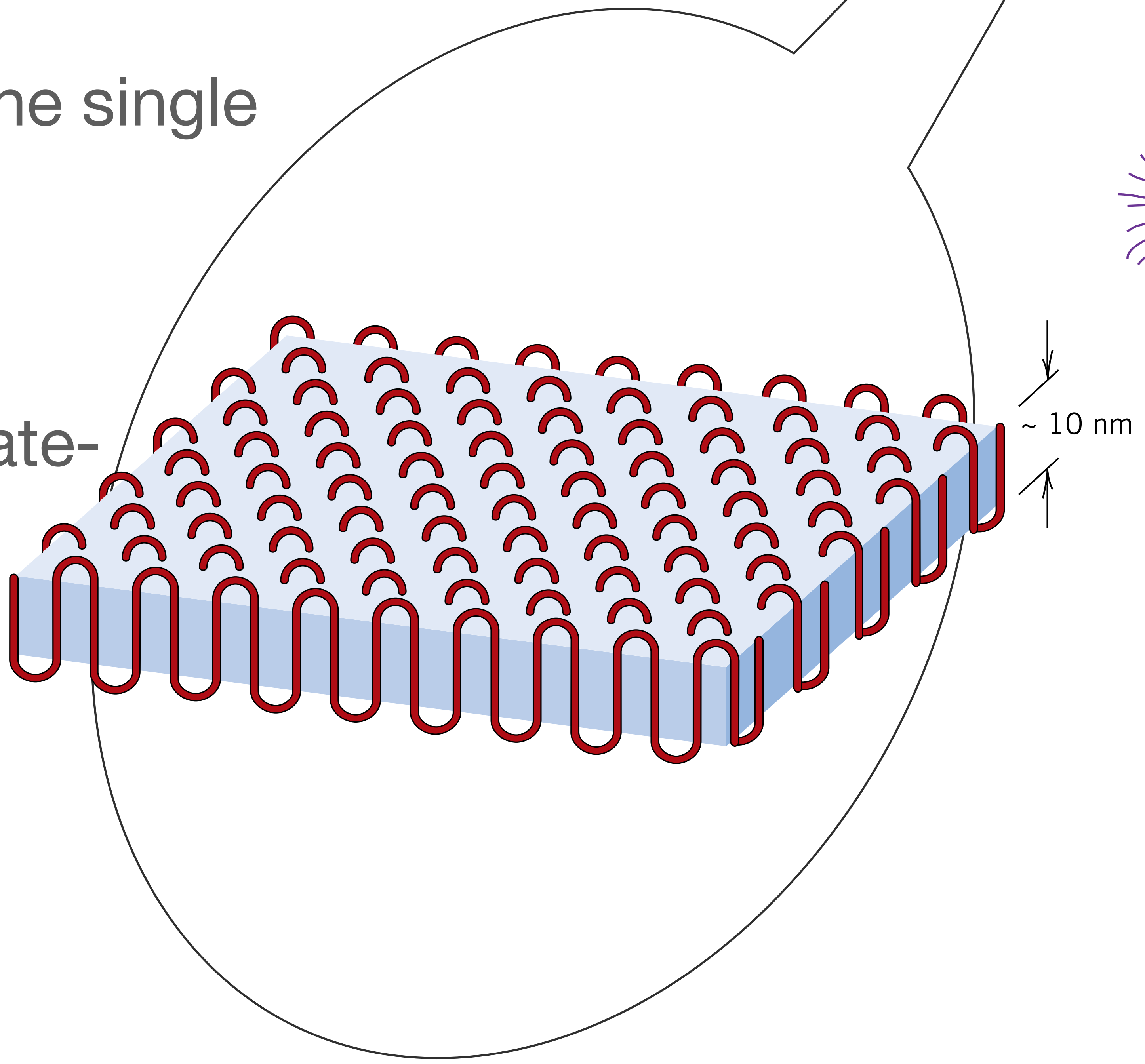
ρ_c : density of the perfectly crystalline polymer.

Polymer crystals: Lamellae and Spherulites

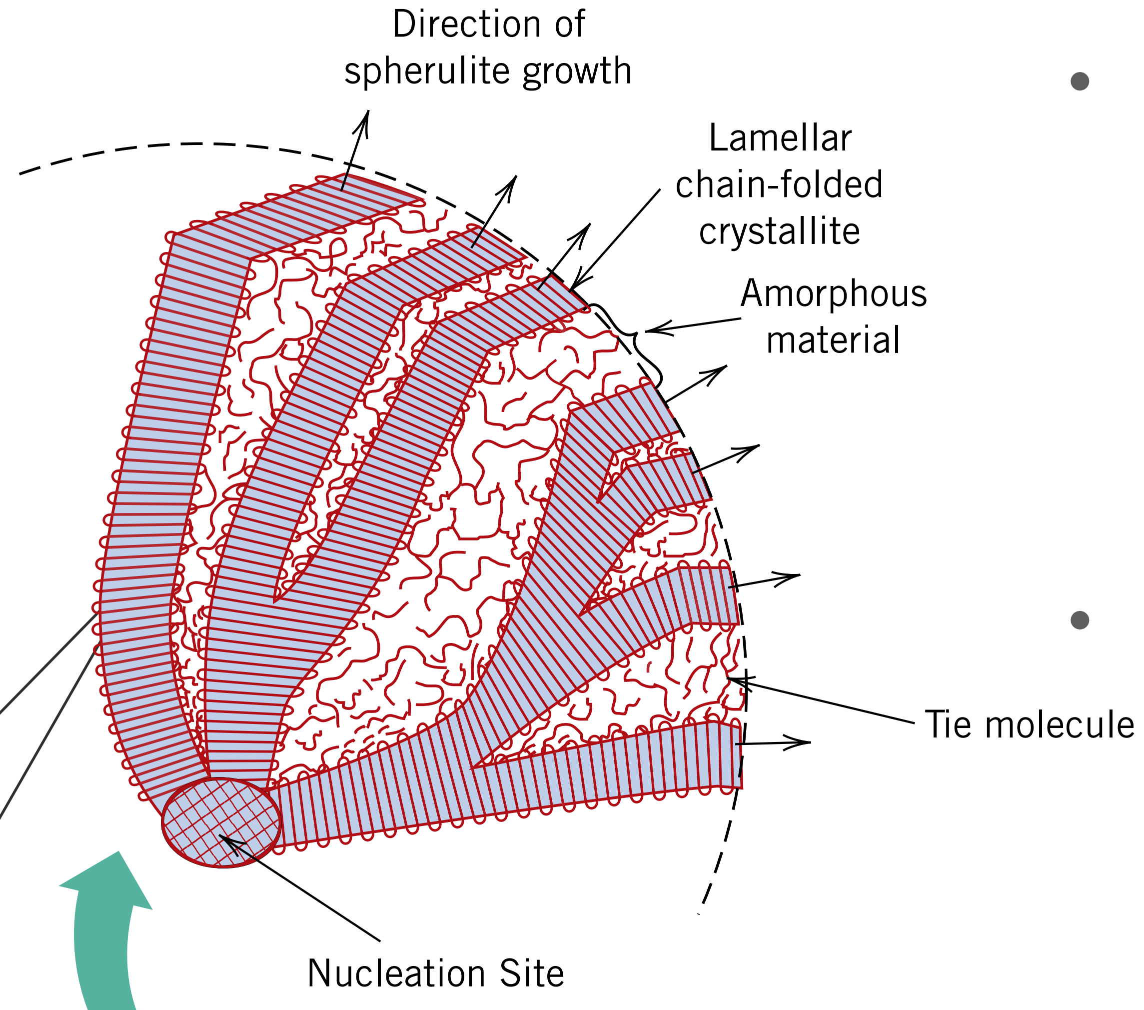


- These crystals are regularly shaped, thin platelets (or lamellae), approximately 10 to 20 nm thick, and on the order of 10 micrometer long.
- platelets will form a multilayered structure

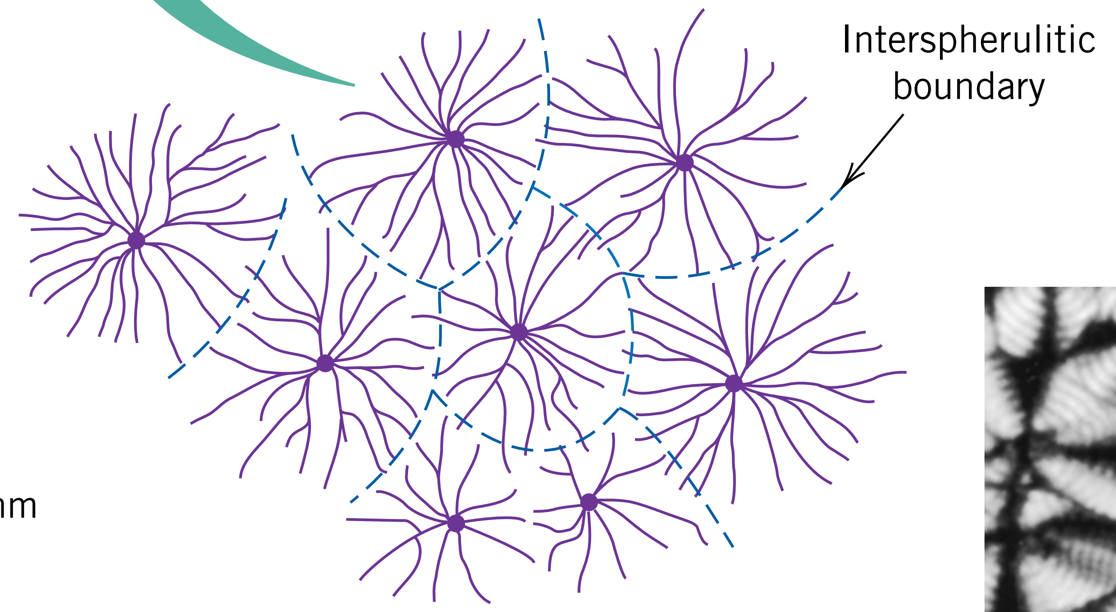
Electron micrograph of a polyethylene single crystal. 20,000X

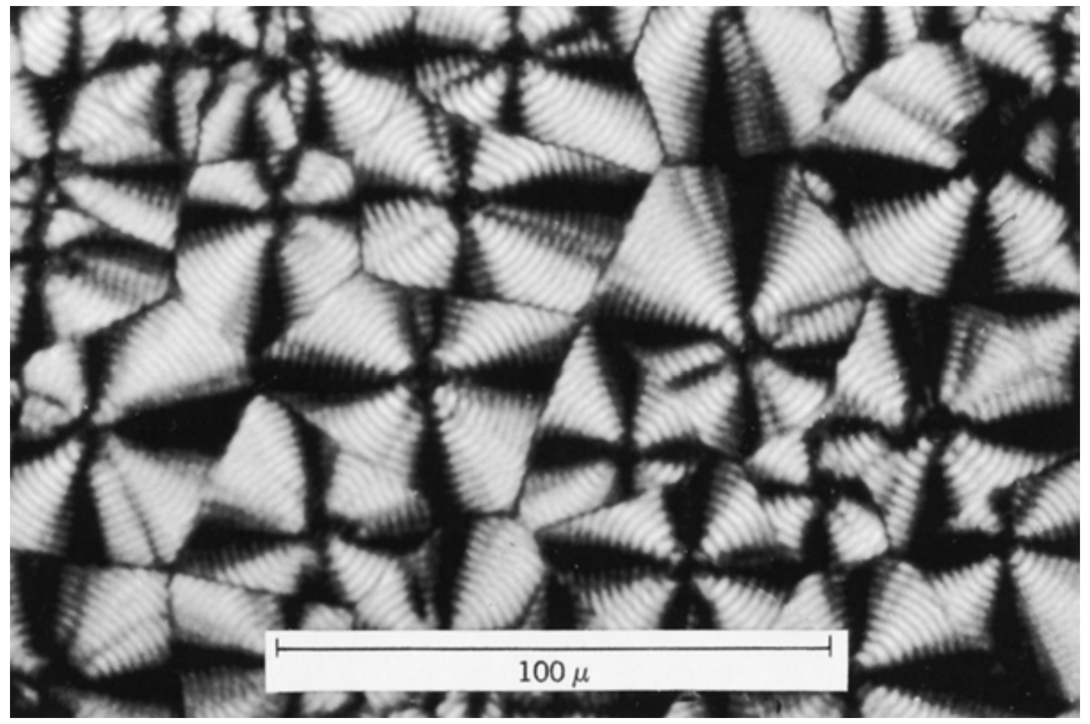


The chain-folded structure for a plate-shaped polymer crystallite



- The spherulite consists of an aggregate of ribbon-like chain-folded crystallites (lamellae) approximately 10 nm thick that radiate outward from a single nucleation site in the center.
- individual chain-folded lamellar crystals that are separated by





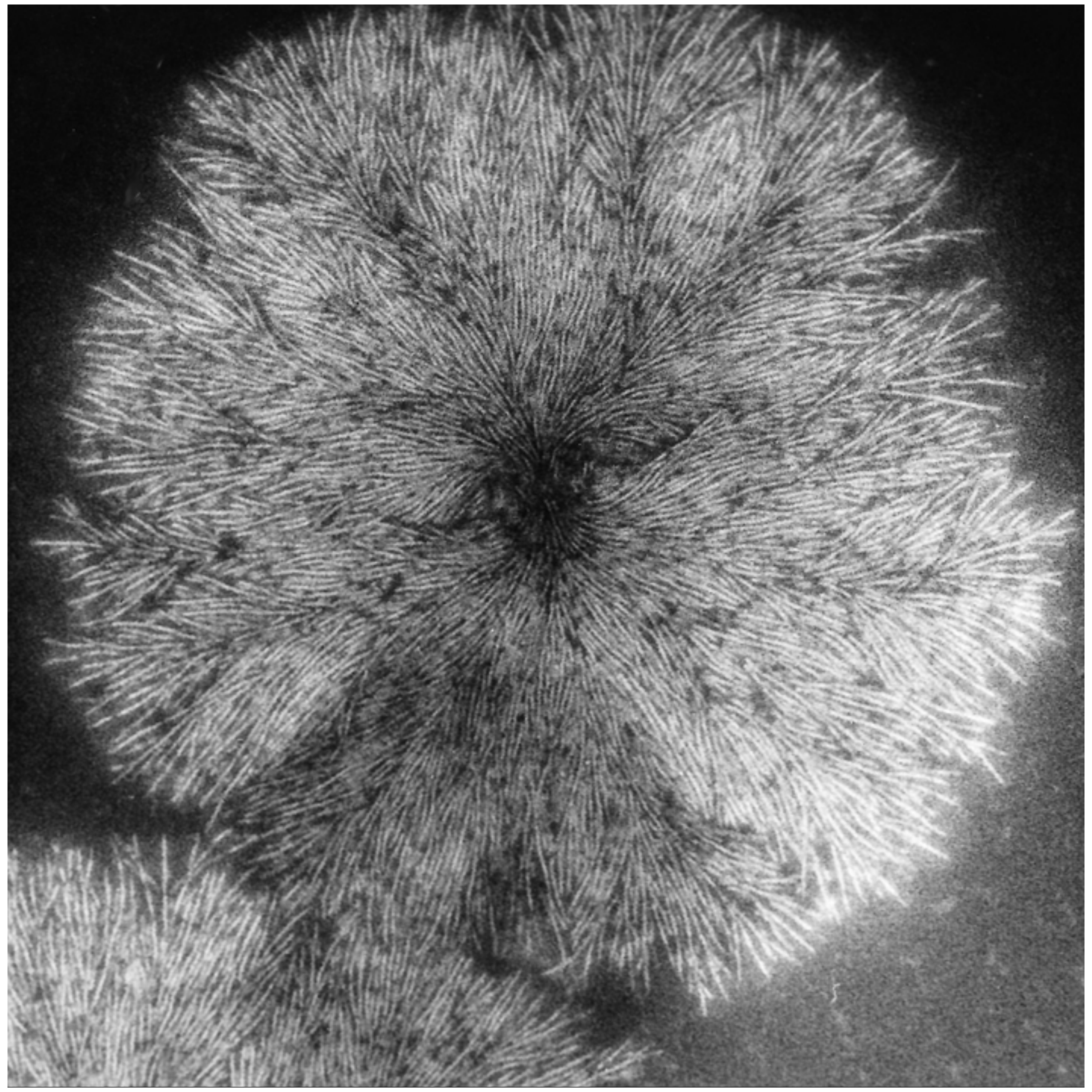
TEM image of spherulite structure of polyethylene

Callister

What are the factors affecting crystallinity in polymers?

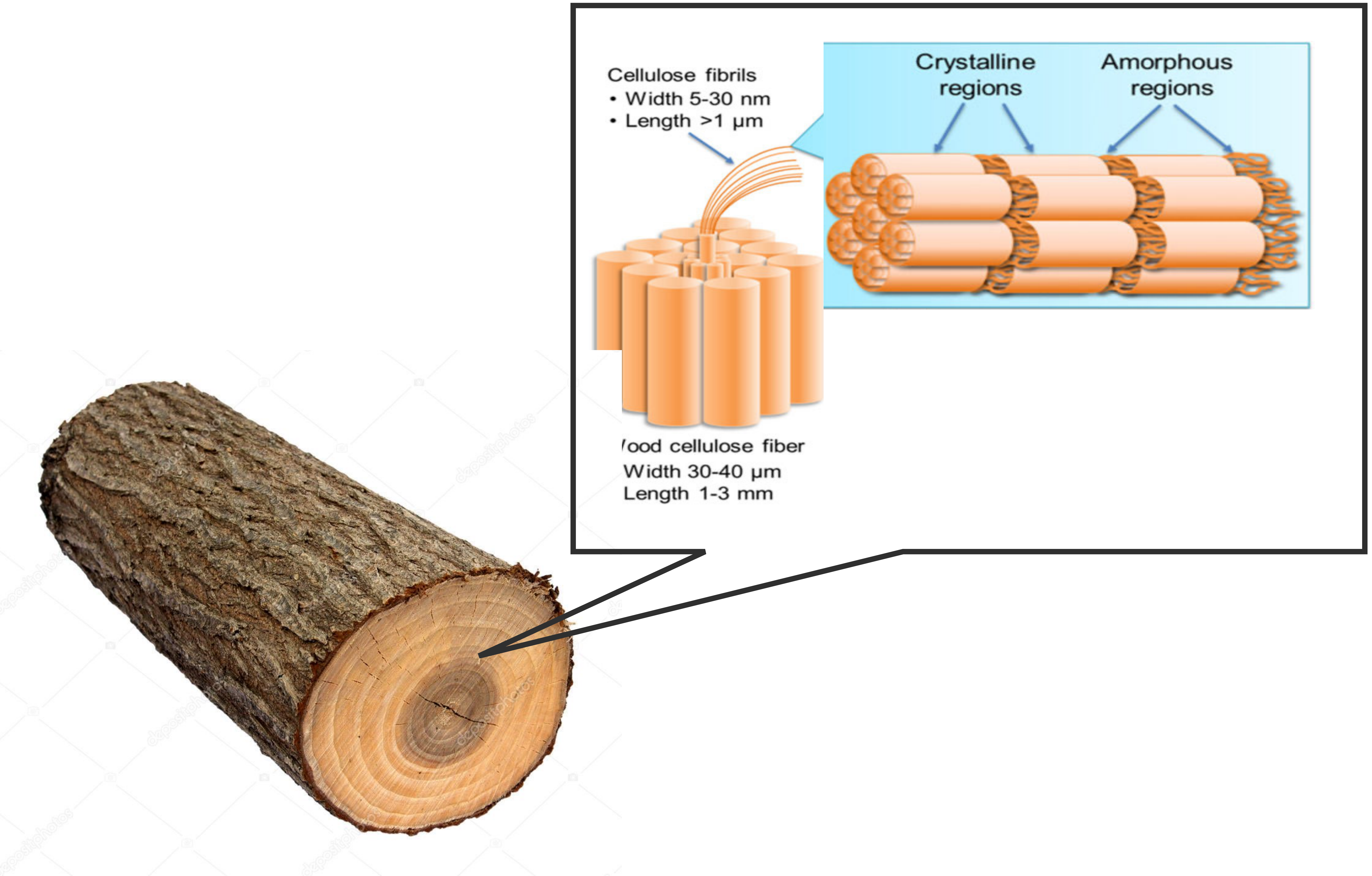
- Length of chain: longer chain→ amorphous
- Branching of chains: branched chains, cross-linked→ amorphous
- Copolymers: alternating copolymer→ crystalline, rest form amorphous
- Tacticity or Stereoisomerism: isotactic and syndiotactic→ crystalline, atactic→ amorphous
- Plasticizers: low molecular weight additives added to separate the chains and prevent crystallization e.g. glycerol, polyethylene glycol

Spherulite in natural rubber



Transmission electron micrograph showing the spherulite structure in a natural rubber specimen. Chain-folded lamellar crystallites approximately 10 nm thick extend in radial directions from the center; they appear as white lines in the micro- graph. 30,000X.

Semi-crystalline cellulose fibres in wood



Mechanical behaviour of materials

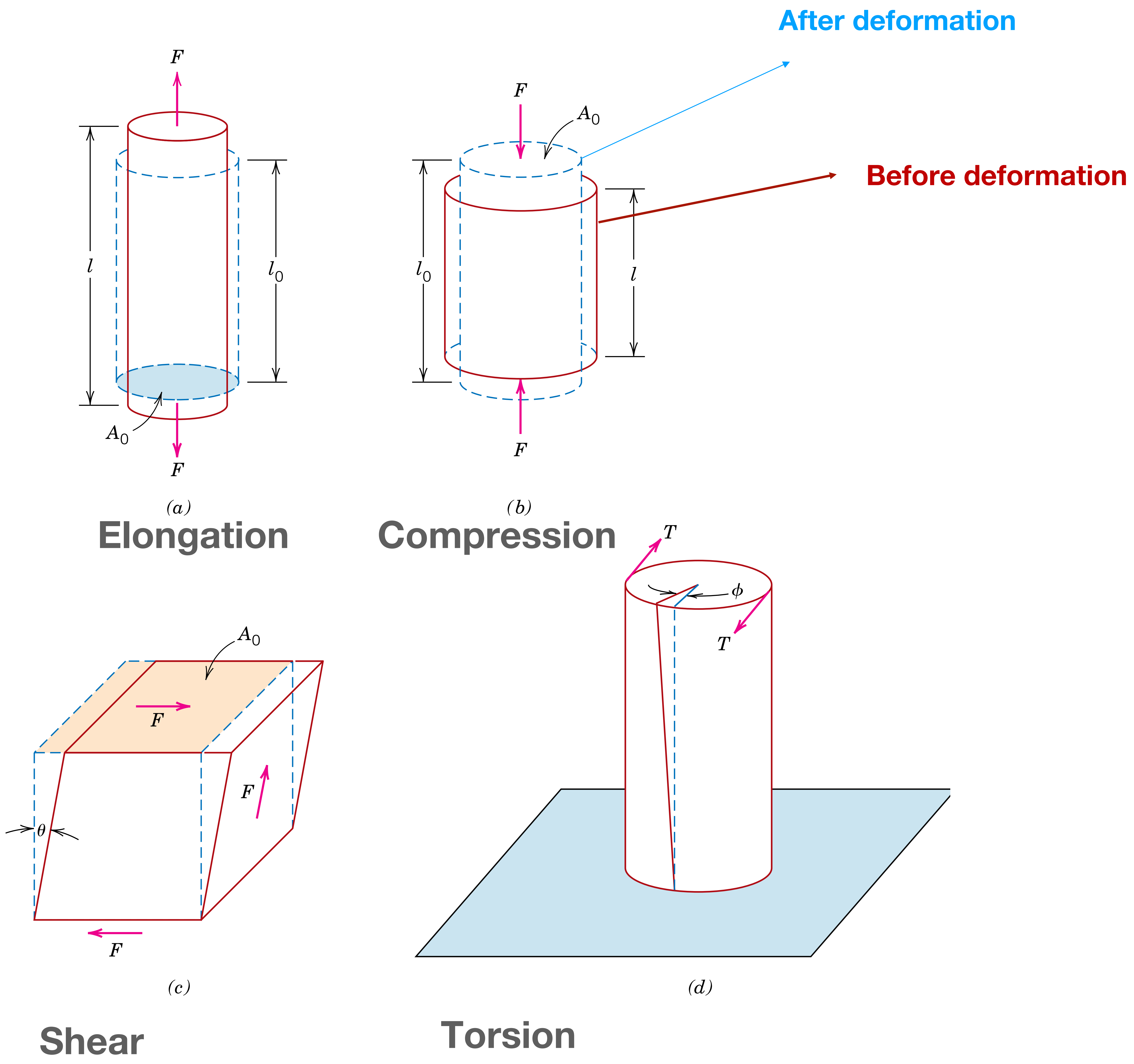
Robert Hooke

Isaac Newton

Mechanical Behaviour of Materials

Force (or Load) on material

- Tension
- Compression
- Shear
- Torsion



Callister

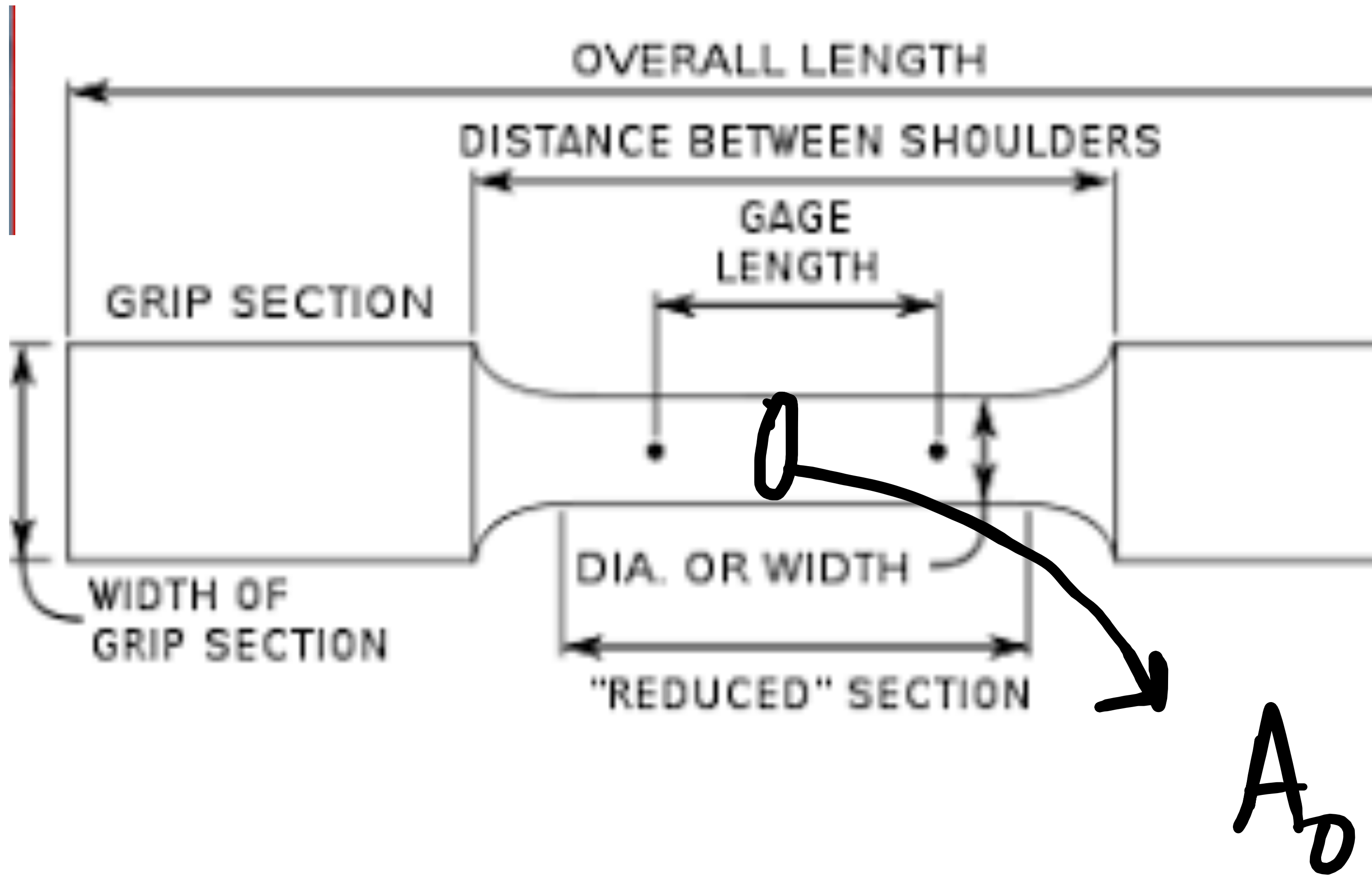
Uniaxial Tensile Test

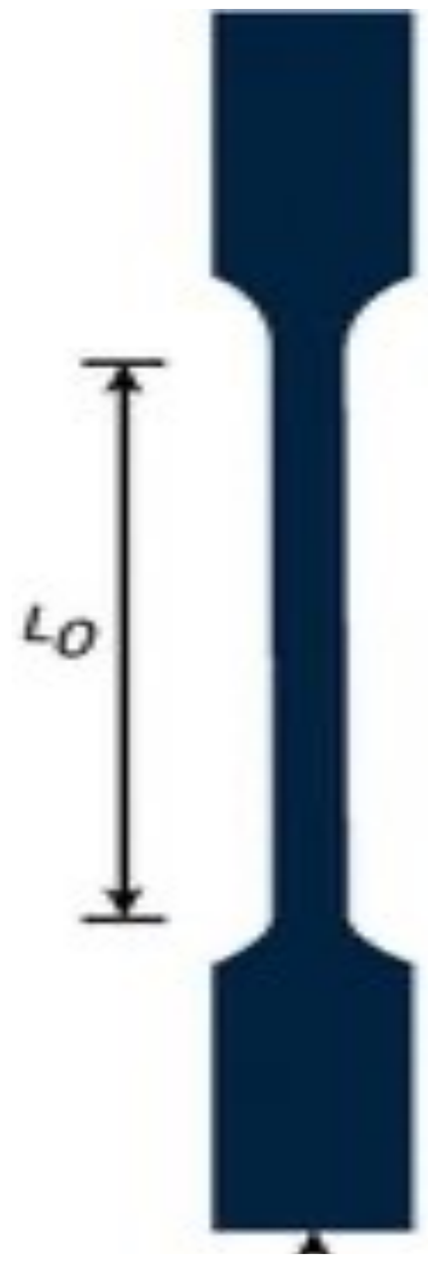
- If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behavior may be ascertained by a simple stress–strain test; these are most commonly conducted for metals at room temperature.

- A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen.

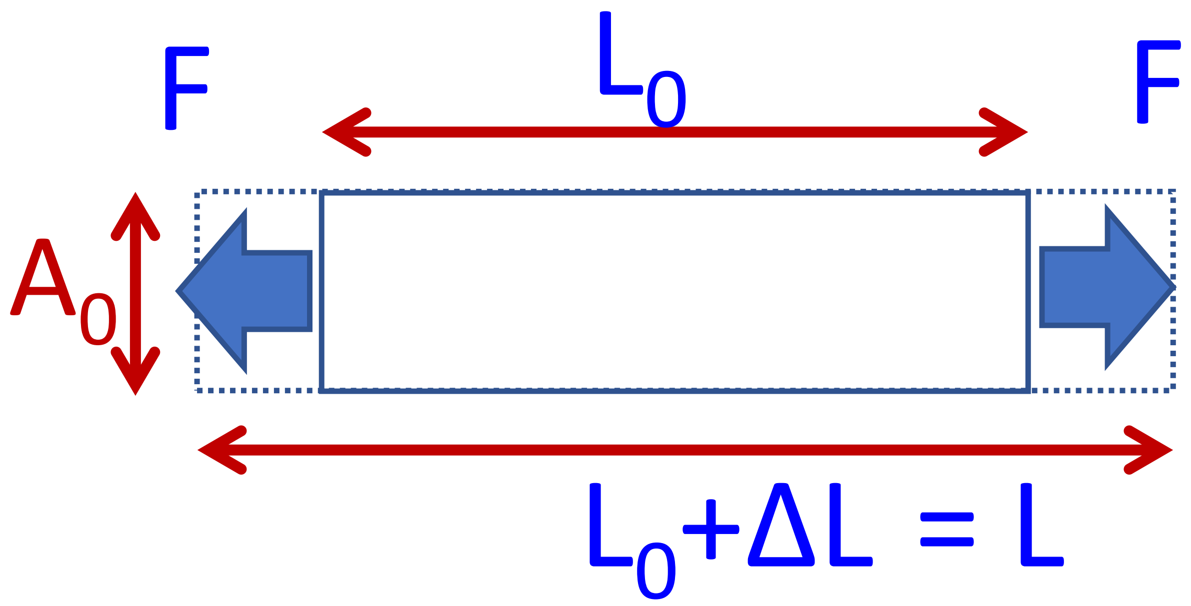
- This “dogbone” specimen configuration was chosen so that, during testing, deformation is confined to the narrow center region (which has a uniform cross section along its length), and, also, to reduce the likelihood of fracture at the ends of the specimen.

- The specimen is mounted by its ends into the holding grips of the testing apparatus.





Engineering Stress and Strain



Engineering Stress = $\dfrac{\text{Instantaneous Force}}{\text{Initial cross-section area}}$

$$\sigma = \frac{F}{A_0} \left(= \frac{N}{m^2} = Pa \right)$$

units

Engineering Strain = $\dfrac{\text{Elongation}}{\text{Initial Length}}$

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

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

(dimensionless quantity)

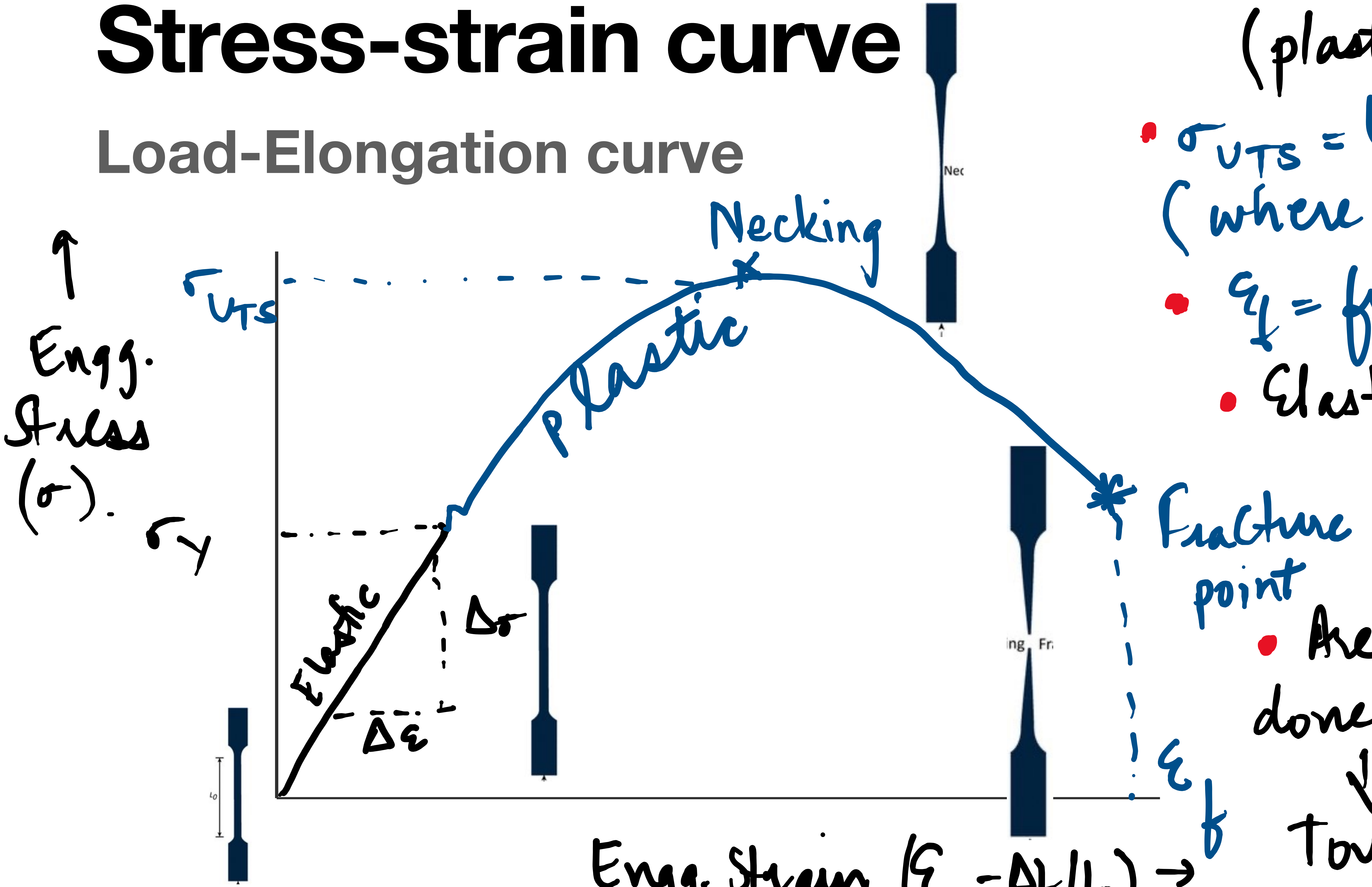
Why divide by area?

Suppose you want to find the stress of a weight of 200 pounds on a steel material of area of 3 inches by 4 inches. And compare the performance of the same steel in a part of a bridge with area 20 feet by 5 feet when it is crossed by a vehicle weighing 100 tons (or 224000 pounds).

The stress in both the cases is 16.67 pounds/sq.inch

Stress-strain curve

Load-Elongation curve



Engg. Strain ($\varepsilon = \Delta L / L_0$) → Toughness

- σ_Y = Yield stress (plastic deformation begins)
- σ_{UTS} = Ultimate tensile stress (where Necking happens: decrease in A_0)
- ε_f = fracture strain
- Elastic modulus or Young's modulus

$$Y = \frac{\Delta\sigma}{\Delta\varepsilon} \text{ (stiffness)}$$

- Area under curve = work done to fracture ⇓ Toughness

Units of area = $N m^{-2} = \frac{Nm}{m^3} = J m^{-3}$

Energy per unit vol. reqd. to cause fracture

- Tensile strength $= \frac{\text{Max load}}{A_0}$

Mechanical Properties derived from Tensile test

- **Strength**: Yield stress or ultimate tensile strength (σ_{UTS})

(σ_Y)

(*Ability to resist plastic deformation*)

- **Stiffness**: Young's modulus: Ability to resist elastic deformation
- **Toughness**: Area under the curve: Energy absorbed per unit volume upto fracture.
- **Ductility**: Elongation strain at fracture point: Ability to undergo plastic deformation

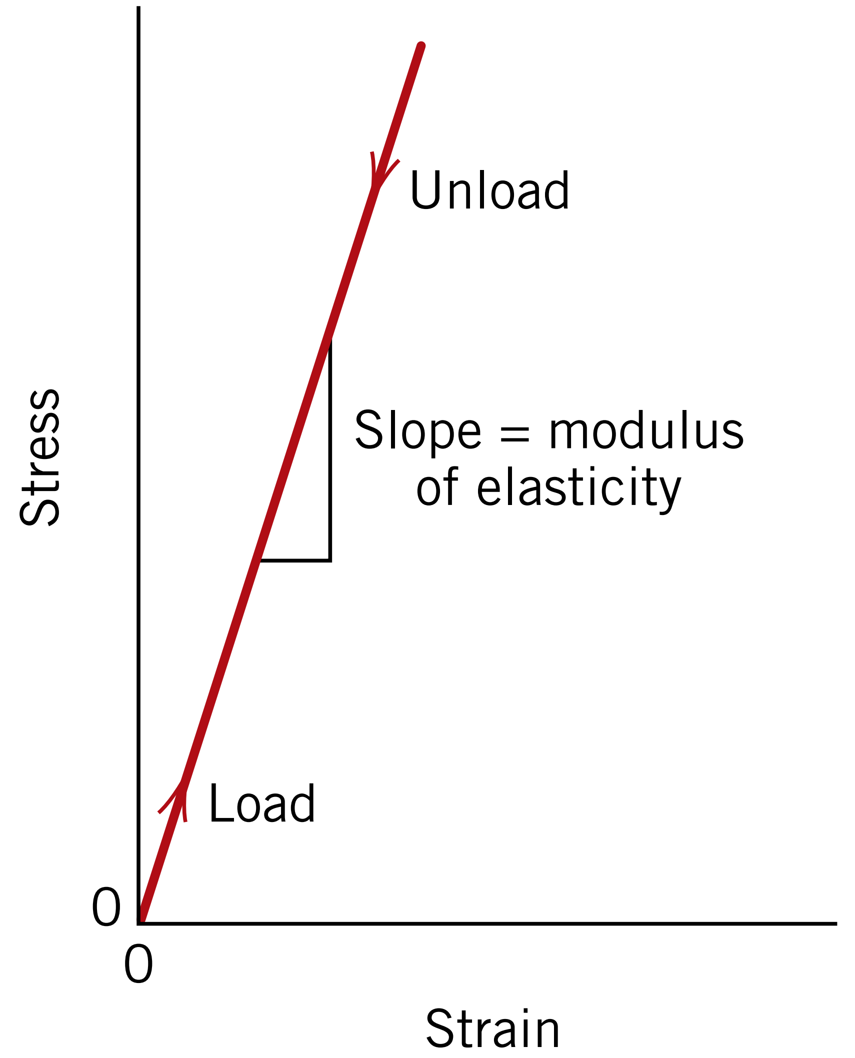
Elastic deformation

Deformation in which stress and strain are linearly proportional

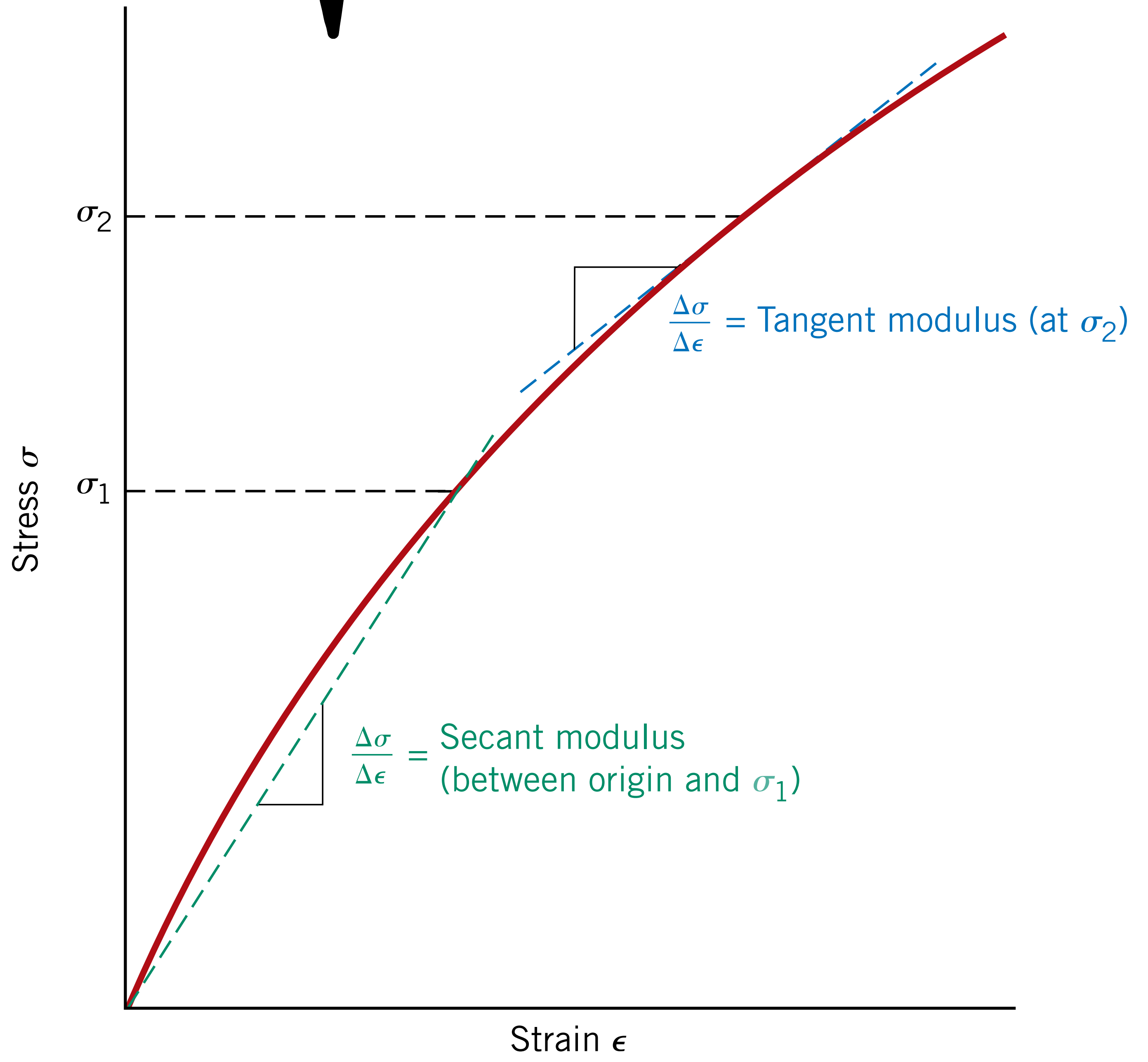
- Hooke's law:

$(F = k \cdot \Delta x) \Rightarrow \sigma = Y \varepsilon$, where Y = Young's modulus or modulus of elasticity

- For most typical metals the magnitude of this modulus ranges between 45 GPa (6.5 X 10^6 psi), for magnesium, and 407 GPa (59 X 10^6 psi), for tungsten.
- The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress.
- Elastic deformation is *non-permanent*: when the applied load is released, the piece returns to its original shape
- Young's modulus is a characteristic of each substance due to its chemical nature.

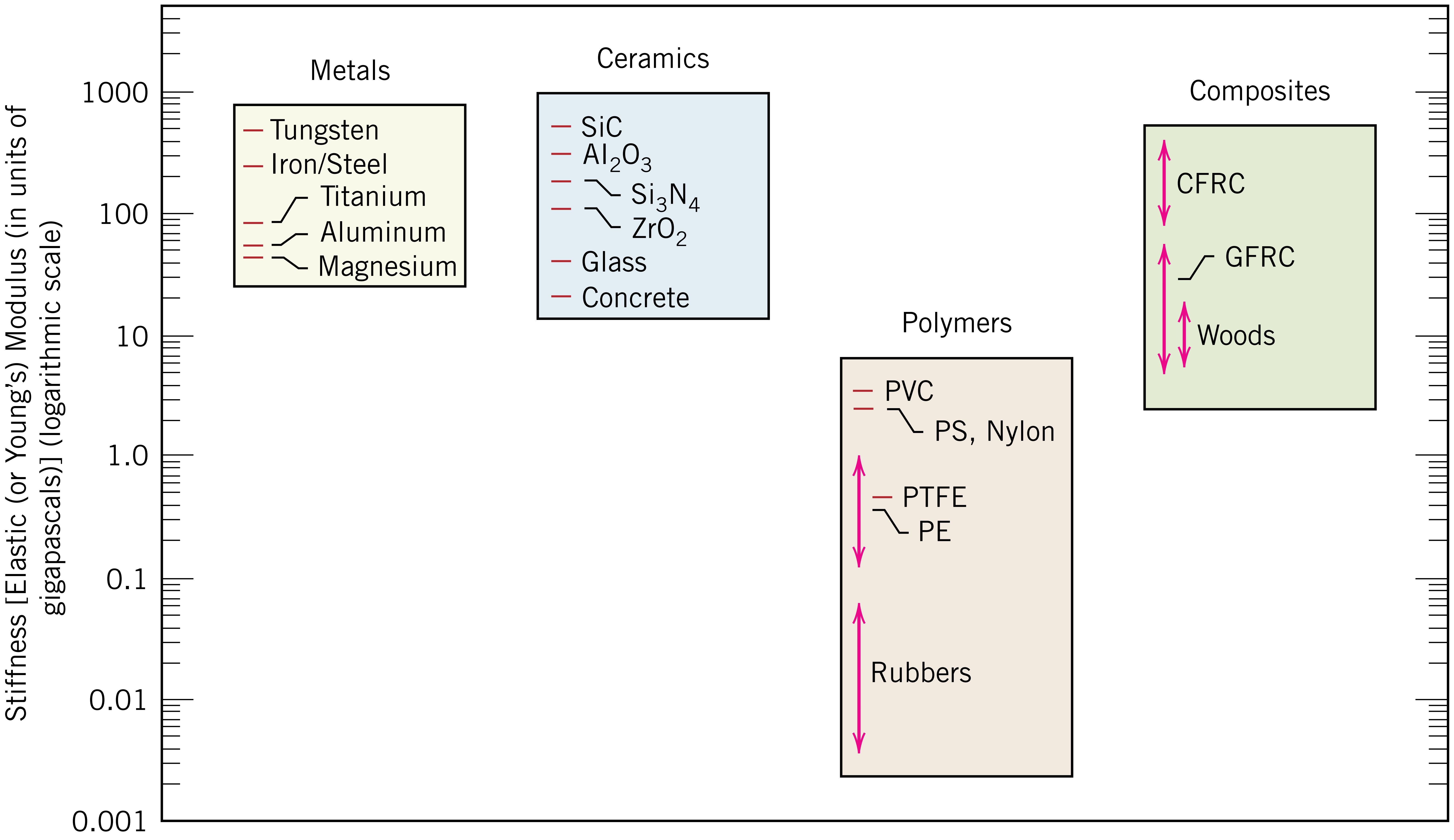


stress–strain diagram showing linear elastic deformation for loading and unloading cycles



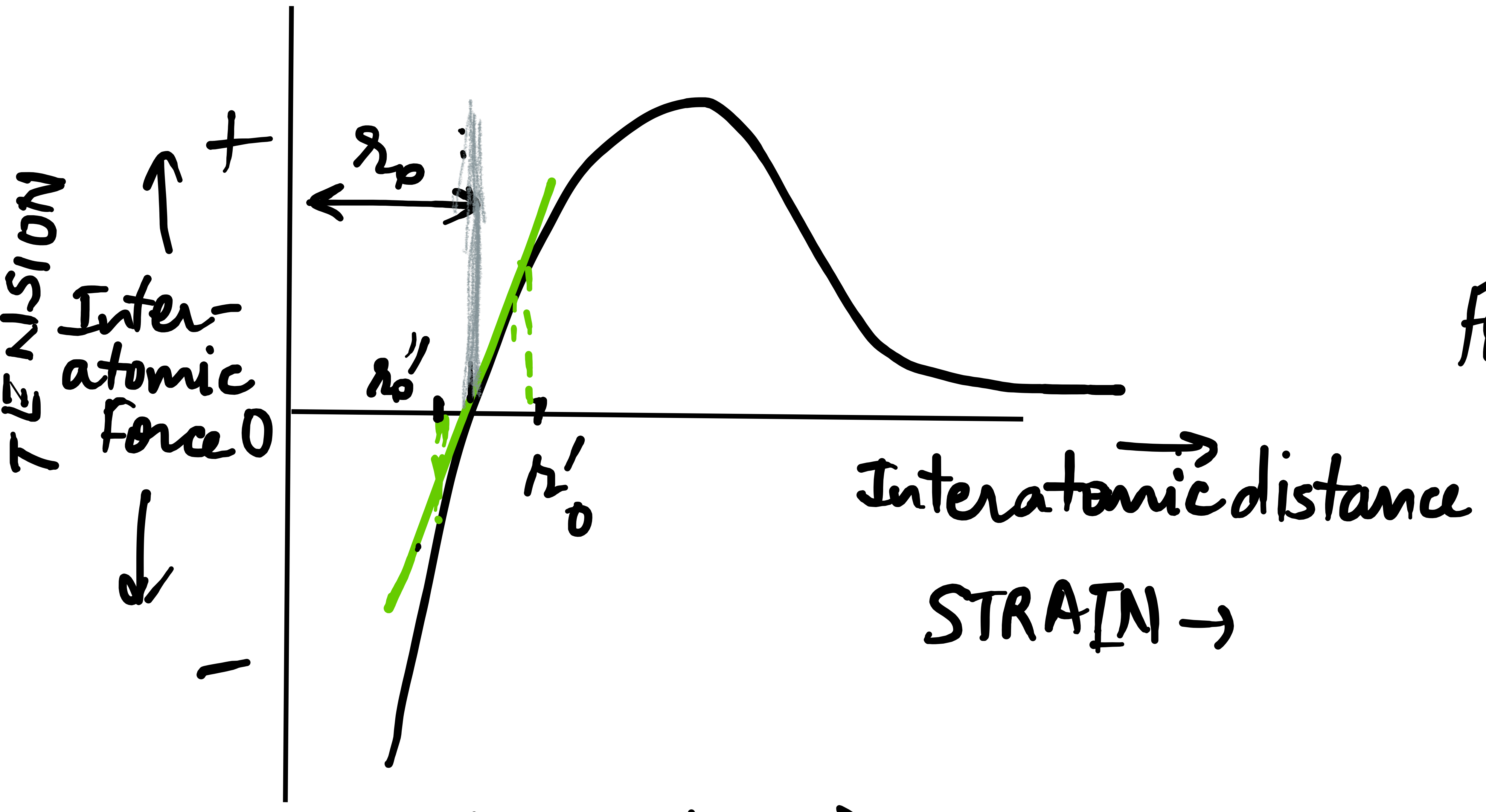
tangent or *secant modulus* for gray cast iron, concrete, and many polymers

Classification of materials based on elastic modulus

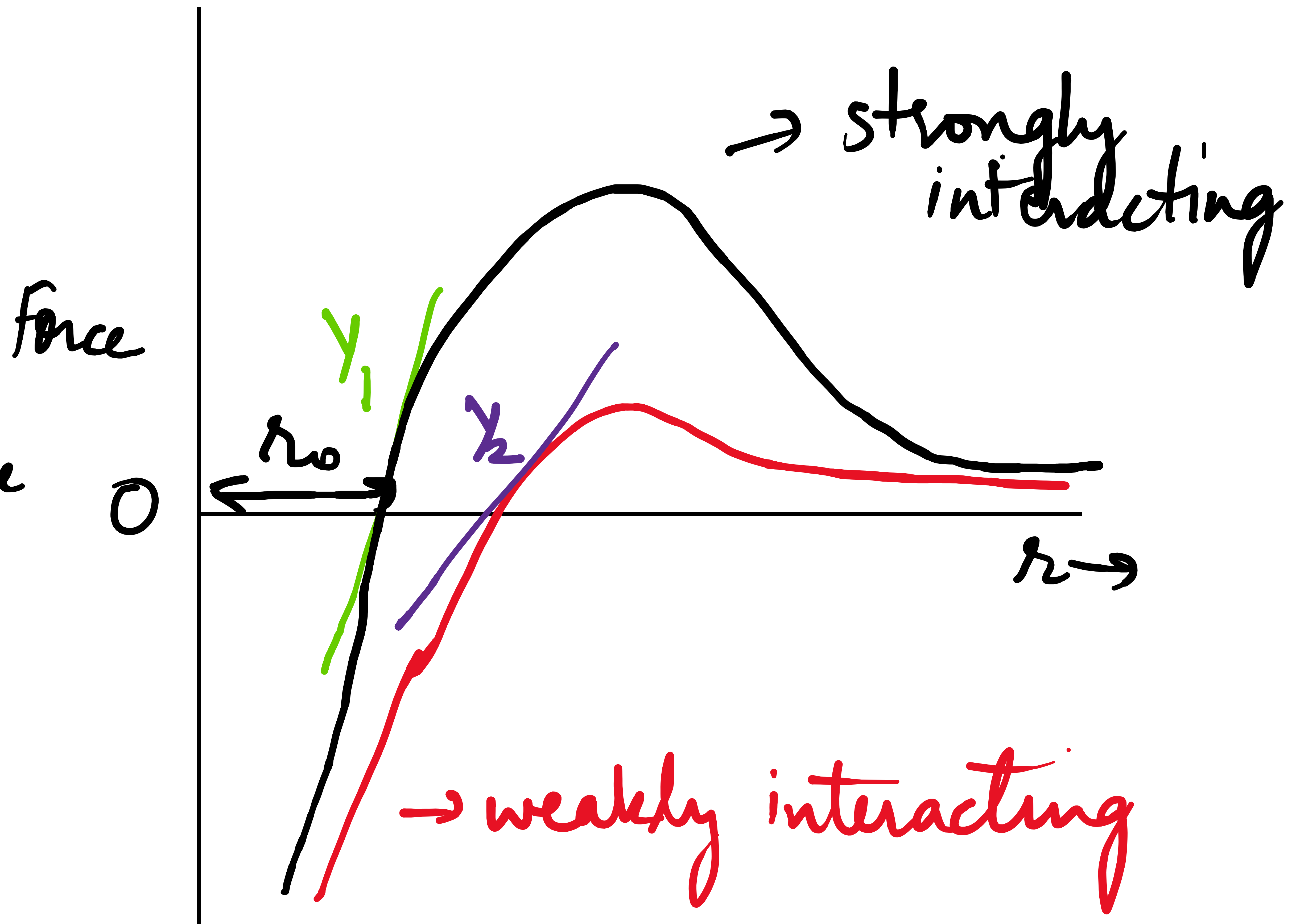


Atomic model of Elastic deformation

- Elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds.
- Magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces.



$$Y \propto -\left(\frac{dF}{dr}\right)_{r_0} = \left(\frac{d^2W}{dr^2}\right)_{r_0}$$

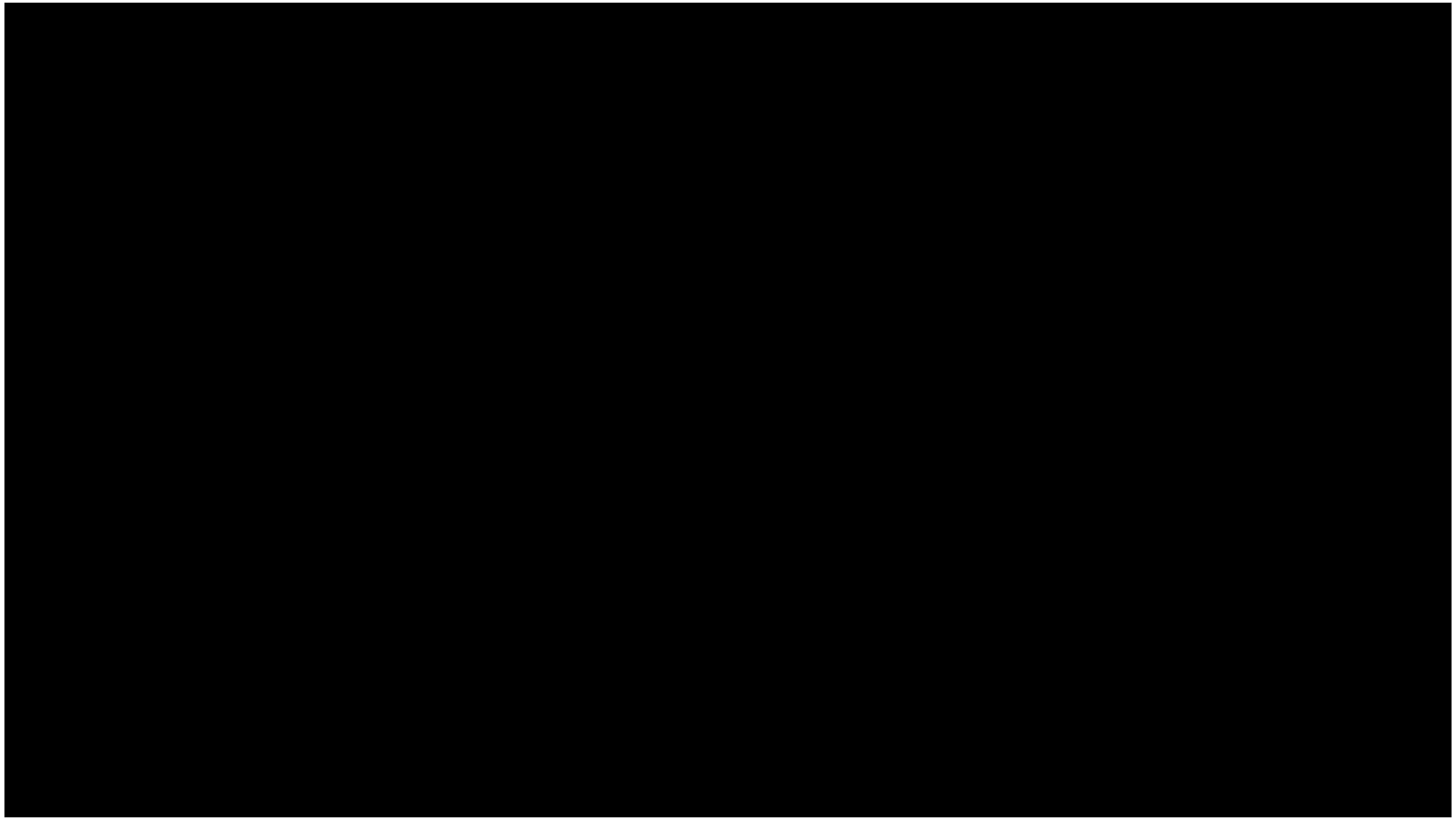


$Y_2 < Y_1$

Hold on to it!

We will study *why we don't fall through the floor* in the next class using concepts studied today and as given by both the geniuses: Hooke and Newton!

Here's a preview…



The Hooke and Newton Song: https://www.youtube.com/watch?v=HPu0PfGPo8s

Quiz-3 on 15th March 2022 (Online mode)

- Syllabus: topics covered after Minor till 11th March (including lecture 26)