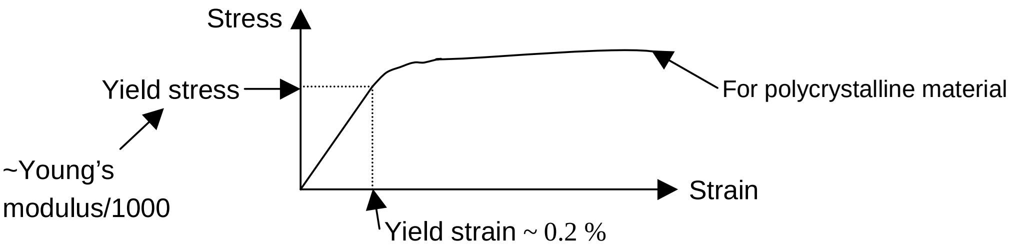
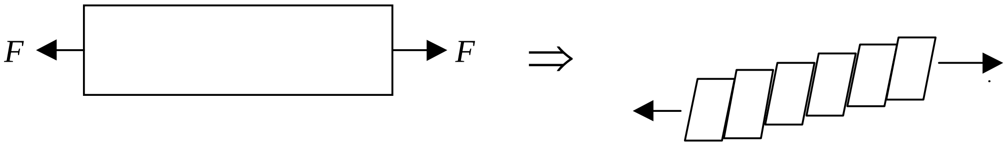
6. Plastic Deformation of Solids

We shall seek a microscopic understanding of plastic deformation.

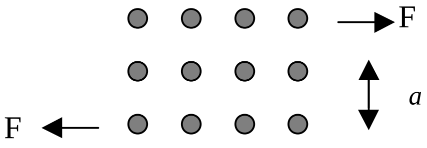


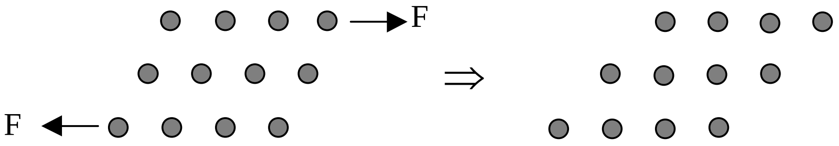
Plastic strains (those which do not vanish when the stress is removed) occur due to shear stresses, even when the applied stress is tensile. Slip occurs along 'slip planes' when the yield stress is exceeded.



(Incorrect) theoretical Yield Stress:

Consider a simple cubic structure and apply shear stress:





$\varepsilon_y =$ yield strain ~ $\dfrac{a/2}{a} = \dfrac{1}{2}$

$\therefore$ yield stress $\tau_y = G\varepsilon_y = \dfrac{G}{2}$

According to experiment: $\varepsilon_y \sim 10^{-3}$ and $\tau_y \sim 10^{-3}G$.

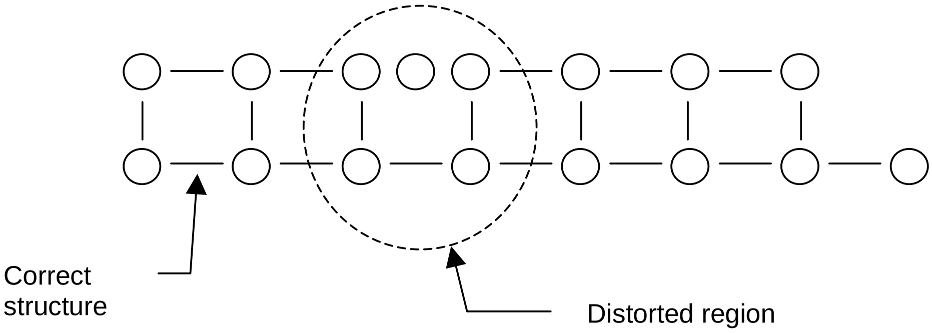
What is wrong?

6.1 Dislocations

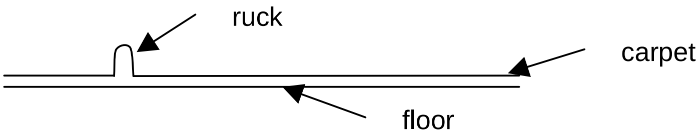
In order to understand why a material yields in plastic deformation at a shear stress far below the theoretical yield stress, we have to appeal to the existence of linear imperfections or "line defects" called dislocations in the otherwise perfect structure of a crystal.

They are the consequence of incorrect registry between crystal planes.

e.g. place two linear chains of atoms on top of one another.



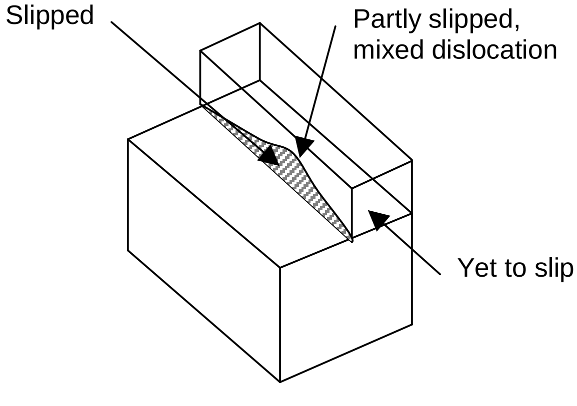
In 3-d, this disregistry produces an edge dislocation. Symbol $\perp$.
By a sequence of small distortions, the edge dislocation (region of distortion) can move, or glide on the slip plane. For example, shifting a carpet! The ruck is the dislocation. It has a direction perpendicular to the paper, and glides to left or right, carry a unit of horizontal slippage.



The motion produces slip between the upper and lower parts of the crystal. The direction and magnitude of this slip is given by the Burgers vector $\vec{b}$. This characterises a dislocation. For an edge dislocation, the slip is perpendicular to the direction, or 'sense' of the dislocation line. This is a vector which is tangent to the dislocation line. b, the magnitude of $\vec{b}$, is often equal to a lattice spacing.

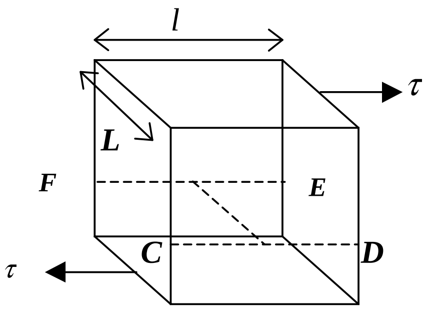
There is another sort of dislocation called a screw dislocation. The Burgers vector of a screw dislocation is parallel to the sense.

There are also mixed dislocations, part edge, part screw. *See handout for diagrams.*



Glide of dislocations is brought about by relatively low shear stress, only small distortions and rearrangement of atoms are needed.

6.2 Force on a Dislocation



If a dislocation on the slip plane *CDEF* moves from *CF* to *DE*, the upper block slips a distance b to the right. Work done is shear force times distance moved, i.e. $\tau A b$ with $A = Ll$.

Equivalent picture: there is a force F_d per unit length acting on a dislocation.

Work done $= \underbrace{F_d L}_{\text{Force on dislocation}} \times \underset{\uparrow\ \text{Distance moved from } C \text{ to } D}{l} = \tau A b$ so $F_d = \tau b$ is the force per unit length.

(For an edge dislocation. Analysis is more complicated for screws).

6.3 Energy per unit length, or line tension of a dislocation

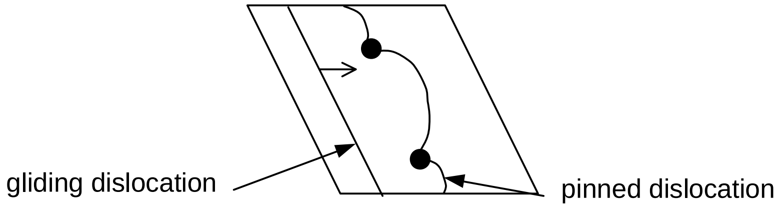
Energy is due to distortion of the structure

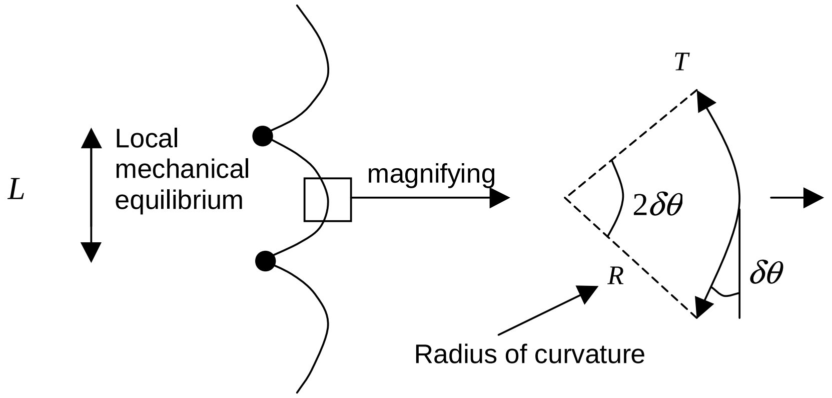
Stored elastic energy ~ G x (typical strain)^2 x (affected volume) ~ G x (1)^2 x (b^2L)

so line tension $T \sim Gb^2$

6.4 Pinning of Dislocations

Glide is easy on a perfect glide plane, which leads to too low a yield stress (Peierls stress), but imperfections on the glide plane (impurities, vacancies, other dislocations etc) can pin the dislocation at *pinning centres*:





Balance forces, assume $\delta\theta$ is small, insert $T = Gb^2$:

$$F_d\, 2R\delta\theta = 2T\sin\delta\theta$$

$$\Rightarrow \quad R = \frac{Gb}{\tau}$$

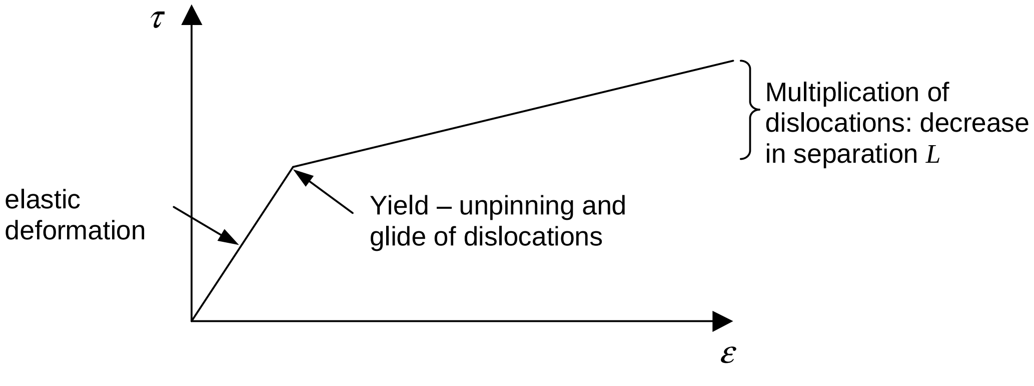
As the stress increases, the bowing radius decreases. But R can not be less than $L/2$ where L is the separation of pinning centres. Yield occurs at $R = L/2$, i.e. for a semicircular bowed dislocation line. Dislocation is unpinned: escape corresponds to yield.

So yield stress $\tau_y = \frac{2Gb}{L}$ and if $b \approx 1$ Å and $L \approx 10^3$ Å then $\tau_y = 10^{-3}G$ as required.

6.5 Dislocation Multiplication

Some dislocation configurations can operate under stress as a source of additional dislocations. For example, the Frank-Read source, where a pinned, isolated segment of dislocation on a glide plane can bow out and around, creating concentric, expanding dislocation loops.

We now arrive at an understanding of the stress-strain curve:



The dislocations tangle as they are created and glide.
Produces the Frank net, also known as a *forest* of dislocations.