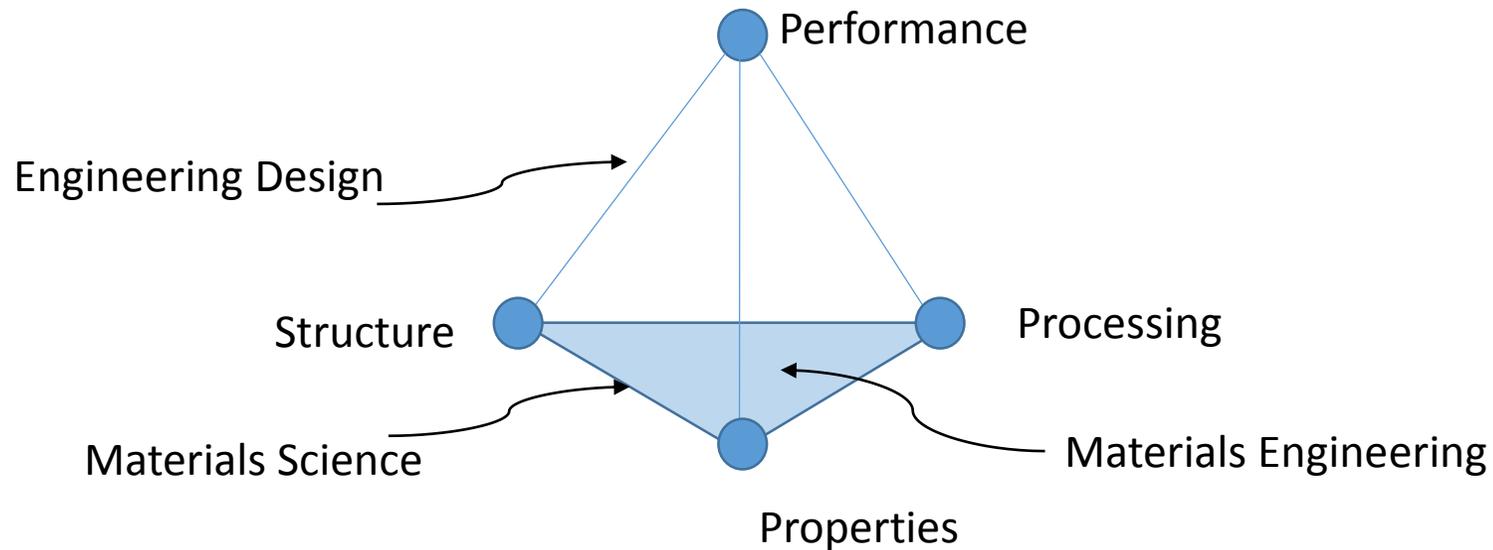


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Materials

What is Materials Science and Engineering?



The goal of materials science is to empower scientists and engineers to make informed decisions about the design, selection and use of materials for specific applications.



Photograph: Nils Jorgensen/REX

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http://www.healthbase.com/resources/images/ortho/hip_replacement_implants/healthbase_zimmer_total_hip_replacement_implant_components.jpg

Four Fundamental Tenets Guide Materials Science

1. The principles governing the behavior of materials are grounded in science and are understandable
2. The properties of a given material are determined by its structure. Processing can alter the structure in specific and predictable ways
3. Properties of all materials change over time with use and exposure to environmental conditions
4. When selecting a material for a specific application, sufficient and appropriate testing must be performed to ensure that the material will remain suitable for its intended application throughout the intended life of the product

A materials scientist or engineer must be able to:

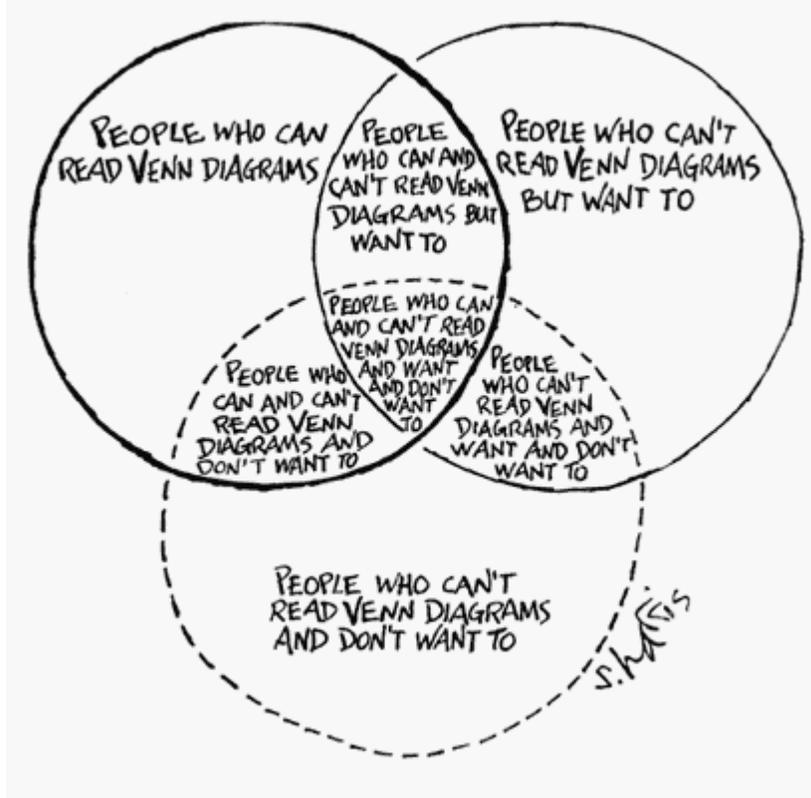
1. Understand the properties associated with various classes of materials
2. Know why these properties exist and how they can be altered to make a material more suitable for a given application
3. Be able to measure important properties of materials and how those properties will impact performance
4. Evaluate the economic considerations that ultimately govern most material issues
5. Consider the long-term effects of using a material on the environment

Fundamental types of materials important to engineering:

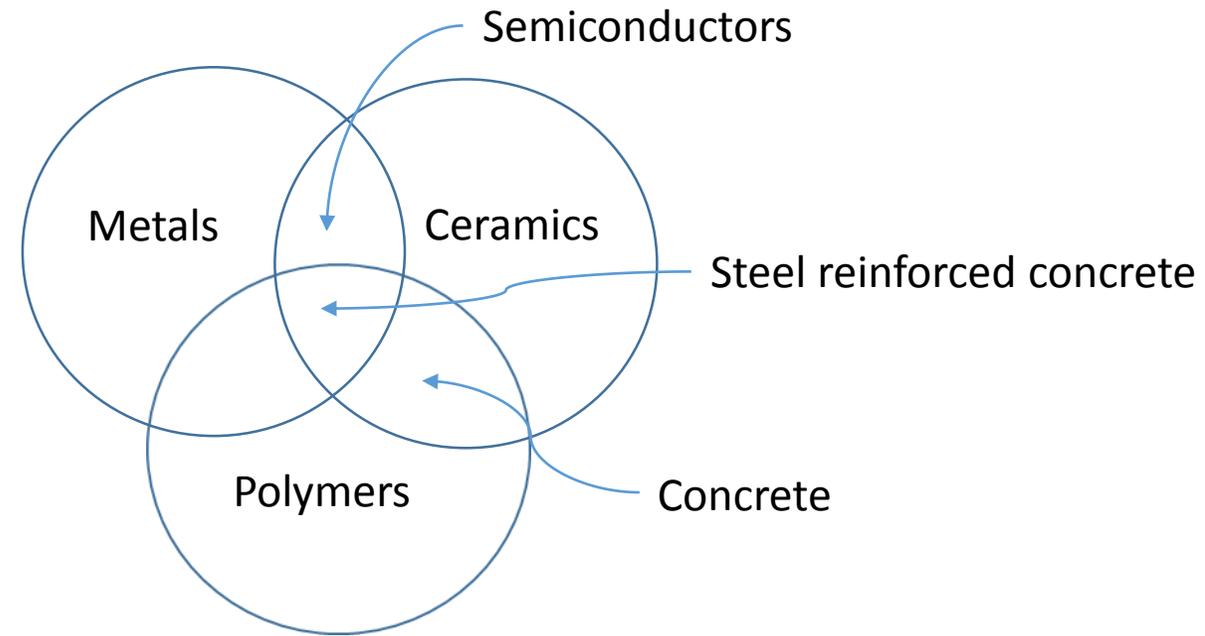
1. Crystals - Engineering metals and alloys
Systemic, regular pattern, minimize volume
2. Engineering Ceramics (including glass)
High viscosity at liquid-solid point prevents crystallization. These materials are usually amorphous
3. Polymers
Long chains of simple, molecular structures. Plastics and living things
4. Elastomers
Long chain polymers which fold or coil. Natural and artificial rubber. Enormous extensions associated with folding and unfolding of chains.

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<http://www.buzzfeed.com/scott/nerd-venn-diagram>



The Fundamental Material - Atom

1. What are the atomic building blocks?
 - a) Nucleus – Protons (+) and Neutrons (0)
 - b) Electrons (-)
 - c) Atoms have a neutral charge (#protons =#electrons)
2. How are electrons distributed through an atom?
 - a) Electrons in organized shells in an electron cloud
 - b) # electrons/shell = $2N^2$ (N = the shell number)
3. What are valence electrons? Why are they important?
 - a) Valence electrons are in the outermost shell
 - b) Reactivity of atom depends upon valence electrons
4. Why are noble gases inert?
 - a) The noble gases have full shells of electrons

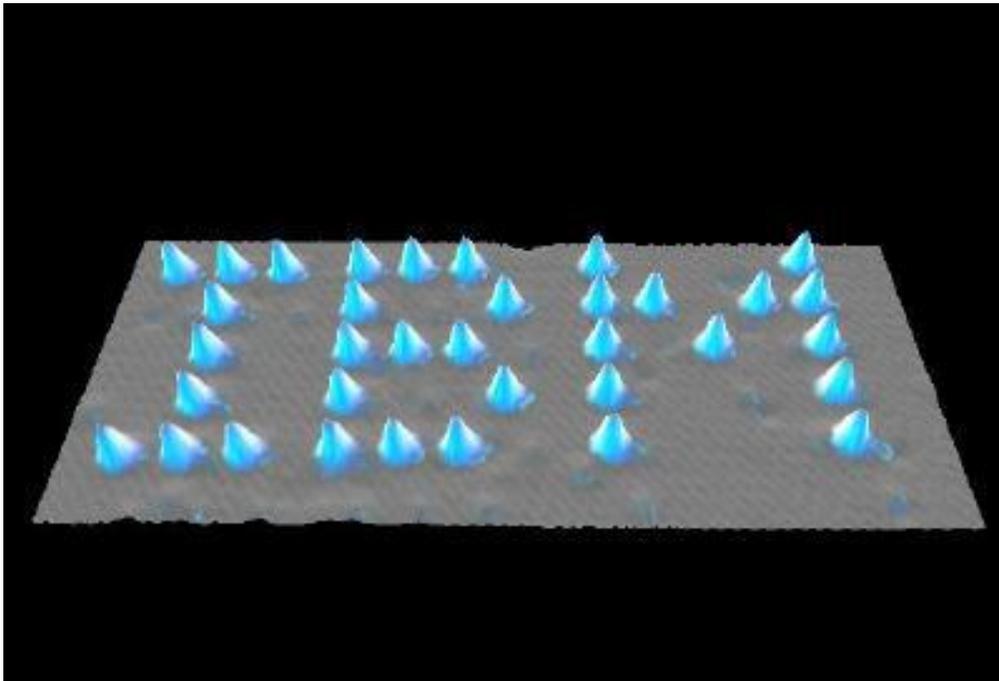


Atom = stadium

Nucleus = housefly in the center of the field

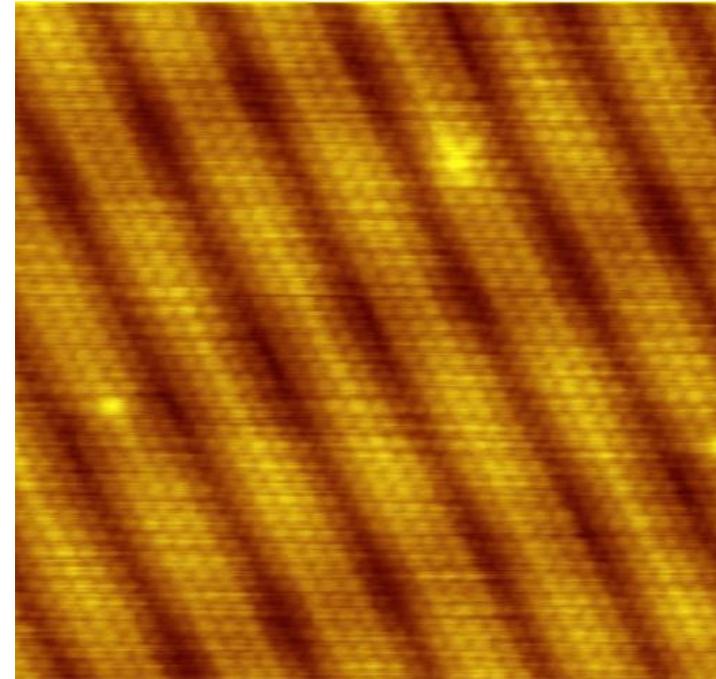
Atoms – Can we see them?

Electron Microscopy and Scanning Probe Microscopy



Xe on Ni

<http://s.hswstatic.com/gif/atom-ibm.jpg>

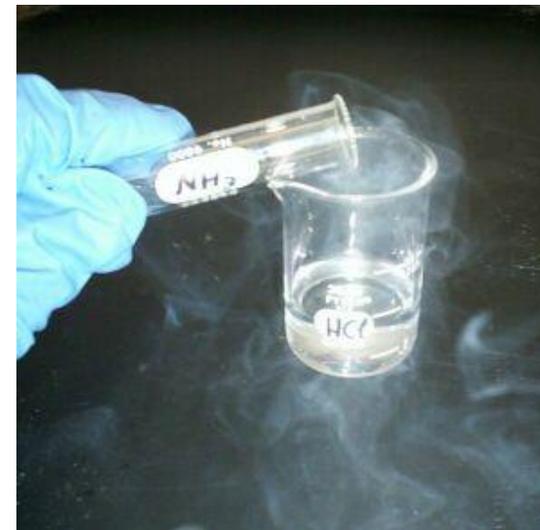
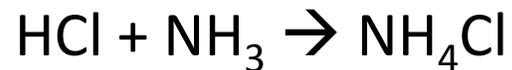


Au

http://upload.wikimedia.org/wikipedia/commons/thumb/e/ec/Atomic_resolution_Au100.JPG/200px-Atomic_resolution_Au100.JPG

The Fundamental Material - Atom

1. All atoms of a given element are _____
2. Atoms of different elements have different _____
3. A compound is a specific combination of atoms of more than one element
4. In a chemical reaction, atoms are neither created nor destroyed – only change partners to produce new substances



http://upload.wikimedia.org/wikipedia/commons/a/a0/Hydrochloric_acid_ammonia.jpg

**What holds the atoms in metals/crystals, ceramics,
polymers and elastomers together?**

BONDS!

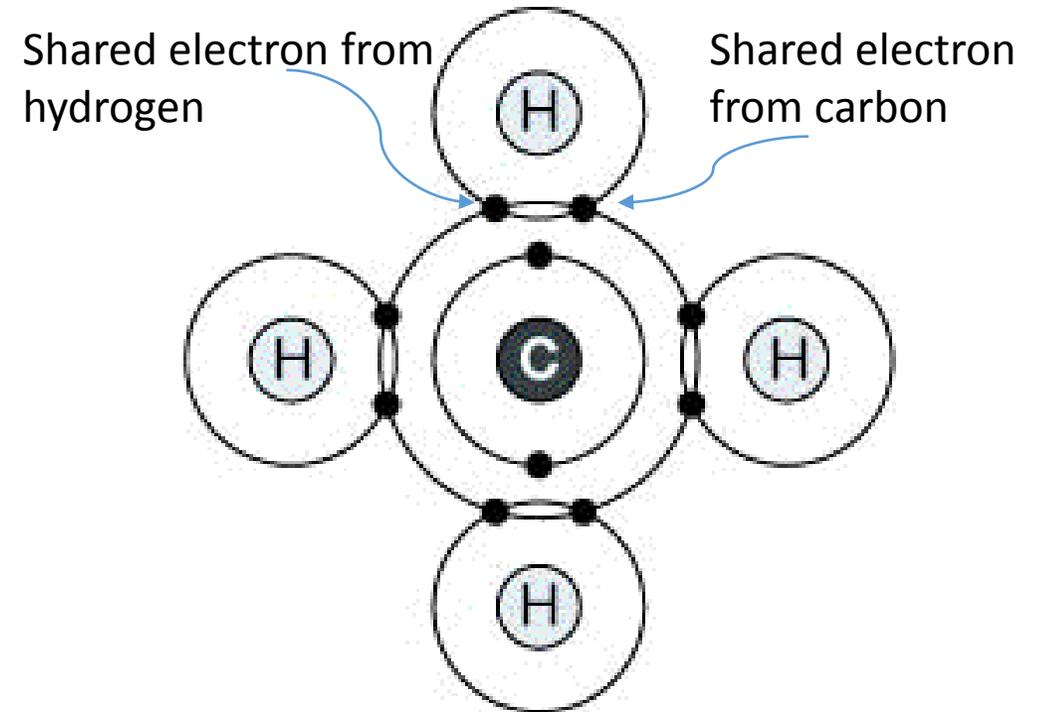
Covalent Bonds

- Two or more atoms share electrons
- Strong and rigid
- Found in organics and sometimes ceramics
- Strongly directional
- Methane CH_4

Carbon has ___ valence electrons

Hydrogen has ___ valence electrons

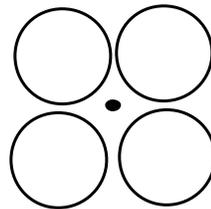
- Elemental solids – diamond
- Can be stronger – diamond
- Can be weaker - Bi



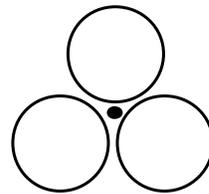
<http://myhome.sunyocc.edu/~weiskirl/methane2.GIF>

Ionic Bonds

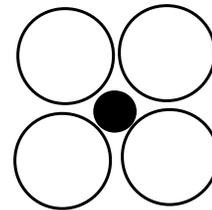
- Bonding between a metal and a non-metal
- Metal gives up valence electron(s) to non-metal
- Results in all atoms having stable electron configuration
- Na^+Cl^-
- Metal becomes +ly charged (cation); non-metal becomes -ly charged (anion)
- Coulombic attraction
- Close-packed



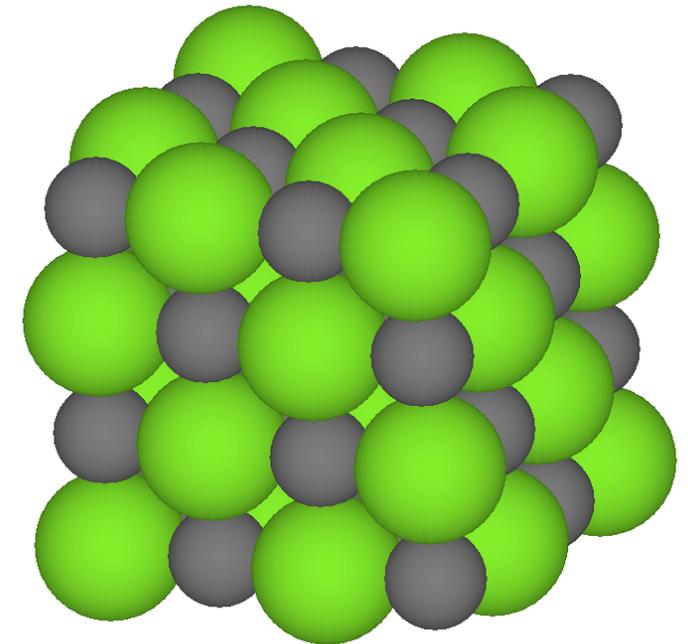
NO



YES



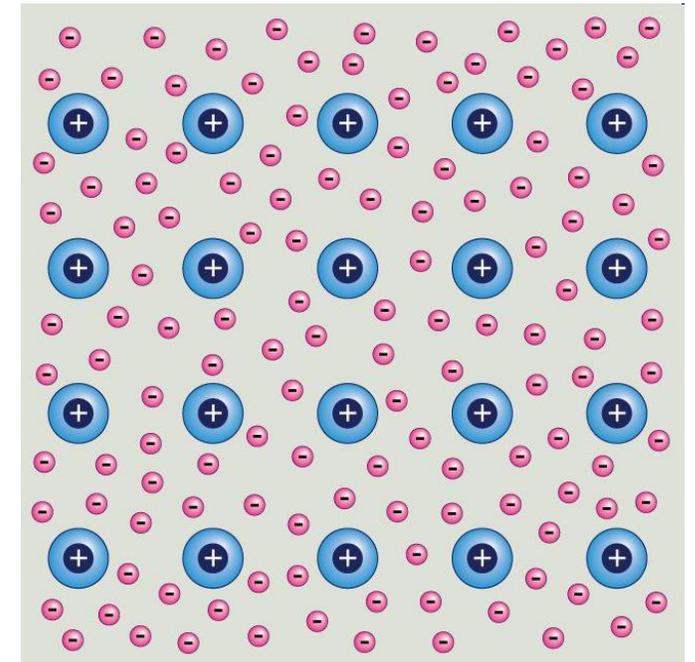
YES



Example: Na^+ (small) and Cl^- (large)
Packing: as close as possible.

Metallic Bonds

- Hold metals and alloys together
- Allows for dense packing of atoms (why metals are heavy)
- Valence electrons are not bound to a particular atom and are free to drift through the entire material = “sea of electrons”
- Nonvalence electrons + atomic nuclei = ion core (with a net + charge)
- Good electrical conductivity
- Good heat conductivity

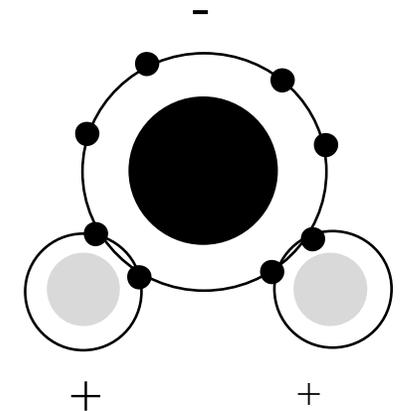


Intermolecular Forces

Bonds holding molecules together

Hydrogen bonds

- Intermolecular attraction in which a H atom bonded to a small, electronegative atom (N, O or F) is attracted to a lone pair of electrons on another N, O or F atom.
- Weak interactions
- Due to the charge distribution on molecule
- Often seen in organic compounds
- 5 to 30 kJ/mole (as compared to about 100kJ/mole for chemical bond)



Example: H₂O



Intermolecular Forces

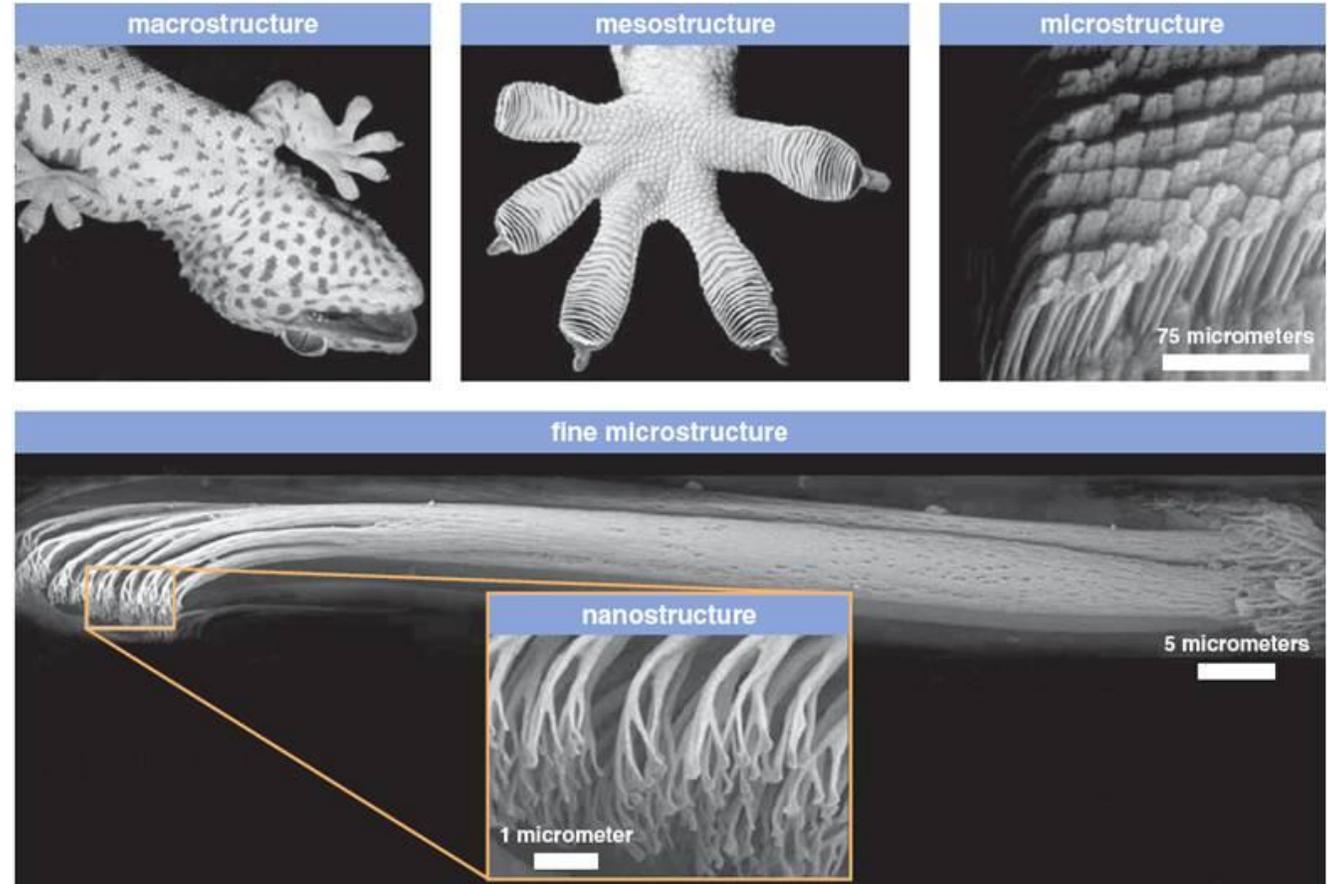
Bonds holding molecules together

Van der Waal forces:

- Short-time interactions
- Arise from surface differences across molecules
- Weaker forces (~ 10 kJ/mole)
- Gecko feet: Microscopic branched elastic hairs on toes which take advantage of these atomic scale attractive forces to grip and support heavy loads

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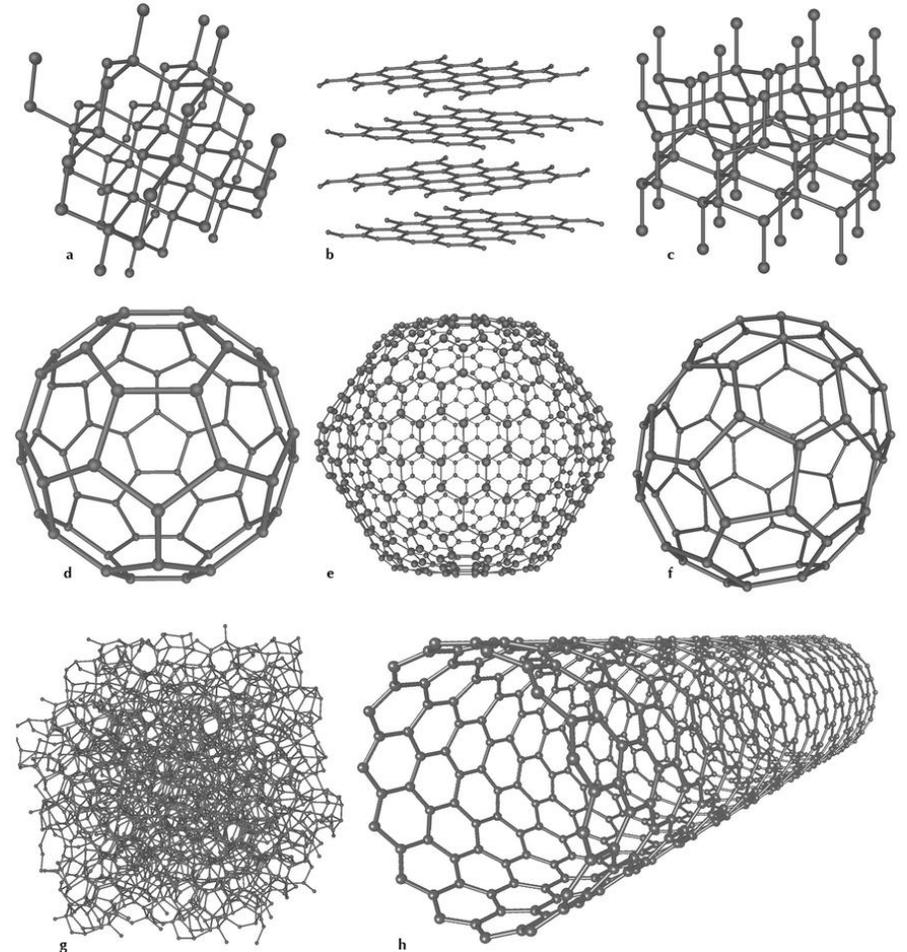


Consequences of Structure

- Structure is related to the arrangement of the components of a material
 - This could be on any length scale – atomic, nano-, micro-, macro-
 - All length scales matter
- Types of carbon (literally just carbon!)
 - a) Diamond
 - b) Graphite
 - c) Lonsdaleite
 - d) Buckminster Fullerene C₆₀
 - e) C₅₄₀
 - f) C₇₀
 - g) Amorphous carbon
 - h) Carbon Nanotube

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Spaghetti!

Take a 10 minute break

During the break take time to think about spaghetti

How does it break?

How many ways can it break?

How can it be made stronger?

Material Properties

We will determine for Spaghetti

- Young's Modulus**
- Tensile Strength**
- Yield Strength**
- Compressive Strength
- Shear Strength
- Ductility
- Poisson's Ratio
- Specific Weight
- Specific Modulus
- Hardness

Stress-Strain Curve

Mechanical Properties

How easy does spaghetti break in tension (by pulling)?

Is thicker spaghetti easier or harder to break in tension?

Theory says that force needed to break in tension increases with cross-sectional area.

How easily does spaghetti buckle in compression?

Depends on force, material strength, length and thickness of spaghetti

A longer piece buckles easier than a shorter piece

A thinner piece buckles easier than a thicker piece

How easily does spaghetti bend if you push on it perpendicularly?

Is it in tension or compression?

Deflection depends on force, material strength, span length and cross-sectional area.

A larger force yields a larger deflection

For a given force, longer pieces bend easier

For a given force, thin pieces bend easier

Terms associated with material properties

Hardness --resistance to scratching and denting.

Malleability --ability to deform under rolling or hammering without fracture.

Toughness --ability to absorb energy, e.g., a blow from a hammer. Area under stress-strain curve is a measure of toughness.

Ductility --ability to deform under tensile load without rupture; high percentage elongation and percent reduction of area indicate ductility

Brittleness --material failure with little deformation; low percent elongation and percent area reduction.

Elasticity --ability to return to original shape and size when unloaded

Plasticity --ability to deform non-elastically without rupture

Stiffness --ability to resist deformation; proportional to Young's Modulus E (psi) $E = \text{stress/strain}$ (slope of linear portion of stress/strain curve).

Stress and Strain

Stress is related to the force or load applied to a material

Stress = σ = Force/original area

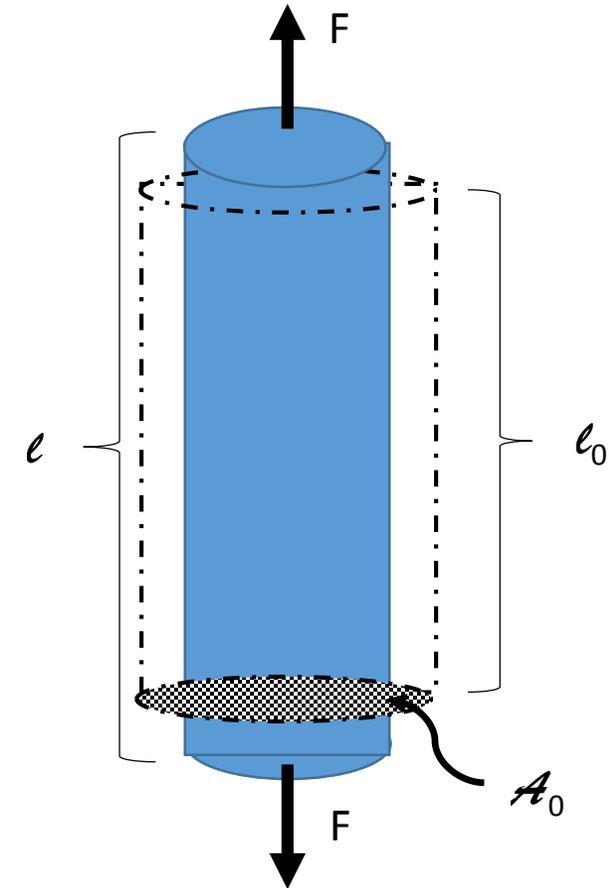
From Figure: $\sigma = F/A_0$

Force - units? Newton = $\text{kg}\cdot\text{m}/\text{s}^2$

$\sigma = F/A_0 \rightarrow$ units = N/m^2 = Pascal

MPa = 10^6 Pa

GPa = 10^9 Pa



Stress and Strain

Strain

Strain = ϵ = change in length divided by original length

From Figure: $\epsilon = \Delta l / l_0$

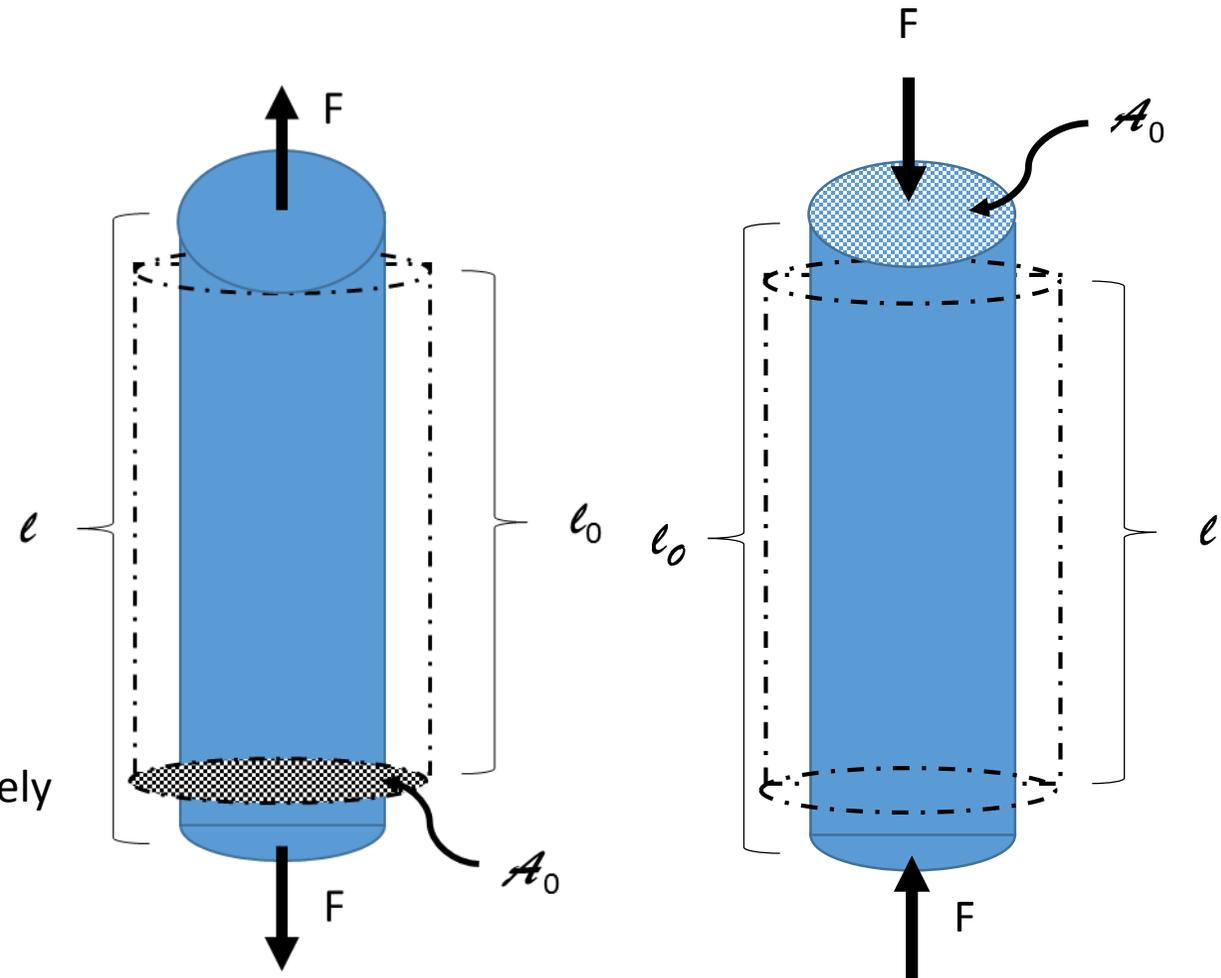
Units? Strain is unitless
May be reported as:
m/m, in/in or %

Elastic Strain vs. Plastic Strain

(Rubber Band vs. Silly Putty)

Elastic--loading and unloading returns material to original length--can be done repeatedly, e.g., a watch spring.

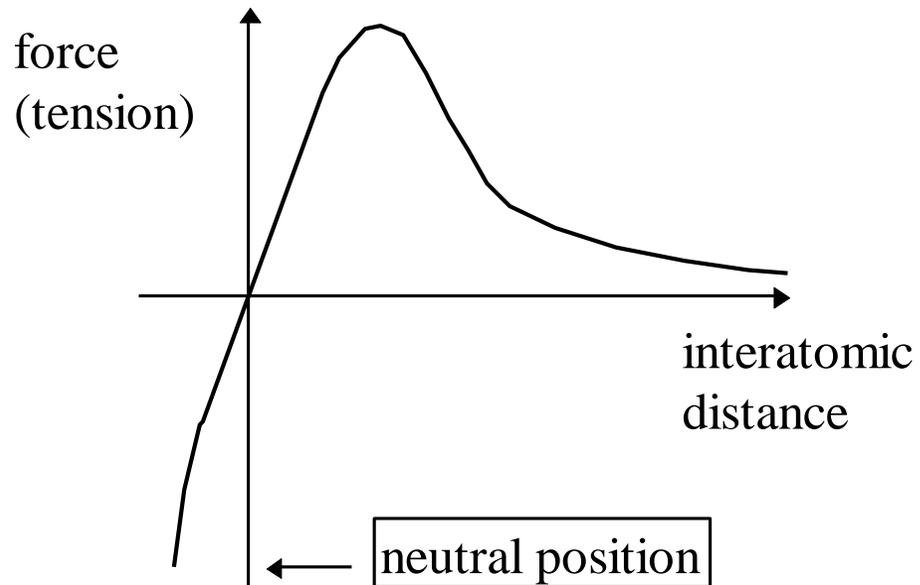
Plastic--larger deformations are not reversible when "elastic limit" is exceeded. Some materials are almost purely plastic, e.g., putty.



Hooke's Law

Robert Hooke, 1679 “As the extension, so the force”
i.e., stress is proportional to strain

Hooke's Law: an approximation of the relationship between the deformation of molecules and interatomic forces.



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Hooke's Law

Hooke's Law of Spring Extension

$$F = k * x$$

Hooke's Law applied to Linear Elastic Solids

$$\sigma = E * \epsilon$$

Young's Modulus

- The ratio of stress to strain within the linear (elastic) region of the stress-strain curve
- A measure of the “stiffness” of a material
- Also known as the Modulus of Elasticity
- Units are the same as the units of stress (F/A)

$$E = \sigma / \epsilon$$



Thomas Young (1773 – 1829)

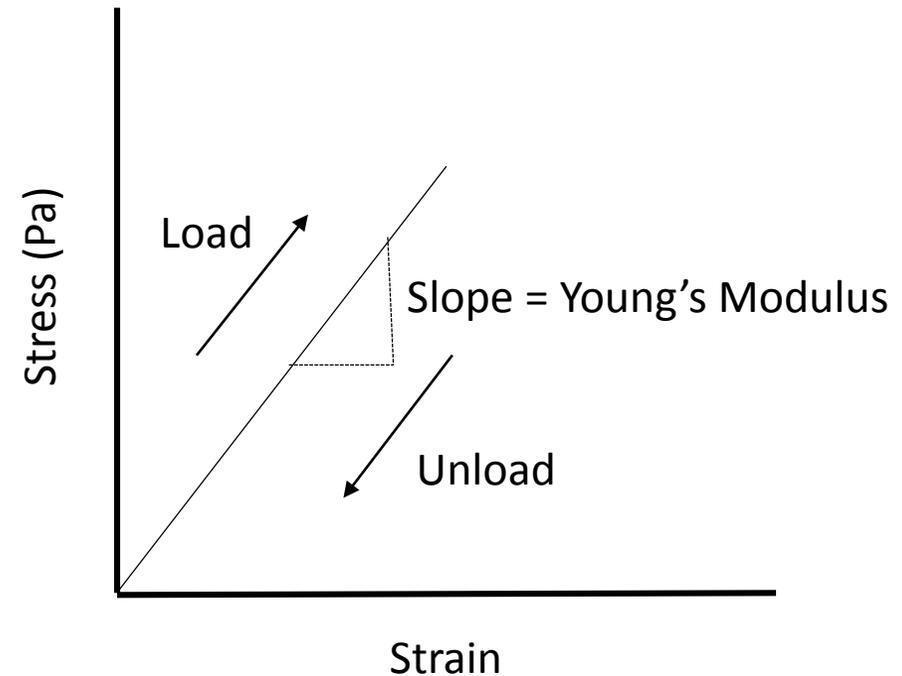
Elastic solids – Young’s Modulus

Think of E as the stress required to deform a solid by 100%. (Most solids will fail at an extension of about 1%, so this is usually hypothetical).

Range of E in materials is enormous:

E (metal)	45-400 GPa
E (Ceramics)	60-500 GPa
E (Polymers)	0.01-4 GPa
E (Spaghetti)	4.8 GPa

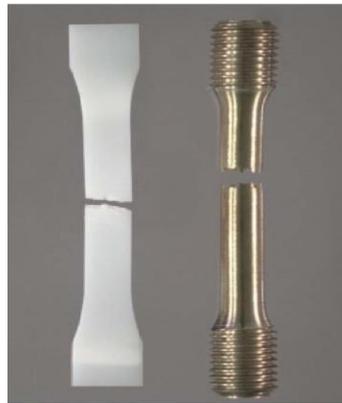
Higher E implies? Greater Stiffness



Material testing – Tensile Strength

Usually tested by controlling extension (strain) and measuring resulting load (stress*area), i.e., independent variable is strain, dependent variable is stress

Can also be determined by subjecting material to a predetermined load and measuring elongation, i.e., independent variable is stress, dependent variable is strain



Tensile Test Specimens



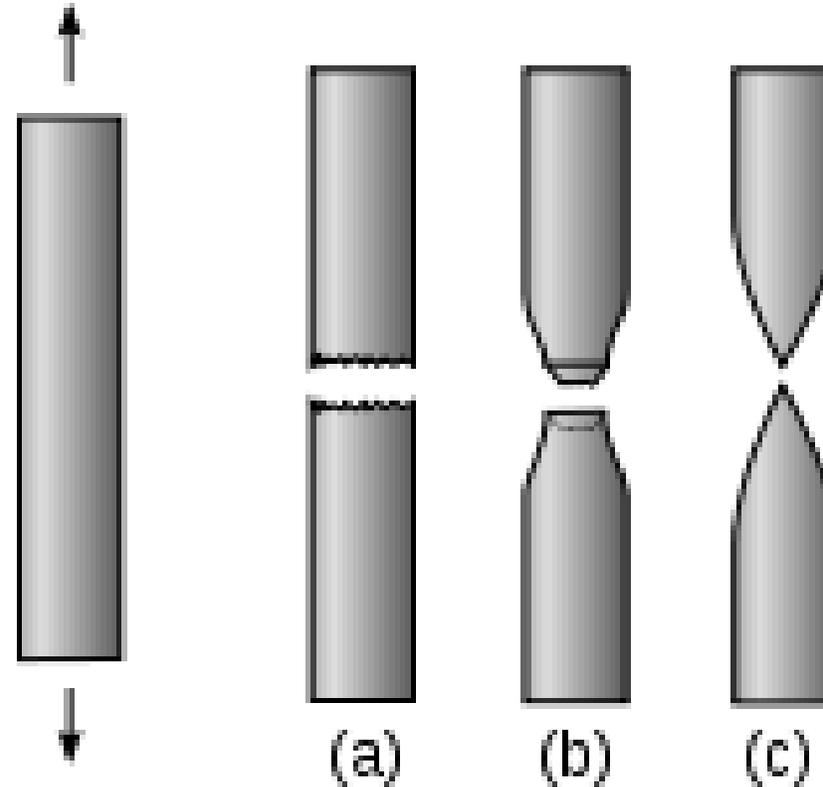
Solid Behavior - Tension

After tensile testing:

- a) Brittle
- b) Ductile
- c) Completely Ductile

Examples:

- a) Cast Iron
- b) Aluminum
- c) Putty*



Stress-Strain Curves

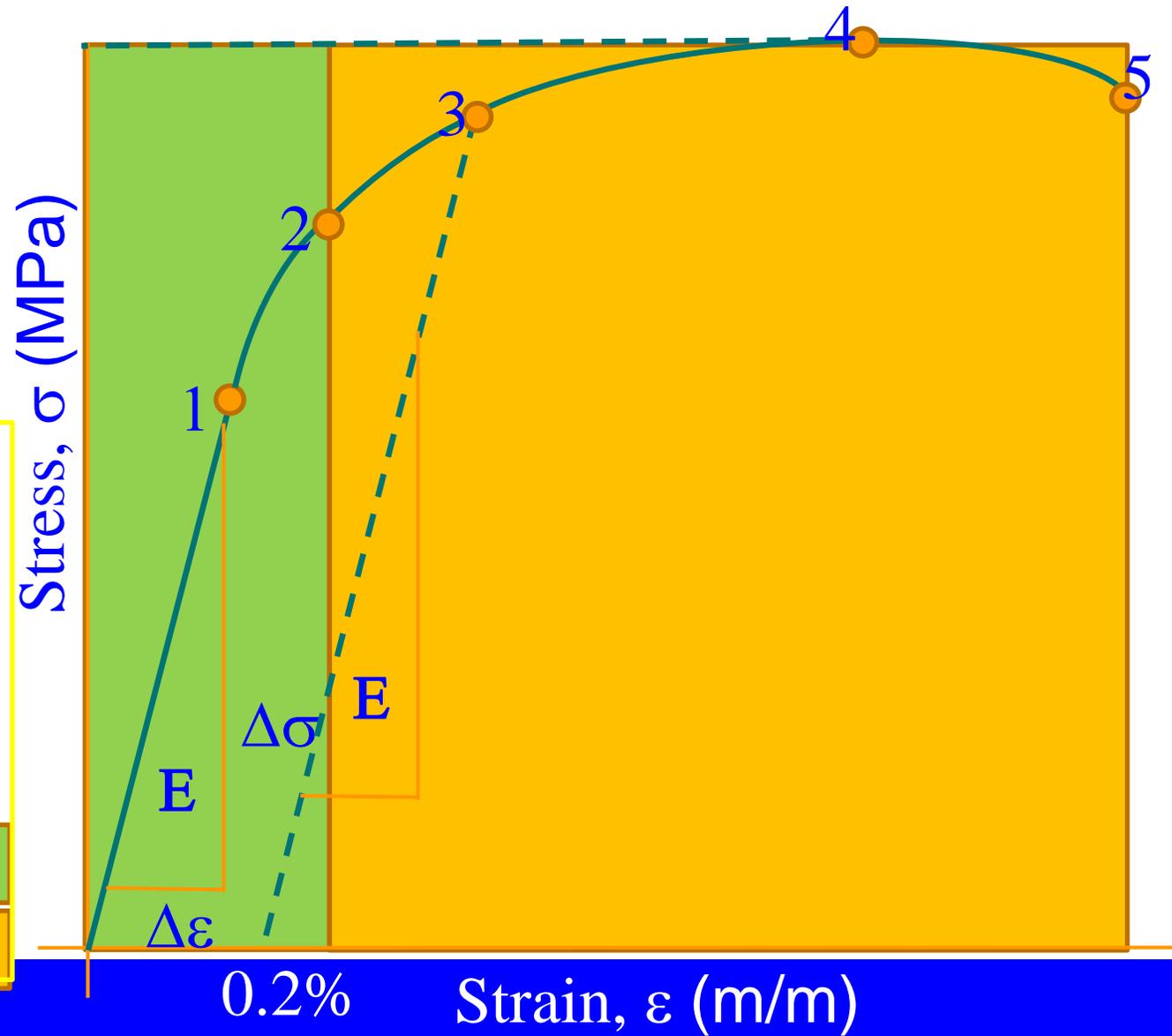


Tensile Test

1. Proportionality Limit
 2. Elastic Limit
 3. Yield Strength
 4. Ultimate Tensile Strength
 5. Fracture Strength
- E = Young's Modulus,
Modulus of Elasticity

Elastic Region

Plastic Region



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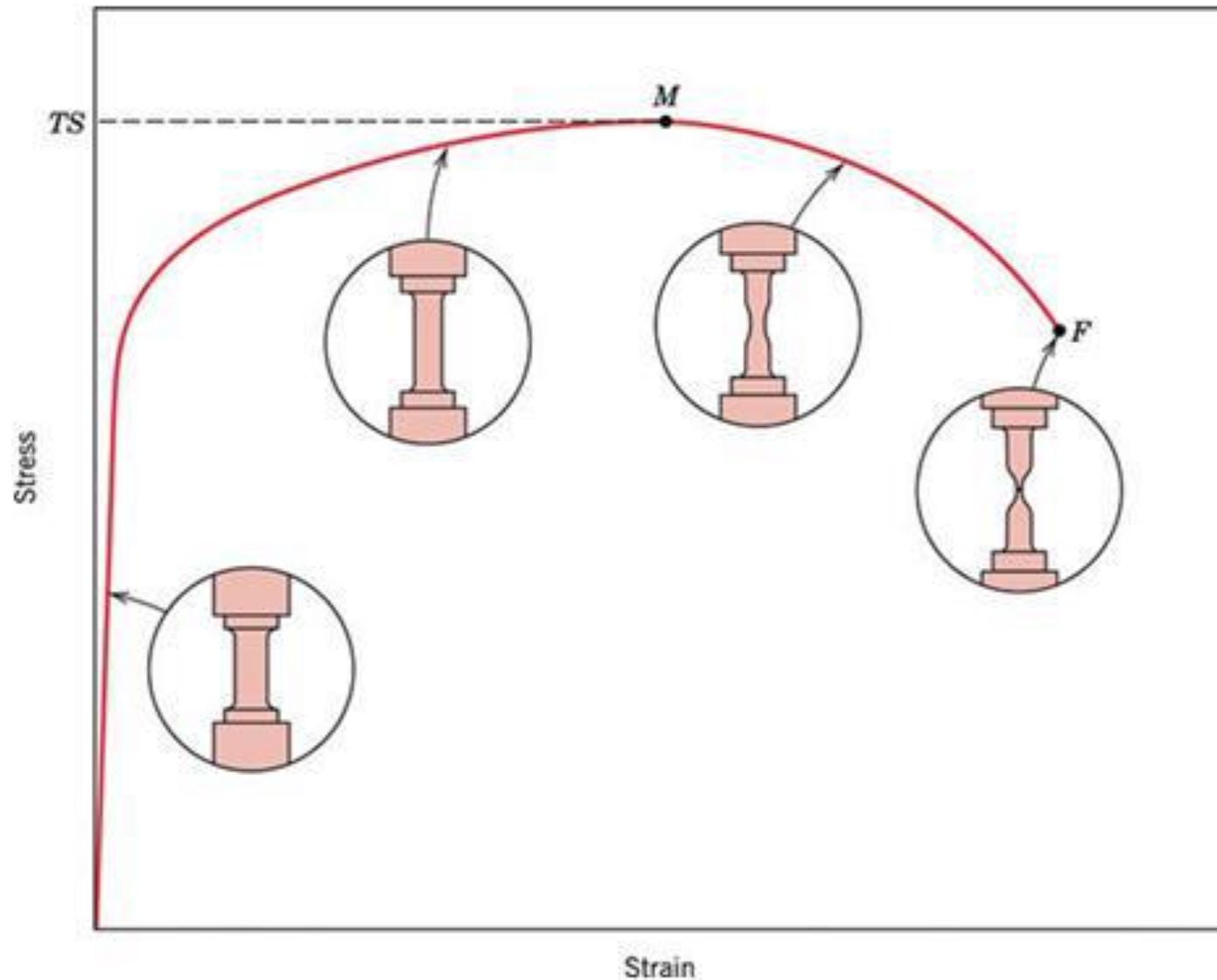
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Range of Tensile Strengths (TS) - How hard a pull is required to break material bonds?

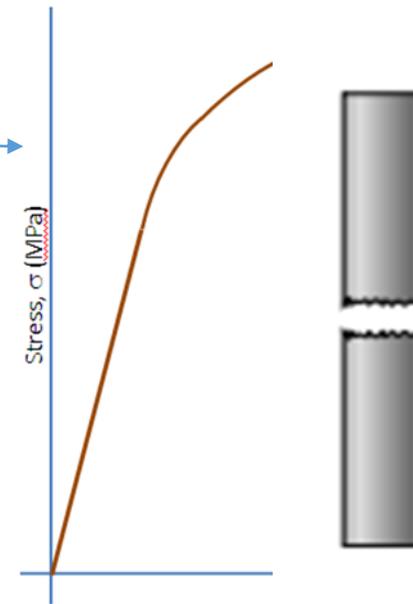
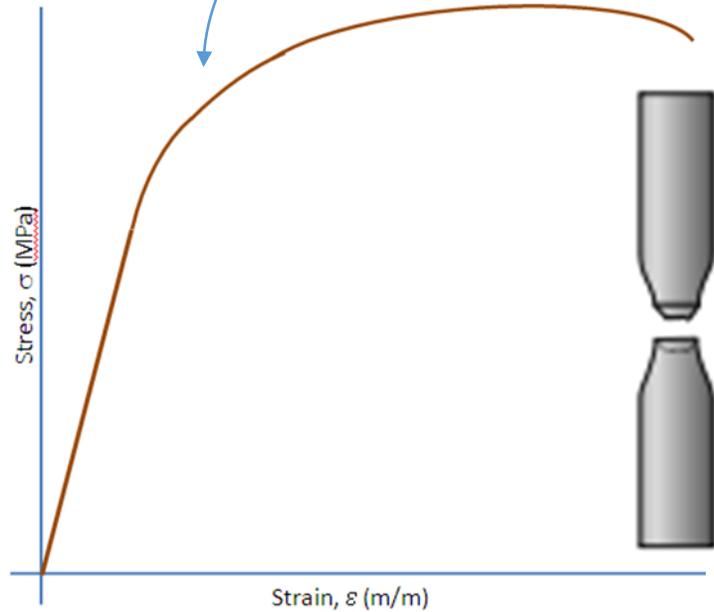
steel piano wire = 450,000 p.s.i.

aluminum = 10,000 p.s.i.

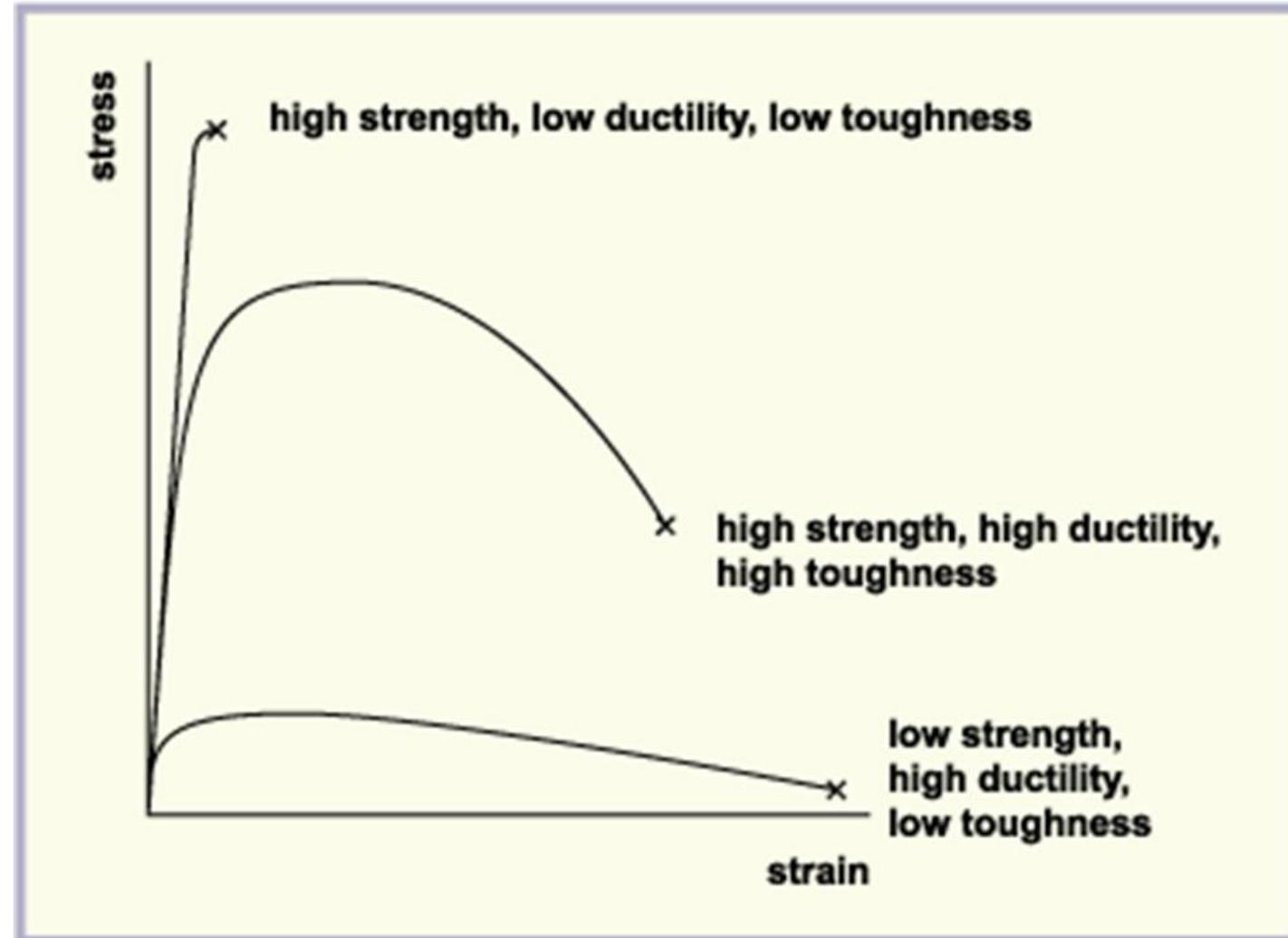
concrete = 600 p.s.i.



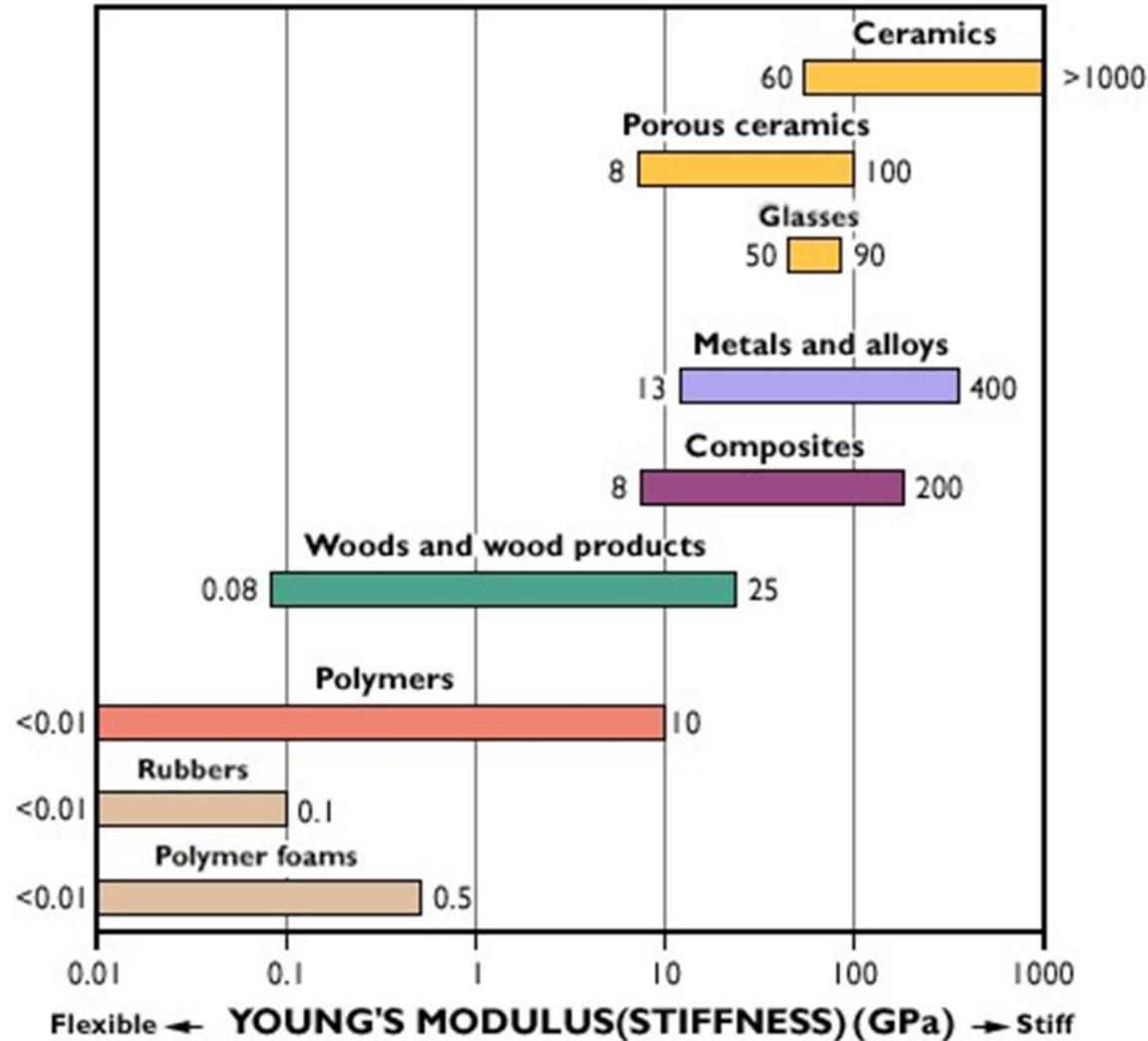
Which curve is typical of:
A ductile material
A brittle material



Stress – Strain Curves



Young's Modulus



Material Strength - Compression

Materials fail in compression in many ways depending on their geometry and support

- a) buckling--hollow cylinders, e.g., tin can
- b) bending--long rod or panel
- c) shattering--heavily loaded glass

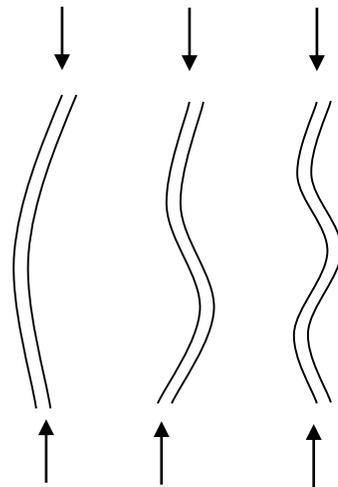
No relation between compressive and tensile strength in part because distinction between a material and a structure is often not clear. e.g., what is a brick? or concrete?

Compressive strength of material

Under compression a beam will fail either by crushing or buckling, depending on the material and L/d ; e.g., wood will crush if $L/d < 10$ and will buckle if $L/d > 10$ (approximately).

Crushing: atomic bonds begin to fail, inducing increased local stresses, which cause more bonds to fail.

Buckling: complicated, because there are many modes

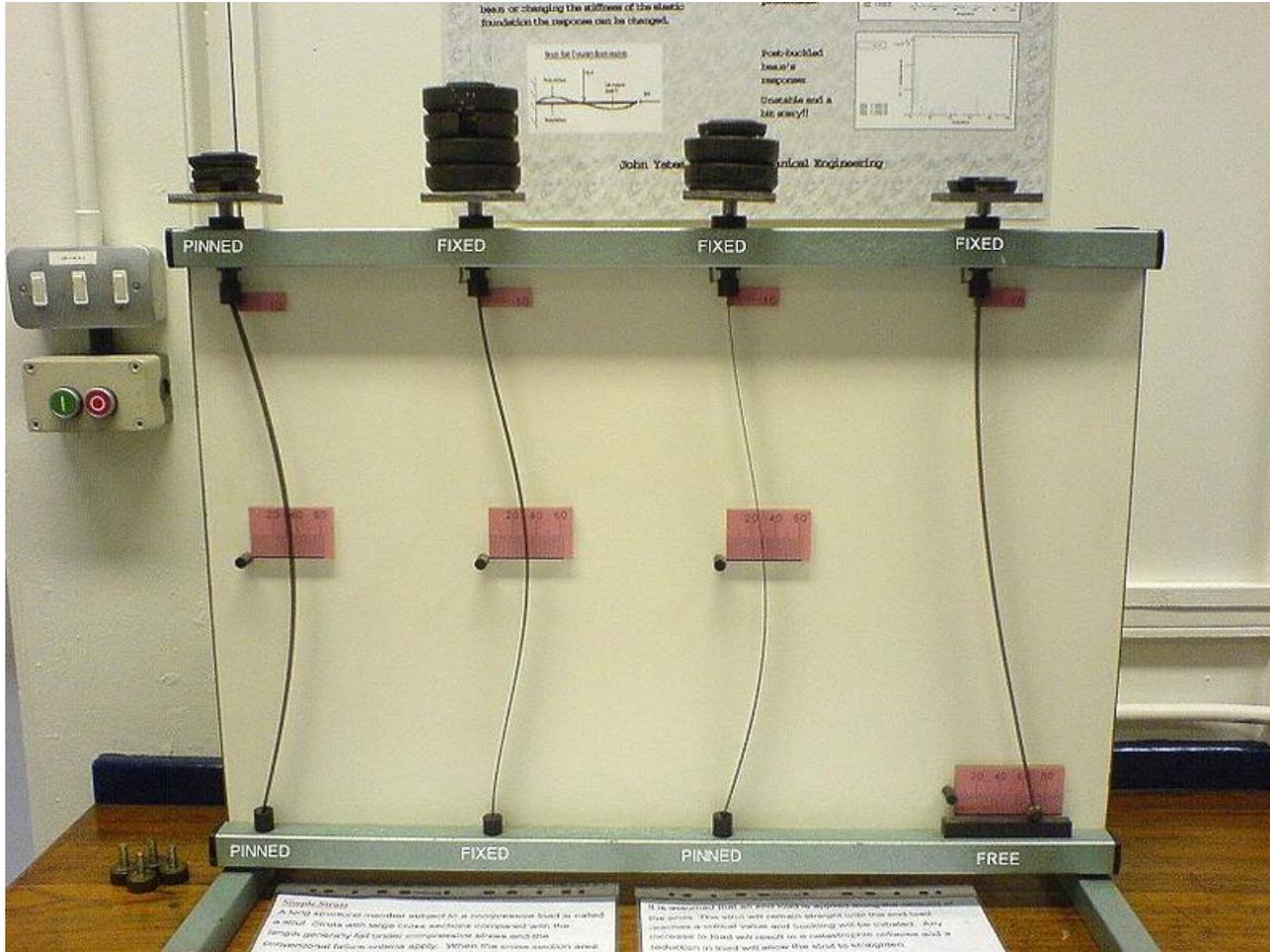


1st, 2nd, and 3rd order
bending modes. Lowest
order is most likely
to occur.

Euler buckling

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How the specimen ends are supported must be considered.

Material testing - Euler buckling load, P_c

P_c	load (MLT^{-2})
I	moment of inertia (L^4)
E	Young's modulus ($ML^{-1}T^2$)
L	length (L)

We have 4 variables, 3 primitive dimensions = 1 dimensionless group

$$0 = P^a I^b E^c L^d = (MLT^{-2})^a L^{4b} (ML^{-1}T^{-2})^c L^d$$

$$M: a + c = 0$$

$$L: a + 4b - c + d = 0$$

$$T: -2a - 2c = 0$$

Begin with $a = 1, b = -1 \Rightarrow c = -1, d = 2$; get $\pi_1 = \frac{PL^2}{EI}$, or $P \propto \frac{EI}{L^2}$.

For a cylindrical rod, Euler buckling load $P = P_c \propto \frac{Er^4}{L^2}$.

(This equation can be deduced from the beam deflection equation which determines deflection y

at a position x from one end in terms of load P : $EI \frac{d^2 y}{dx^2} = -P_c y$)

Euler buckling load

The force at which a slender column under compression will fail by bending

$$F = \frac{\pi^2 EI}{(KL)^2}$$

E = Young's modulus

I = area moment of inertia

L = unsupported length

$K = 1.0$ (pinned at both ends)

= 0.699 (fixed at one end, pinned at the other)

= 0.5 (fixed at both ends)

= 2.0 (free at one end, pinned at the other)

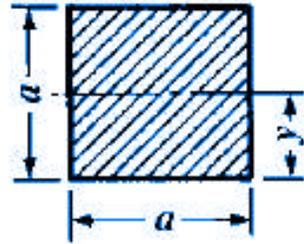
Area moment of inertia

I = *area* moment of inertia (dim L^4)—associated with the bending of beams.
Sometimes called second moment of area.

Not to be confused with

I = *mass* moment of inertia (dim ML^2) — associated with the energy of rotation)

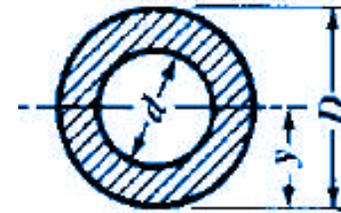
Some area moments of inertia



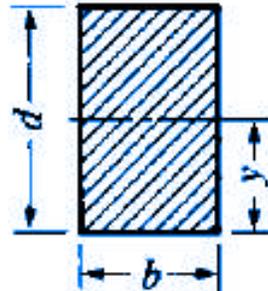
$$I = \frac{a^4}{12}$$



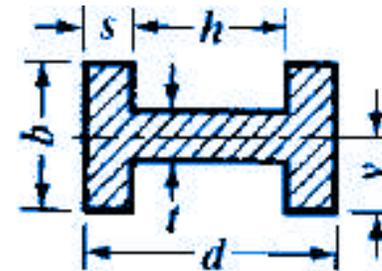
$$I = \frac{\pi d^4}{64}$$



$$I = \frac{\pi(D^4 - d^4)}{64}$$

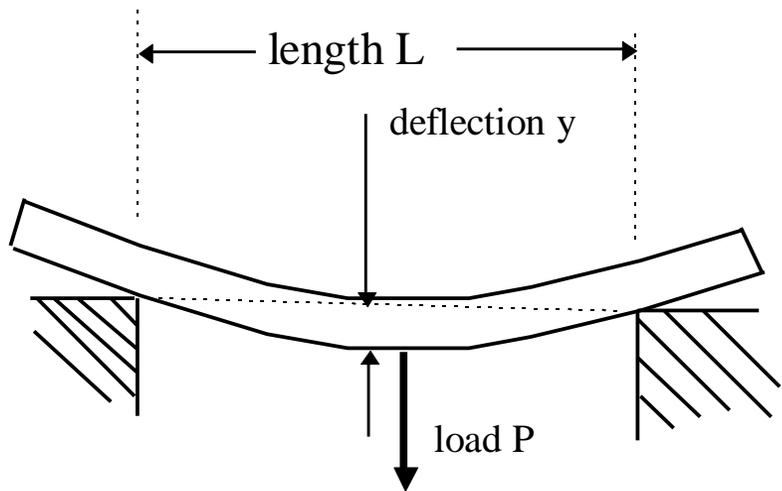


$$I = \frac{bd^3}{12}$$

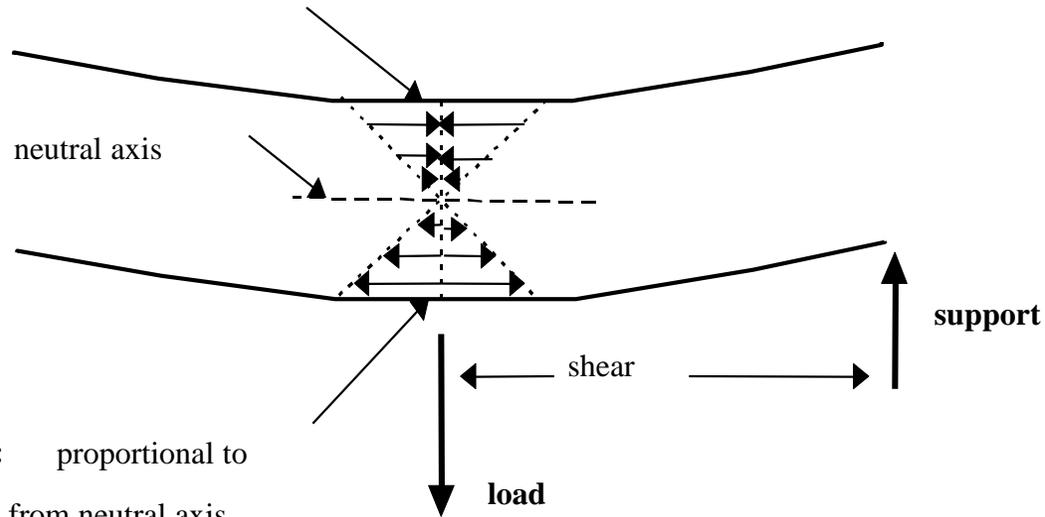


$$I = \frac{2sb^3 + ht^3}{12}$$

Material Strength - Bending



compression: proportional to distance from neutral axis

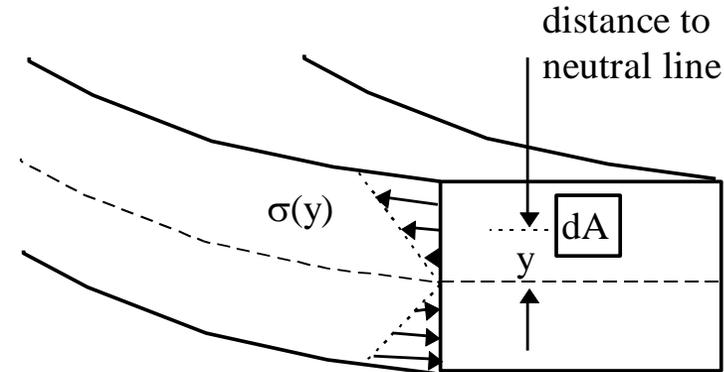


tension: proportional to distance from neutral axis

Restoring moment = (moment arm about neutral line) x (force) =

$$\sum y \sigma(y) dA$$

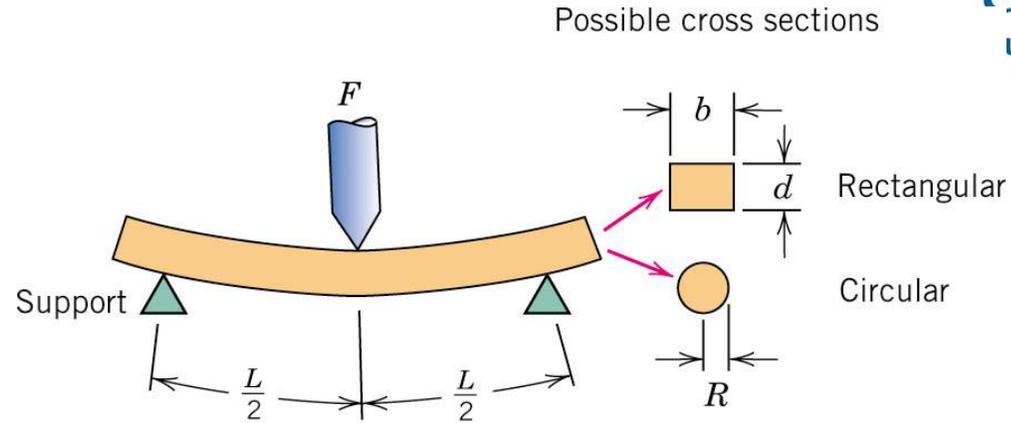
But, σ is proportional to strain ϵ , and strain varies linearly with distance to the neutral line. Therefore, $\sigma = y \sigma_{\max}$, where σ_{\max} is the stress at the maximum distance from the neutral line. So, Restoring moment = $\sigma_{\max} \sum y^2 dA = \sigma_{\max} I$



where I is the area moment of inertia of the cross section of the beam about the neutral axis.

Moment of inertia depends on cross-section geometry and has units L^4 .

Material testing - bending



$$\sigma = \text{stress} = \frac{Mc}{I}$$

where M = maximum bending moment

c = distance from center of specimen to outer fibers

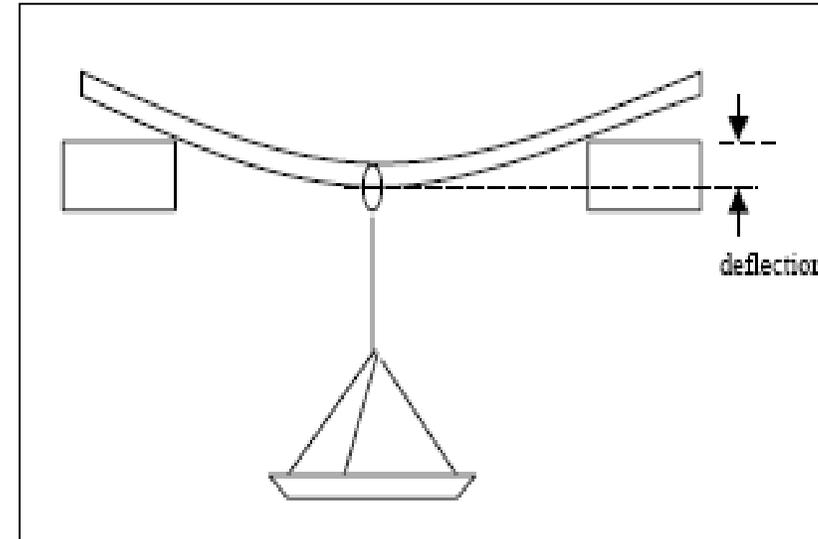
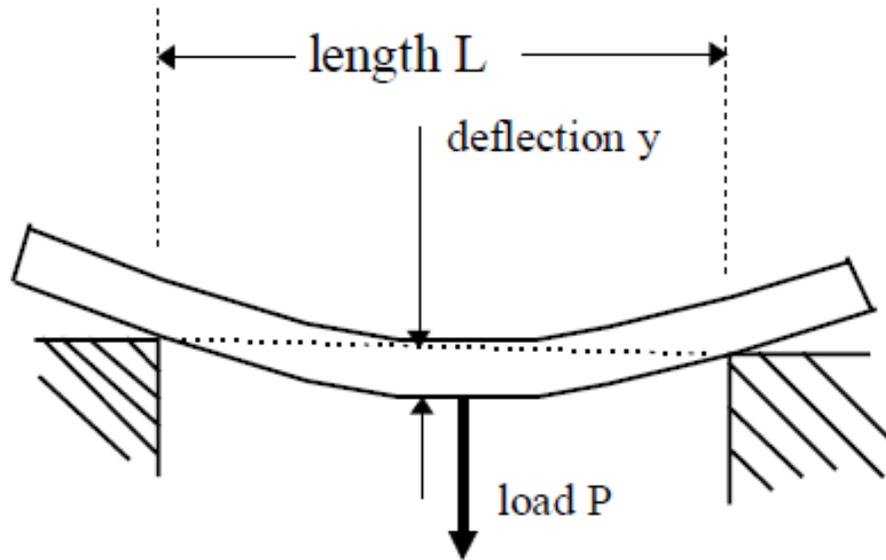
I = moment of inertia of cross section

F = applied load

	$\frac{M}{FL}$	$\frac{c}{d}$	$\frac{I}{bd^3}$	$\frac{\sigma}{FL}$
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

[3-point Bend Test](#)

- Bending Test – Setup



Materials good in compression

stone, concrete

Materials good in tension

carbon fiber, cotton, fiberglass

Materials good in both compression and tension

steel, wood

Other strengths

Shear strength--rotating axles fail because their shear strengths were exceeded

Ultimate tensile strength--maximum possible load without failure

Yield strength--load required to cross line from elastic to plastic deformation

NEXT: How do we put materials together to form structures. . .?

Beams and loads--tension:



Failure occurs when ultimate tensile strength is exceeded.

Maximum load is tensile strength times cross-sectional area.

$$L_{\max} = T * A_{cs}$$

For regular spaghetti (diameter = 2mm), maximum load is ~ 10 pounds.

Load capacity does not depend on length.

Beams and loads--compression:



Beam in compression

Failure occurs two ways:

- 1) When $L/d < 10$, failure is by crushing
- 2) When $L/d > 10$, failure is by buckling

We are almost always concerned with failure by buckling.

Beams and loads--compressive buckling:

Buckling strength $F = k * d^4/L^2$

To determine constant of proportionality k:

- 1) Measure length and diameter of a piece of spaghetti
- 2) Hold spaghetti vertically on postal scale
- 3) Press down on spaghetti until it begins to bend
- 4) Read load F on postal scale
- 5) Calculate k

Some consequences of buckling properties:

If a beam of length L and diameter d can support a compressive load of F ,



then a beam of length $L/2$ and diameter d can support a compressive load of

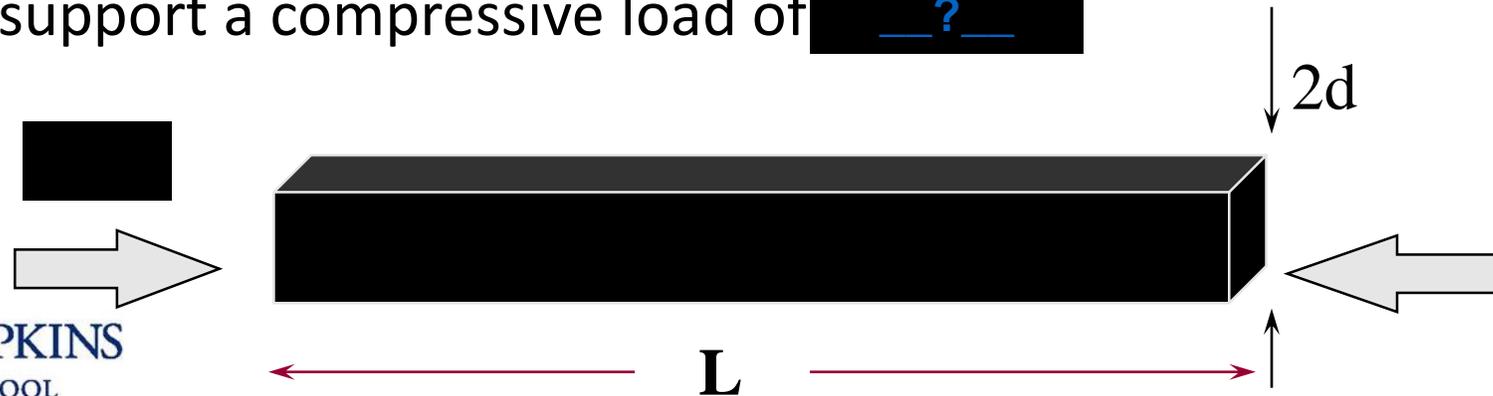


ALSO...

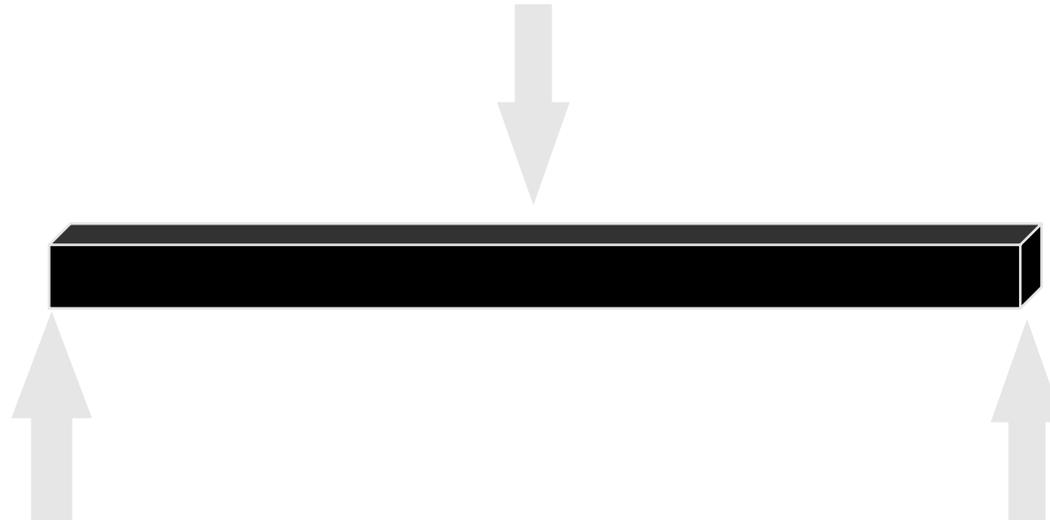
If a beam of length L and diameter d can support a compressive load of F ,



then a beam of length L and diameter $2d$ can support a compressive load of **___?___**



Beams and loads--bending:



Very little strength. Never design a structure that relies on bending strength to support a load.