Unit M5.2
Physical Origins of Failure/Strength

Readings:

A & J 9, 10, 18, 19

16.003/004 -- “Unified Engineering”
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

LEARNING OBJECTIVES FOR UNIT **M5.2**

Through participation in the lectures, recitations, and work associated with Unit M5.2, it is intended that you will be able to……

- ….**describe** the effects of the atomic/molecular structure of materials on material failure/strength
- ….**explain** the types of realities and imperfections in materials and their contribution to strength and failure
- ….**identify** the role of (length)scale on failure and strength
- ….**recall** the aspects of time-dependent material response

We have characterization material response loading to failure and the property of strength on a *macroscopic level*. Just as we did for elastic properties, we can look at the structure of the material to understand the physical origins of this behavior.

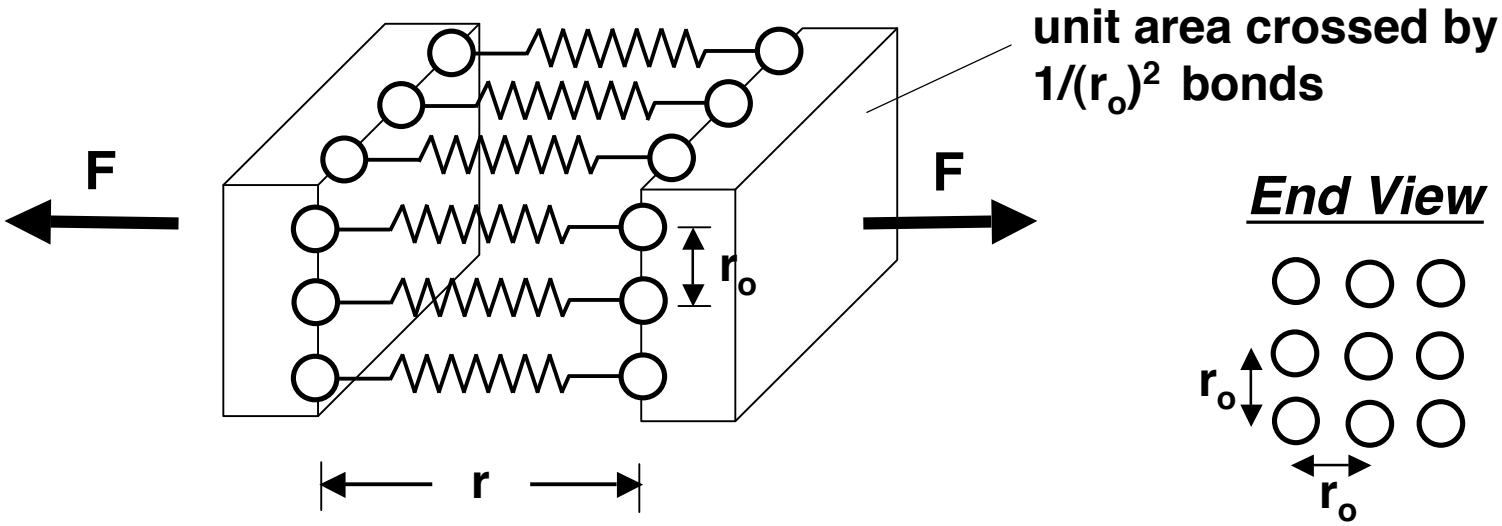
We will consider a number of details and models, let us first look at….

The "Perfect" Crystal

"Perfect" refers to a structure, at the atomic and crystalline levels, with no flaws

Recall the model from Unit M3.3….

Figure 5.2-1 Model of material as (perfect) crystal lattice

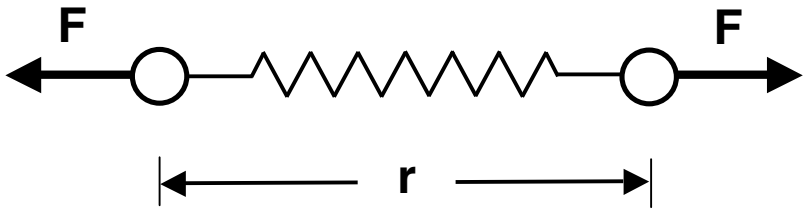


where: —WWWW— = bond

○ = atom

r_o = regular spacing
(from equilibrium considerations)

Recall the model of two atoms joined by one bond:



and the energies associated with this (all from Unit M3.3)….

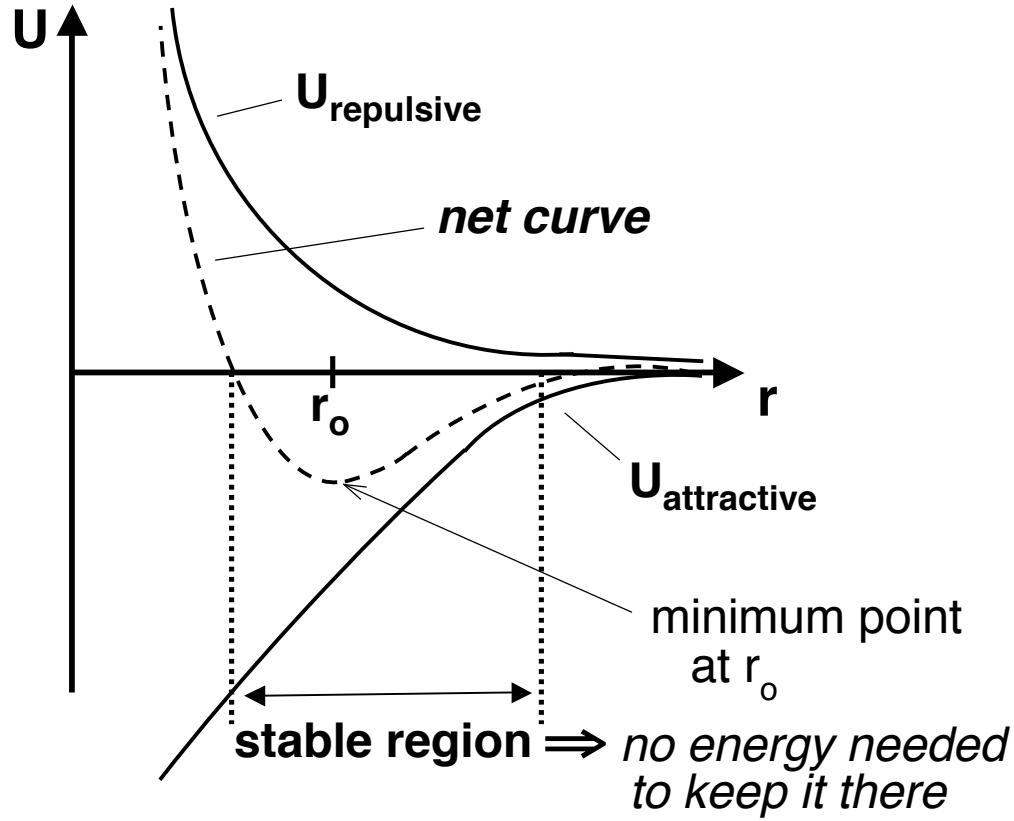
Total Potential Energy = $U = \underbrace{-\frac{A}{r^m}}_{attractive} + \underbrace{\frac{B}{r^n}}_{repulsive}$

How does one fail this single crystal bond?

Apply a force to overcome this basic energy

--> Consider the overall energy curves

Figure 5.2-2 Representation of energies associated with basic bond

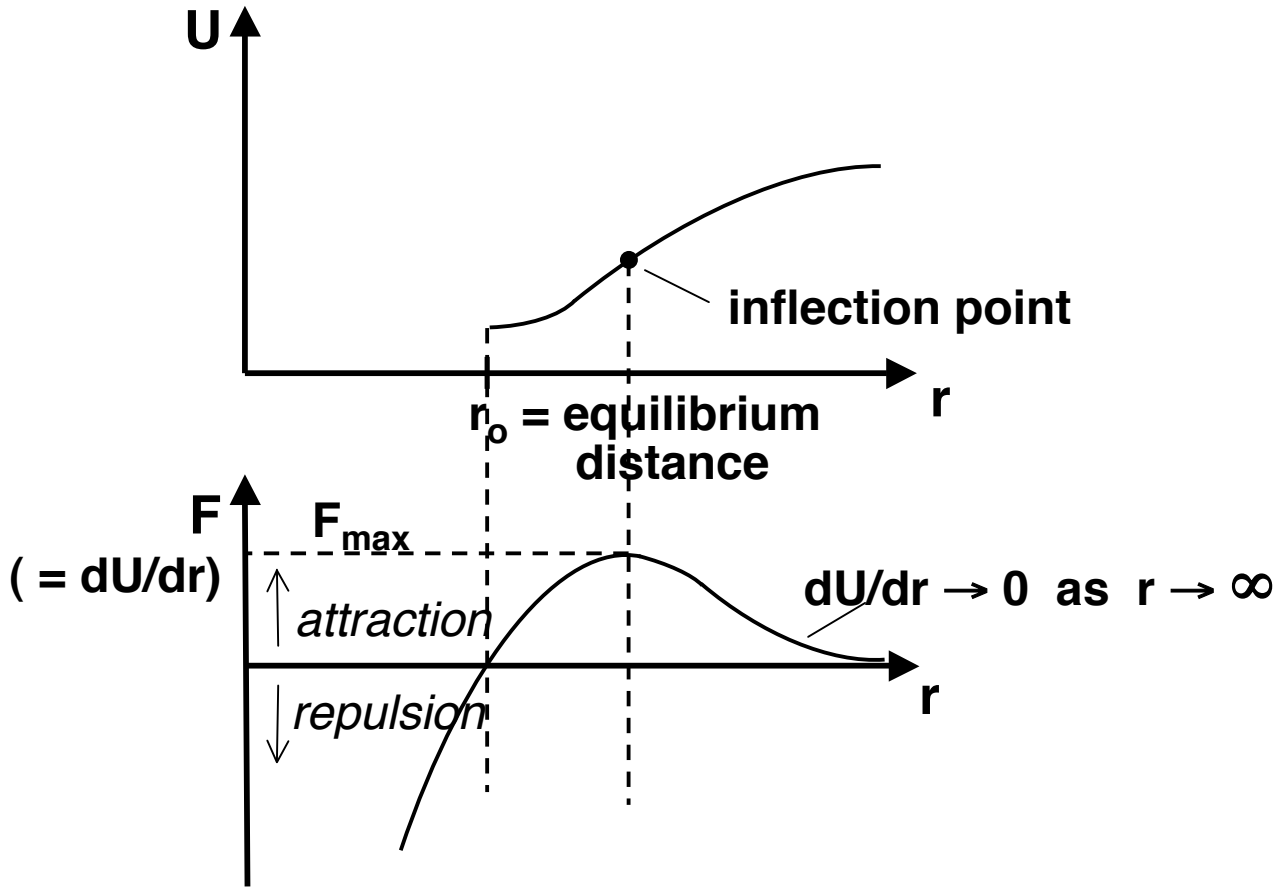


- Atoms begin at equilibrium distance, r_o
- Application and increase in force begins to separate atoms (*up* the energy hill)
- Getting atoms to steepest part of curve (second derivative = 0) is *maximum* force
- Atoms continue separating beyond this with *decreased* force

Mathematically: $$F = \frac{dU}{dr} \Rightarrow F = mAr^{-(m-1)} - nBr^{-(n-1)}$$

Graphically:

Figure 5.2-3 **Relationship of (bonding) energy and force**



--> Some key notes:

1. At F_{max}: $\frac{dF}{dr} = \frac{d^2U}{dr^2} = 0$

   and $\frac{d^2U}{dr^2}$ = stiffness;

   so failure $\Rightarrow$ stiffness becoming negative (like buckling!)

2. F_{max} occurs at approximately 1 1/4 r_o
3. F goes to 0 by approximately 2 r_o

Let's do an…

--> Estimate of strength

- Use the model in a similar manner as in estimating modulus (Unit M3.3)
- Area covered by each atom: $r_o \times r_o = r_o^2$
- Perform same calculations (see Unit M3.3) and another step

--> determine $\frac{dF}{dr} = \frac{d^2U}{dr^2}$

- Yields $\sigma_{max} \approx \frac{E}{15}$

--> find this to be off (high) by an order of magnitude!

Why? Consider the…..

Realities and Imperfections

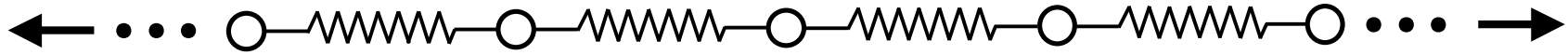
Virtually all materials, structures, etc. have imperfections at some level. No matter how minor, such an imperfection "breaks down" the model….

Consider the…..

--> Weakest Link Analogy

Think of a material as a series of links (bonds):

Figure 5.2-4 **Material represented as a series of bonds**



- For stiffness, behavior is an **average** of each piece
  ⇒ less stiff link is "averaged out"
- For strength, entire series breaks **when weakest link breaks**

⇒ In modeling materials, need to find and model the weakest mechanism, process, etc.

Important to also reconsider the….

--> Concept of (Length) Scales

Recall from Unit 3….

There are many different lengths (and, thus, associated *scales*, at which mechanisms can be manifested)

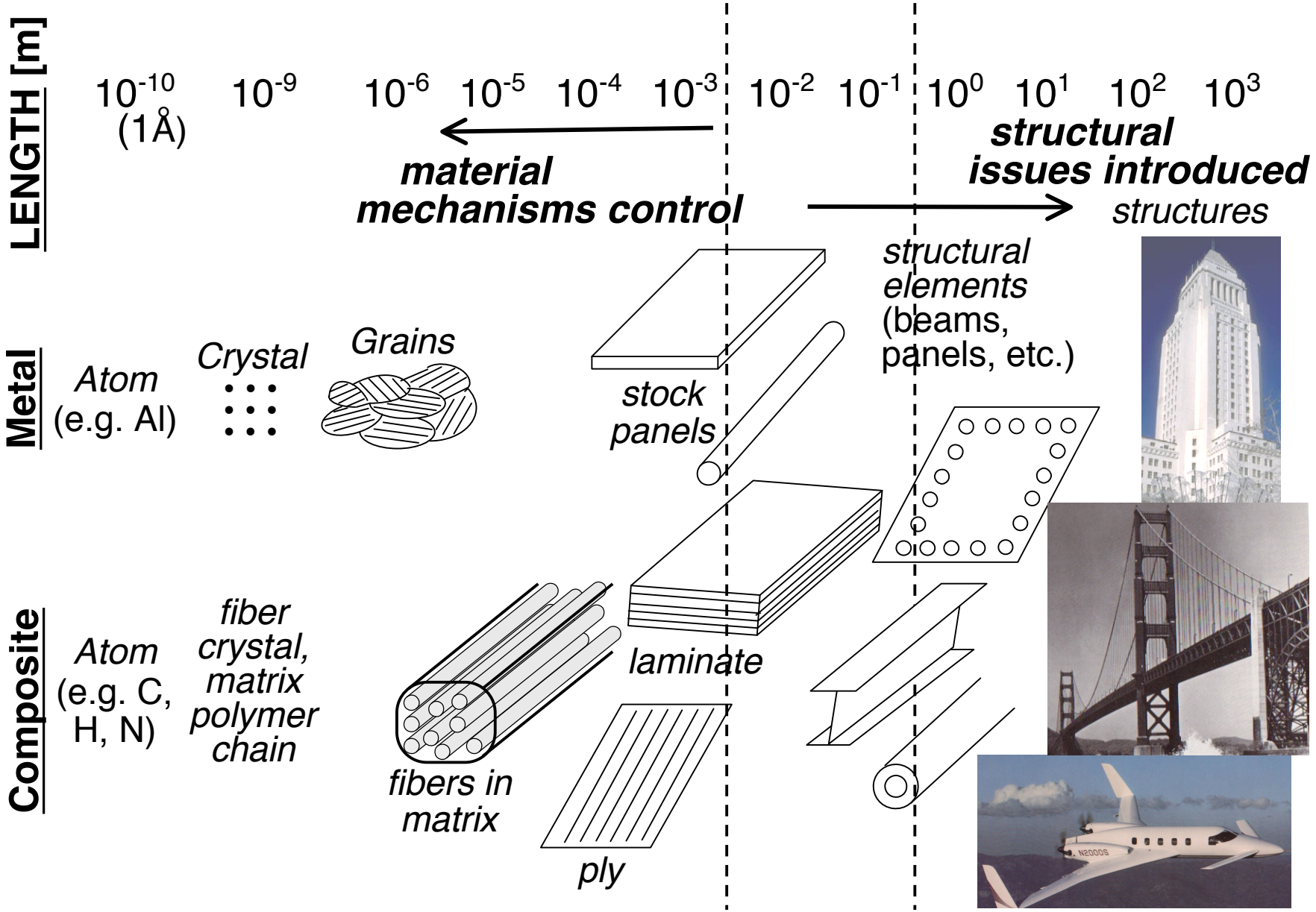
These depend upon the material and its basic structure

As one builds to larger and larger length scales, others and different imperfections and mechanisms can be introduced and they can interact

For example….

- Atom/Molecular bonding
- Crystal or • Polymer chain
- Grain
- Composite
- Panel
- Stiffened Structure
- Upper Wing

Recall discussion in Unit M3.4 concerning effective moduli and length scales/characteristic length


LENGTH [m]
10-10 (1Å)
10-9
10-6
10-5
10-4
10-3
10-2
10-1
100
101
102
103
material mechanisms control
structural issues introduced
structures
Metal
Atom (e.g. Al)
Crystal
Grains
stock
panels
structural elements (beams, panels, etc.)
Composite
Atom (e.g. C, H, N)
fiber crystal, matrix polymer chain
fibers in matrix
laminate
ply

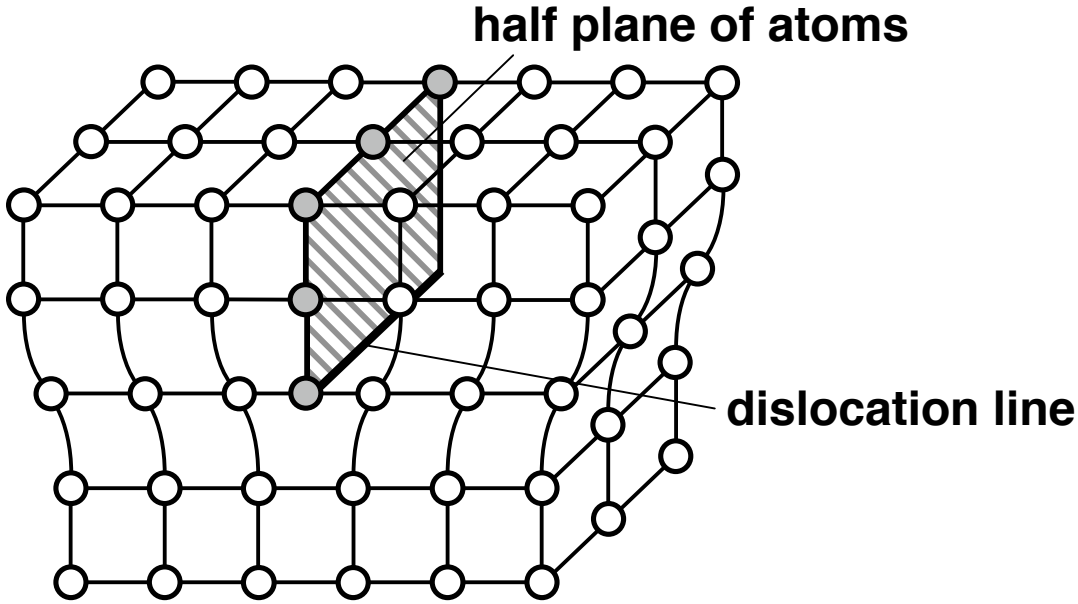
Let's consider a few….

--> Examples of Imperfections

1. Crystals and *Dislocations*

Dislocations are extra half-planes of atoms that disrupt the basic (perfect) pattern/structure of the crystal

Figure 5.2-5 **Representation of dislocation at atomic level**



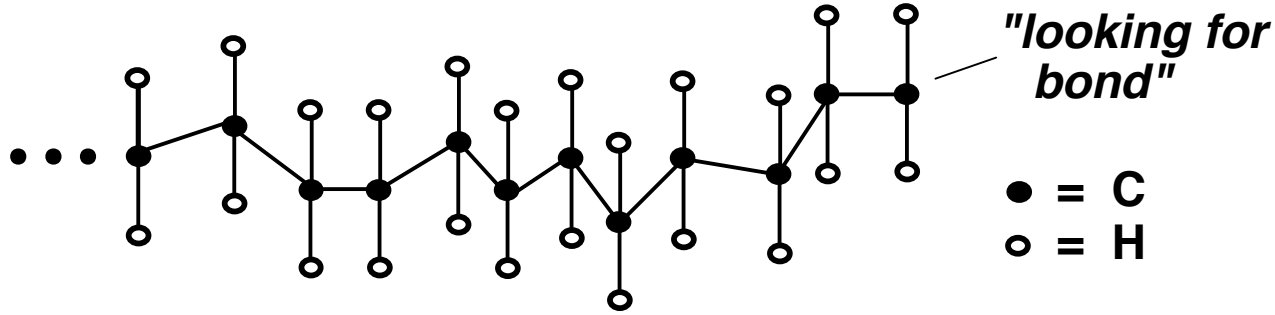
These dislocations will "move" and cause failure (breakdown in basic perfect bond model)

2. Polymers and Chains

Polymer chains are very strong bonds

Imperfection occurs with atom left without bond

Figure 5.2-6 **Representation of finite aspect of polymer hydrocarbon chain**



3. Homogeneous Materials

Consider items on a large scale (macroscopic)

A metal, polymer, etc., is a big “blob” of material that is the same at this level

When one makes a piece, if there are no imperfections, failure occurs at length based on lower level considerations

Imperfections occur in the form of “inclusions” (e.g. dirt), a void (e.g. air bubble), a region of altered material (e.g. poor mixing)

All imperfections reduce strength

With these items in mind, one can consider ways for…..

--> Strengthening against Imperfections

With imperfections being a key operant in reducing strength, a means by which to increase strength is to lessen the influence of imperfections.

Since imperfections move and/or cause damage to propagate from them, a fundamental mechanism is to….

…put something in the way

Some examples are….

- Solid solution hardening-- put bigger atoms into the lattice that “block” the dislocation

- Precipitates/dispersion -- put small hard particles into lattice that "block" the dislocation
- Polycrystalline structure -- put crystals oriented in different directions so dislocations get stopped
- Particulates in polymers -- put pieces into homogeneous material to divert propagating macroscopic damage

With these items as background, we return to the material (macroscopic level) and consider multidirectional stress field due to some structural configuration.

Unit 5.2 (New) Nomenclature

r -- distance between atoms

r_o -- regular spacing between atoms in crystal lattice

U -- Total Potential Energy