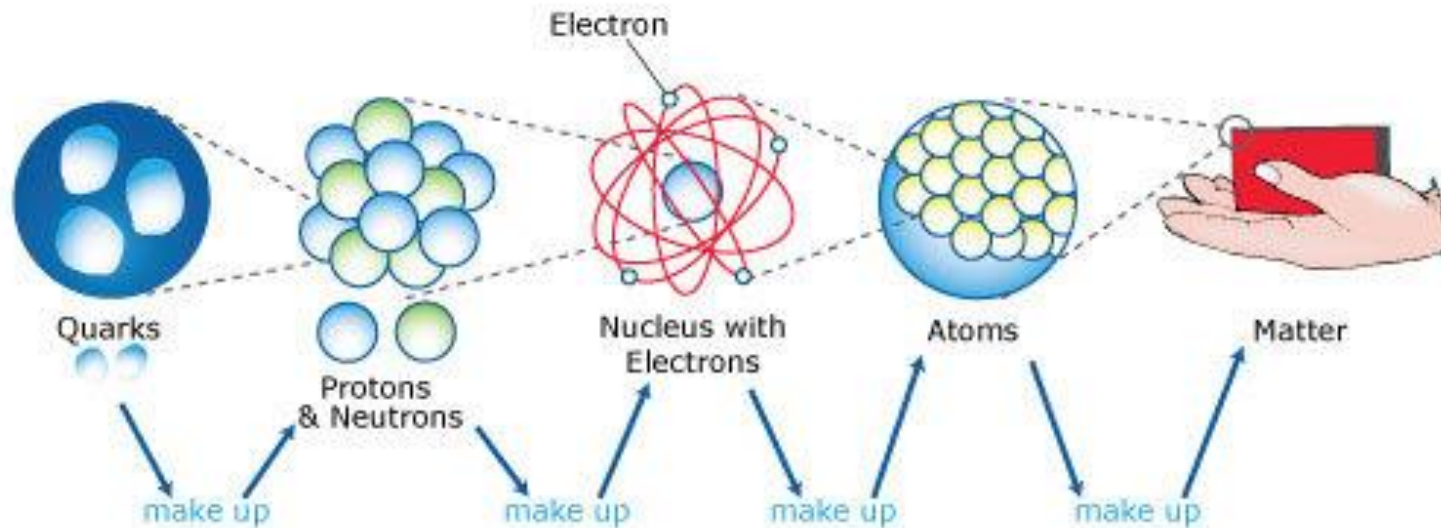


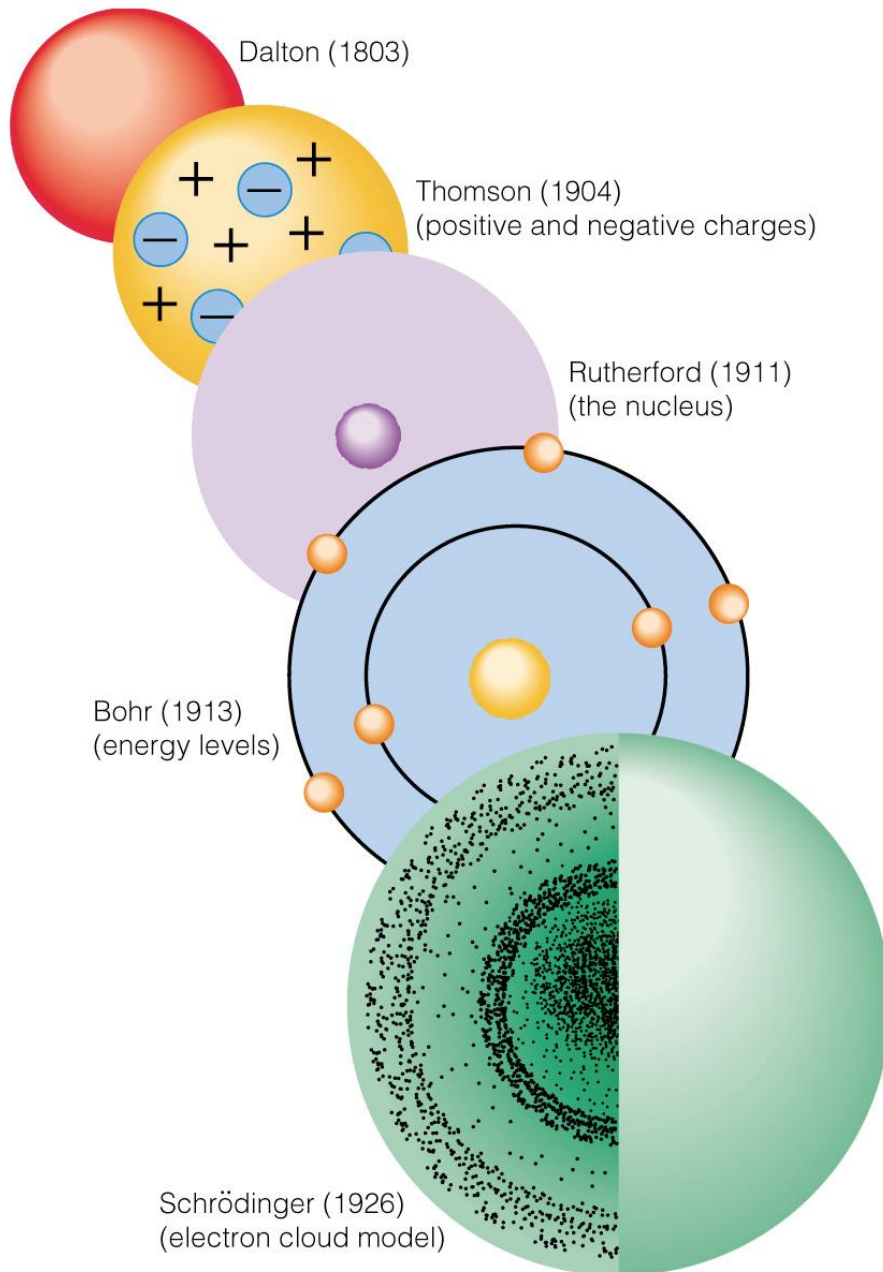
THE NATURE OF MATTER AND MATERIALS

Structure of matter flow diagram

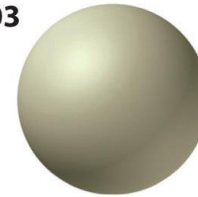


<https://www.sciencelearn.org.nz/images/2151-structure-of-matter-flow-diagram>

5 Models of the Atom

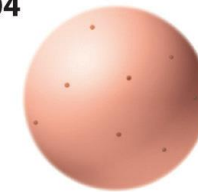


1803



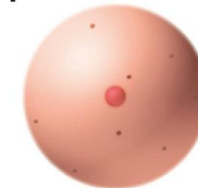
Dalton proposes the indivisible unit of an element is the atom.

1904



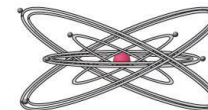
Thomson discovers electrons, believed to reside within a sphere of uniform positive charge (the plum pudding model).

1911



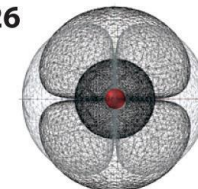
Rutherford demonstrates the existence of a positively charged nucleus that contains nearly all the mass of an atom.

1913



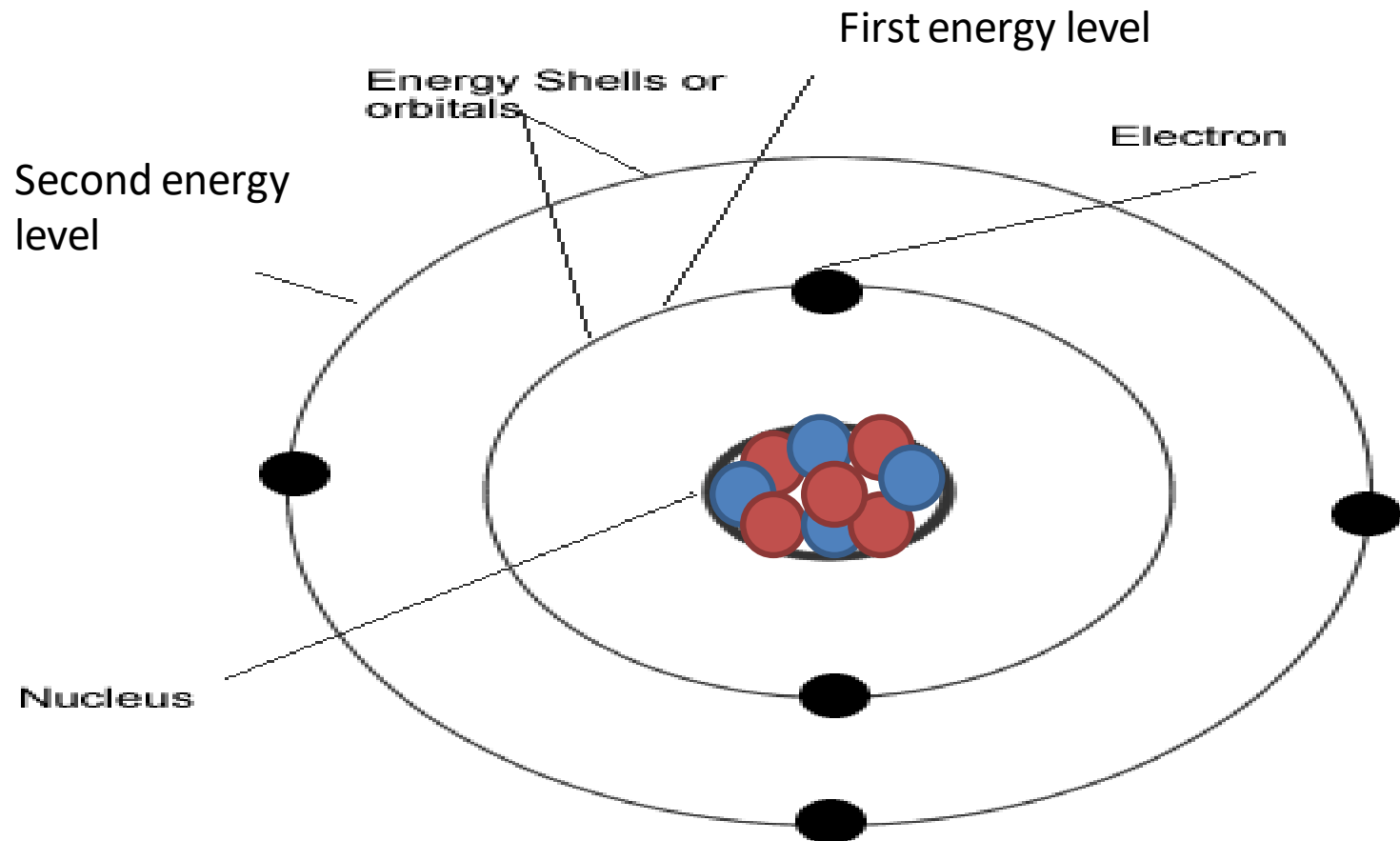
Bohr proposes fixed circular orbits around the nucleus for electrons.

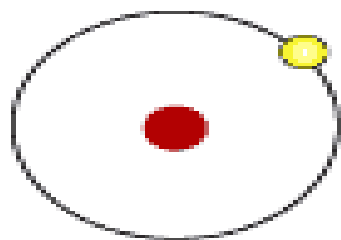
1926



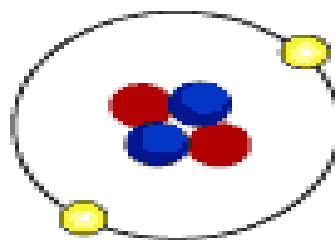
In the current model of the atom, electrons occupy regions of space (orbitals) around the nucleus determined by their energies.

- Bohr Atom Model is known as the "planetary model" of the atom that is used as a symbol for atomic energy levels.
- The neutrons and protons are in the nucleus, and the electrons orbit the nucleus much like planets orbiting the Sun.

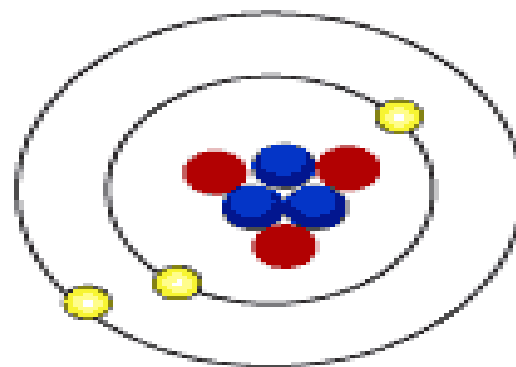




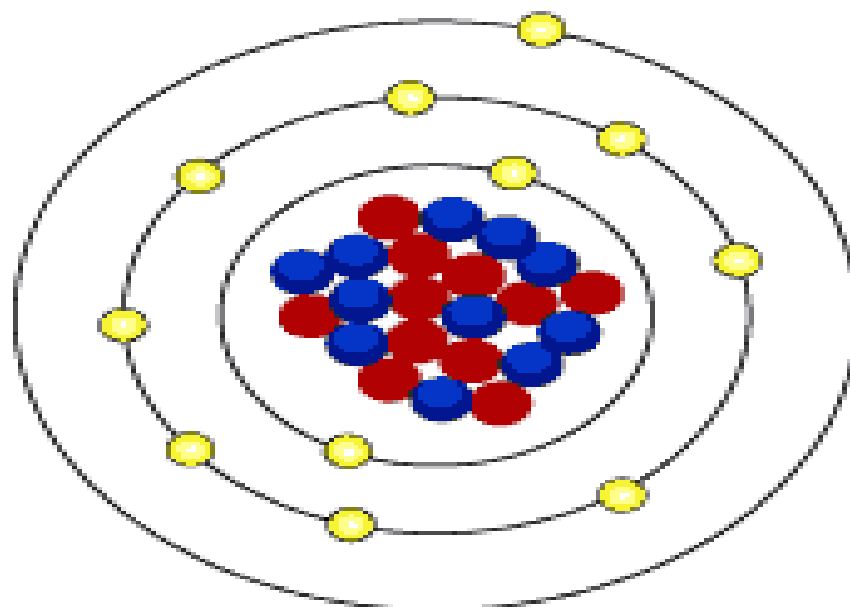
Hydrogen-1



Helium-4



Lithium-6



Sodium-22



Neutron



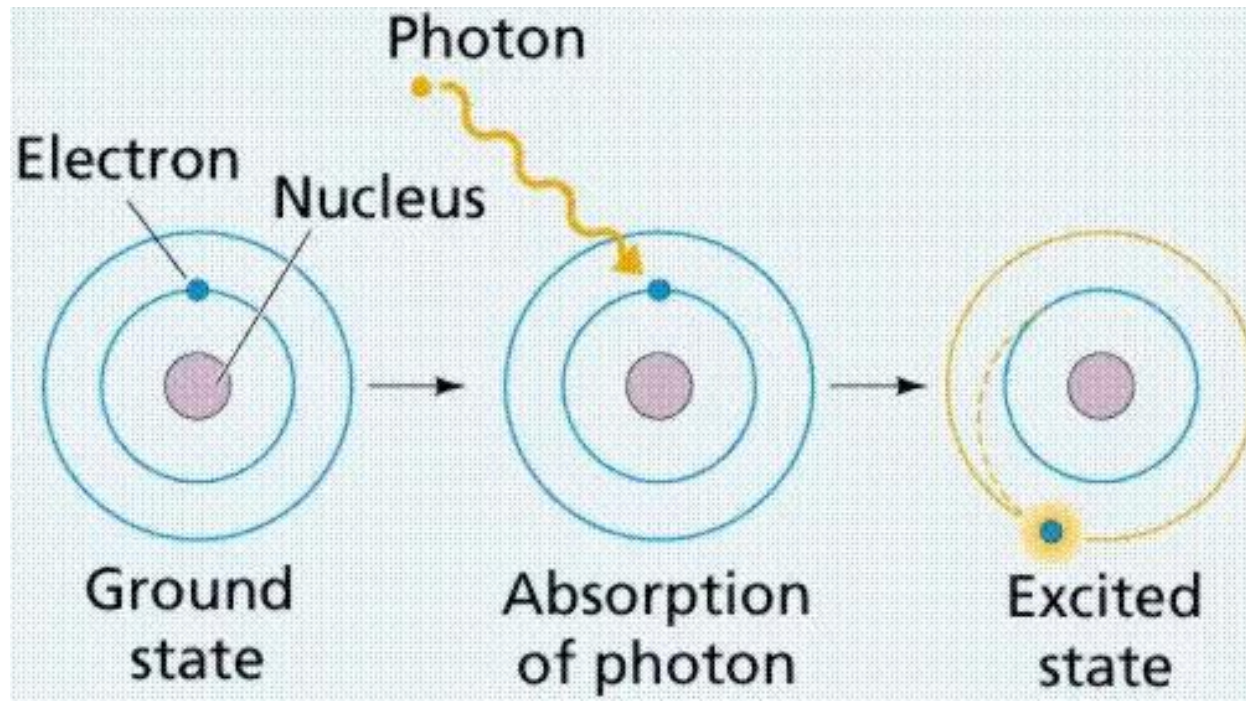
Proton



Electron

- **Principles of the Bohr Model**

1. Electrons assume only certain orbits around the nucleus. These orbits are stable.
2. Each orbit has an energy associated with it. For example the orbit closest to the nucleus has an energy E_1 , the next closest E_2 and so on.
3. Light is emitted when an electron jumps from a higher orbit to a lower orbit and absorbed when it jumps from a lower to higher orbit.



What holds atoms and molecules together to make a strong nylon fiber or a cell membrane or a hard, brittle hydroxyapatite ceramic, or a sheet of gold, or a drop of water?

Isaac Newton was pondering this issue: “ There are agents in nature able to make the particles of bodies stick together by very strong attractions ” (18th century).

- The key to understanding matter is to understand attractive and interactive forces between atoms.
- For example;
 - Argon is a gas at room temperature due to the very weak interaction of an argon atom with another argon atom (weak attraction) → **so at room temperature** thermal fluctuations that randomly propel the atoms exceed attractive forces that might result in the coalescence to a solid material.
 - When It is cooled to extremely low temperatures, Ar gas transforms into liquid form.
 - A titanium atom strongly interacts with another titanium atom. Extremely high temperatures are required to vaporize titanium and liberate those atoms from each other.

➤ Four attractive forces in universe:

❑ **Gravitational force:** Gravity holds us to the surface of the planet Earth.

- For example; but the gravitational potential energy of two argon atoms is only about 10^{-52} J, 30 orders of magnitude weaker than is observed for intermolecular forces.

❑ **Weak and strong nuclear force:** The weak nuclear force and the strong nuclear force are only significant over 10^{-4} nm – but molecular dimensions are 5×10^{-1} nm. So these forces do not explain what holds atoms together.

- The force that binds together protons and neutrons inside the nucleus is called the **Nuclear Force**.
- It does not depend on charge
- It is very short range
- It is much stronger than the electric force

- **Electromagnetic force:** Electromagnetic forces rely on the principle of positive charge attracts negative charge.
- Electromagnetic forces have appropriate magnitudes and distance dependencies to justify why atoms interact.
 - Interactions can be weak, leading to liquids, or stronger, leading to solids.
 - The types of interactions usually observed between atoms (all explained by electrostatics) are summarized in Table I.1.2.1.

TABLE I.1.2.1 Forces that Hold Atoms Together

Interatomic Force	Explanation	Relative Strength	Examples
Van der Waals interactions	Transient fluctuations in the spatial localization of electron clouds surrounding atoms lead to transient positive and negative charges, and consequent interactive forces in molecules would seem to have no permanent polarity	Weak	Argon at cryogenic temperatures. Polyethylene (the forces that hold the chains together to make a solid)
Ionic	Atoms with a permanent positive (+) charge attract atoms with a permanent negative (−) charge	Very strong	NaCl CaCl ₂
Hydrogen (H) bonding	The interaction of a covalently bound hydrogen with an electronegative atom, such as oxygen or fluorine	Medium	Water ice Nylon (the forces that hold the chains together to make a strong, high-melting point solid)
Metallic	The attractive force between a "sea" of positively charged atoms and delocalized electrons	Medium-strong	Gold Titanium metal
Covalent	A sharing of electrons between two atoms	Strong	The carbon–carbon bond Cross-links in a polyacrylamide hydrogel



FIGURE I.1.2.1 (A) Consider the electron clouds (charge density in space) of two atoms or molecules, both without permanent dipole moments. (B) Electron clouds are continuously in motion and can shift to one side of the atom or molecule; therefore, at any moment, the atoms or molecules can create a “fluctuating instantaneous dipole.” (C) The “fluctuating instantaneous dipole” in one molecule electrostatically induces such an “instantaneous dipole” in the next molecule.

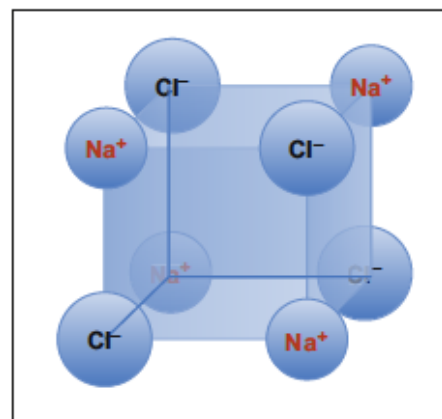


FIGURE I.1.2.2 The unit cell of a sodium chloride crystal illustrating the plus-minus electrostatic interactions.

TABLE I.1.2.1 Forces that Hold Atoms Together

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Covalent	A sharing of electrons between two atoms	Strong	The carbon–carbon bond Cross-links in a polyacrylamide hydrogel

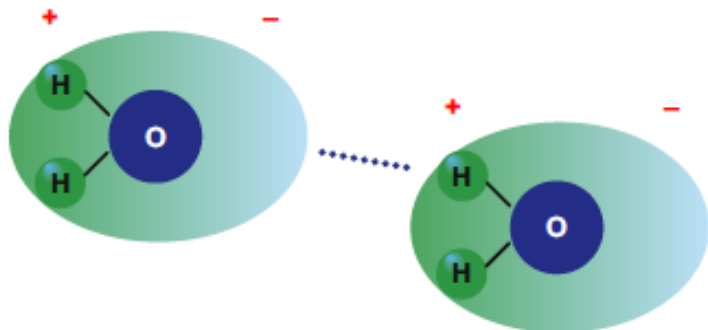


FIGURE I.1.2.3 A hydrogen bond between two water molecules.



FIGURE I.1.2.4 Metallic bonding in magnesium. The 12 electrons from each Mg atom are shared among positively charged nuclear cores (the single + charge on each magnesium atom in the figure is simply intended to indicate there is some degree of positive charge on each magnesium nuclear core).

TABLE I.1.2.1 Forces that Hold Atoms Together

Interatomic Force	Explanation	Relative Strength	Examples
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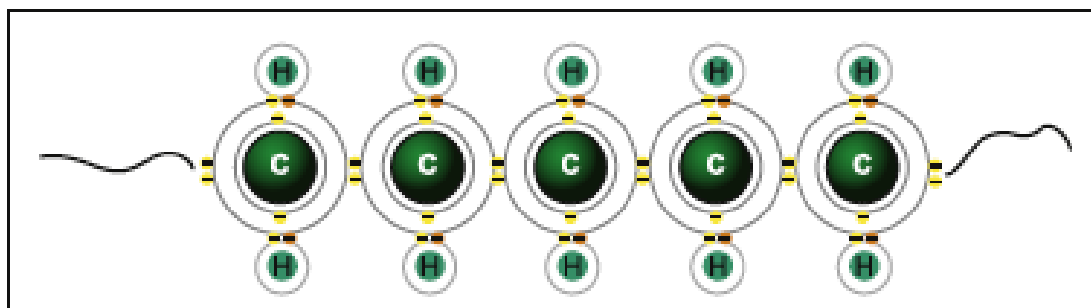
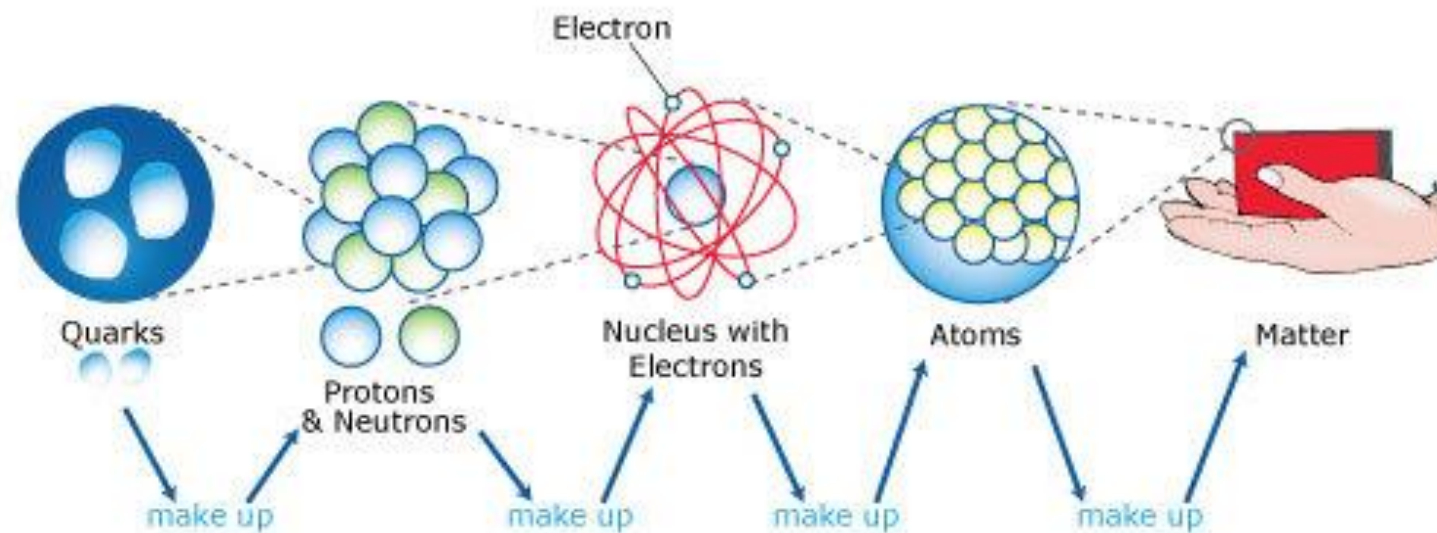


FIGURE I.1.2.5 Covalent bonding along a section of polyethylene chain. Carbons share pairs of electrons with each other, and each hydrogen shares an electron pair with carbon.

➤ Hierarchical structures of material:

- The smallest size scale in materials is atoms (about 0.2 nm, in diameter)
- Atoms combine to form molecules (1 - 100 nm).
- Molecules may assemble or order to form supramolecular structures with dimensions up to 1000 nm or more.
- Supramolecular structures may organize in bundles, fibers or larger assemblies with dimensions reaching into the range visible to the human eye.



Ex: Collagen Fibers

- Collagen fibers make up many structures in the body, for example: tendons
- Tendons are comprised of collagen fibrils, formed of aligned bundles of collagen triple helices that are themselves made up of single collagen protein chains (α - chains)
- α - chains are constructed of joined amino acid units
- The amino acids are made molecules of carbon, oxygen, nitrogen and hydrogen atoms in defined ratios and orders.

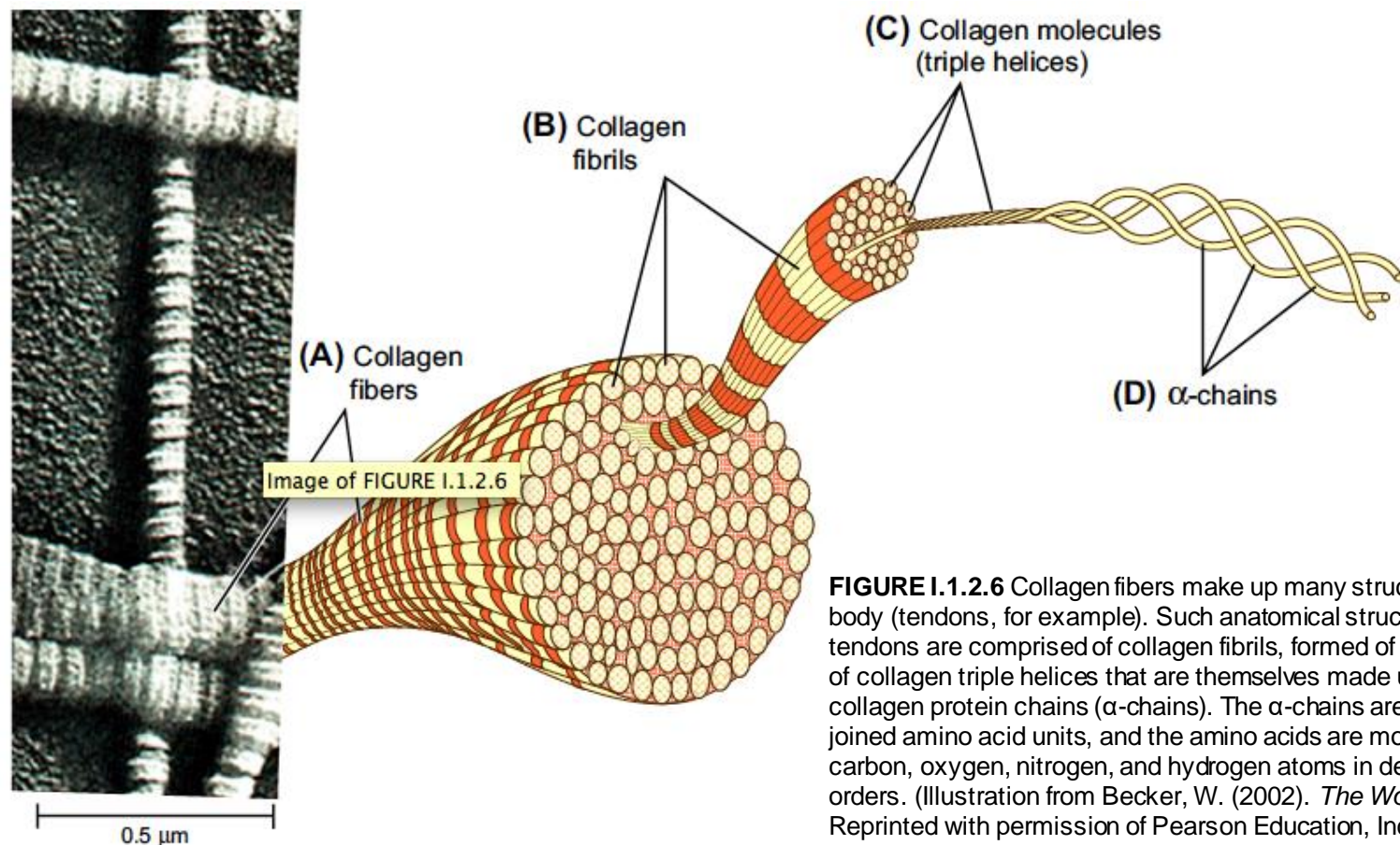
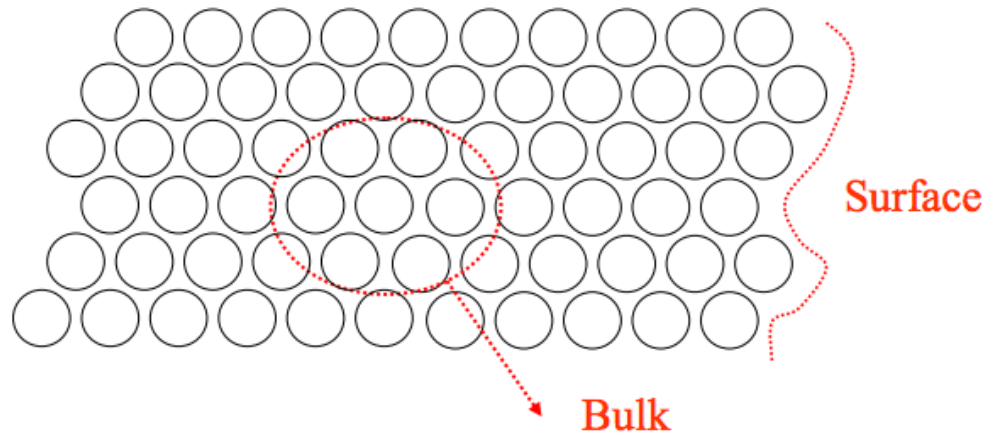


FIGURE I.1.2.6 Collagen fibers make up many structures in the body (tendons, for example). Such anatomical structures as tendons are comprised of collagen fibrils, formed of aligned bundles of collagen triple helices that are themselves made up of single collagen protein chains (α -chains). The α -chains are constructed of joined amino acid units, and the amino acids are molecules of carbon, oxygen, nitrogen, and hydrogen atoms in defined ratios and orders. (Illustration from Becker, W. (2002). *The World of the Cell*. Reprinted with permission of Pearson Education, Inc.)

BULK PROPERTIES OF MATERIALS

Bulk Versus Surface

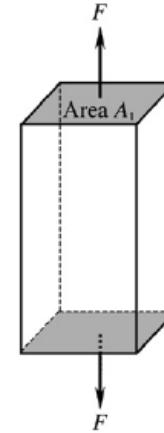


- The success or failure of many biomaterials depends on the physical and chemical characteristics of their **surface**.
- Surface properties dictate interactions between a material and its environment, and thus indicate whether a permanently implanted material will be tolerated or rejected
- In cases where the implanted material is required to degrade at a controlled rate then the bulk material must be capable of sustaining those properties continuously as it becomes the new surface.
 - when the implant is a temporary support, such as a dissolving suture or a scaffolding for cells that regenerate tissue

- Biomaterials are also required to exhibit certain **bulk** characteristics, especially including those attributes (mechanical properties) that relate to the ability to carry loads dependably without undue deflection or premature failure.
- The bulk properties of a material depend on
 - what types of atoms and molecules it contains (composition),
 - how those atoms and molecules are arranged (microstructure).
- Bulk properties that are depend on the composition of materials being characterized, and not on the microstructure are referred to as *intrinsic properties*. e.g. the stiffness of a metal, density, heat capacity.
- Bulk properties that are depend on attributes such as the average grain (crystal) size, as well as the number and distribution of defects in the crystal structure are referred as *extrinsic property*. e.g. yield strength.

NOMINAL (ENGINEERING) STRESS, ELONGATION and NOMINAL (ENGINEERING) STRAIN

- When a load (force) is applied to an object, the possible consequences include translation, rotation, and deformation of the object.
- Let a force F be applied normal to a pair of opposite faces (in this case the top and bottom faces) of the sample, which initially each have area A_1 .
- The actual shape of the sample is not important for the analysis, however the cross-section perpendicular to the applied force should be uniform.



Tensile (normal) stress

FIGURE I.1.3.1 Examples of a tensile (normal) stress, a shear stress, and a mixed stress with both normal and shear components, illustrating the relationship between load direction and surface orientation in each case. For the example of shear stress, the originally rectangular front face of the sample distorts to a parallelogram as shown, and the corresponding shear strain is defined as $\tan \theta$.

- The ratio:

$$\sigma_n = \frac{F}{A_1}$$

defines the *nominal stress (engineering stress)* being applied to the sample.

- The stress is tensile if it is a “pull,” elongating the sample, and it is compressive if it is a “push,” shortening the sample.

- Quantification of the effect of loads (and their related stresses) by considering the resultant length change per unit length is commonly known as *strain*.
- If the initial length of the sample is l_1 , and the applied stress causes a change to length l_2 , then the *nominal (or engineering) strain* is given by:

$$\varepsilon_n = \frac{l_2 - l_1}{l_1} = \frac{\Delta l}{l_1} = \lambda_{1 \rightarrow 2} - 1$$

where λ denotes the extension ratio, i.e., the ratio of final length to initial length.

TRUE STRESS AND TRUE STRAIN

- A more realistic sense of stress imposed on a material during a stress–strain test is obtained if the applied force is scaled with reference to the actual cross-sectional area of the sample, because the actual value of the area (cross-section) to which the load is applied will change as the sample deforms in response to the load
- In that case, we refer to the sample being subjected to a *true stress* defined by:

$$\sigma_t = \frac{F}{A}$$

- because A changes continuously during the course of a stress–strain test, it can be difficult to measure in practice, so nominal stress is so often used instead of true stress.
- Length change of the sample is measured in very small increments dI , with each increment being scaled relative to the length I of the sample immediately prior to that increment. Thus, a small increment in *true strain* is defined as:

$$d\epsilon_t = \frac{dI}{I}$$

SHEAR STRESS AND SHEAR STRAIN

- Consider the effect of applying the force F parallel to a pair of opposite faces (in this case the top and bottom faces), which initially each have area A_1 . For this configuration of applied load, the ratio:

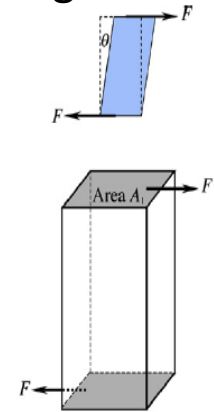
$$\tau = \frac{F}{A_1}$$

defines the *shear stress* being applied to the sample.

- Seen from the front of the sample, the outline becomes distorted from a rectangle to a more general parallelo-gram. This shape change can be used to describe the *shear strain γ* caused by the *shear stress*:

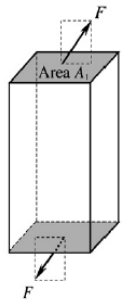
$$\gamma = \tan \theta$$

- If a force is applied obliquely (neither perpendicular nor parallel) to a pair of opposite faces of the sample, the ensuing stress can be resolved into normal and shear components, as can the resulting strain.



Shear stress

FIGURE I.1.3.1 Examples of a tensile (normal stress, and a mixed stress with both normal and shear components, illustrating the relationship between load direction and surface orientation in each case. For the example of shear stress, the originally rectangular front face of the sample distorts to a parallelogram as shown, and the corresponding shear strain is defined as $\tan \theta$.



Stress with normal and shear components

FIGURE I.1.3.1 Examples of a tensile (normal) stress, a shear stress, and a mixed stress with both normal and shear components, illustrating the relationship between load direction and surface orientation in each case. For the example of shear stress, the originally rectangular front face of the sample distorts to a parallelogram as shown, and the corresponding shear strain is defined as $\tan \theta$.

- The relationship between stress and resultant strain is commonly summarized in a stress–strain plot, where by convention the stress is plotted vertically and the strain is plotted horizontally, with data being collected while the sample is deformed at a constant strain rate.

BULK MECHANICAL PROPERTIES DETERMINED FROM STRESS–STRAIN PLOTS

- Simple stress–strain plots can be used to define and quantify several mechanical properties of a material.

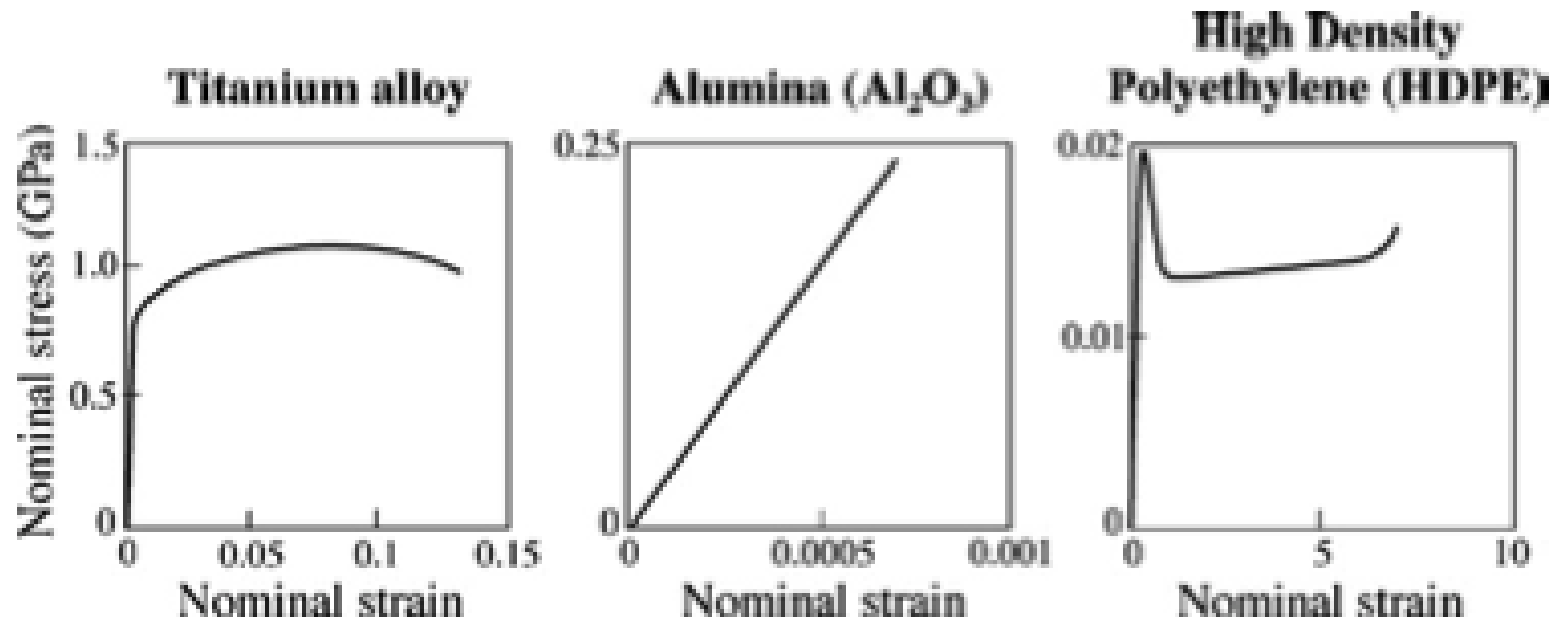


FIGURE I.1.3.2 Representative nominal stress versus nominal strain plots for three different classes of implantable material: ductile metal (titanium alloy; 6 wt% Al, 4 wt% V); ceramic (alumina); and crystalline polymer (high density polyethylene).

Schematic nominal stress versus nominal strain plot for a ductile metal (Titanium)

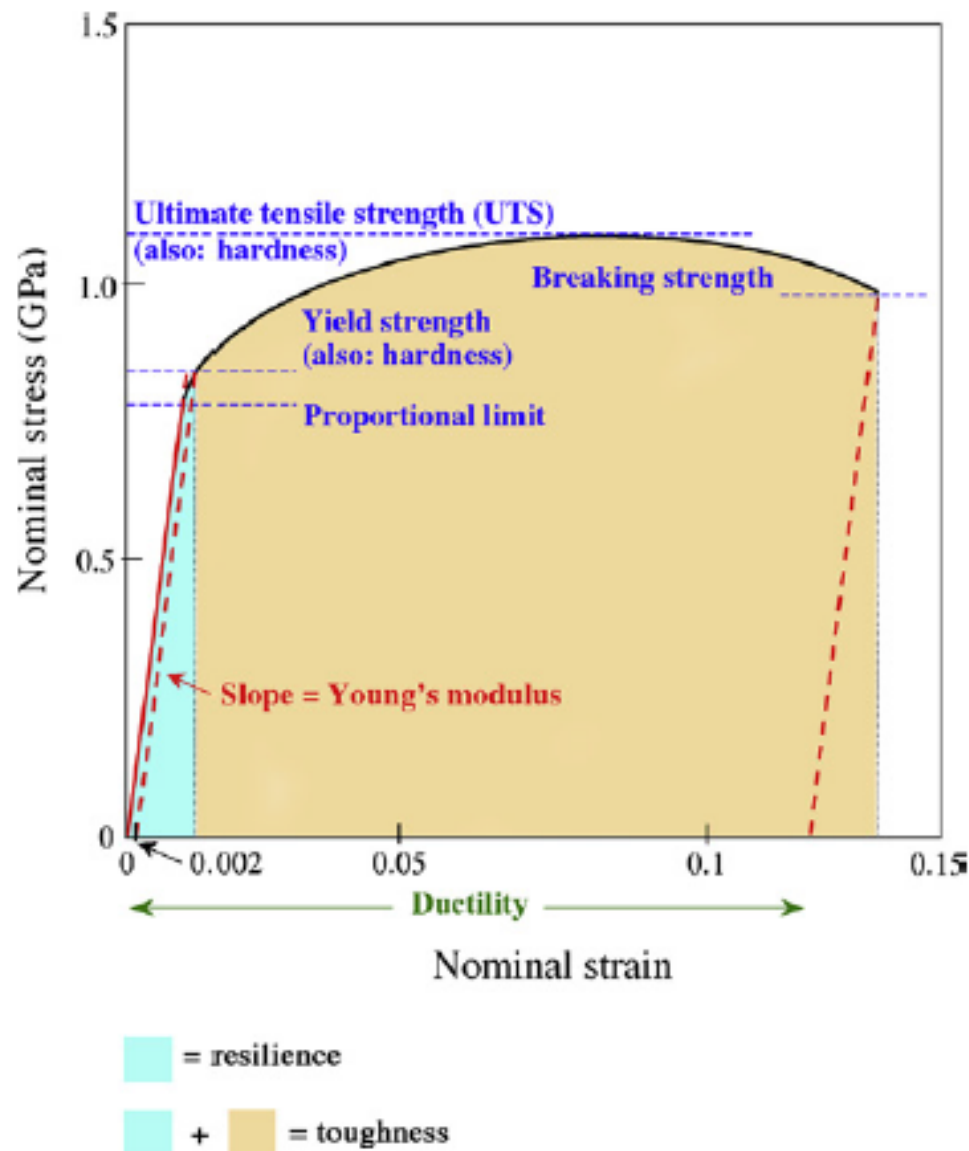


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

Elastic Deformation

➤ Elastic Constants

- The relationship between stress and strain is initially linear as the stress is increased from zero.
- In the case of bulk material, the constant of proportionality between tensile (or compressive) stress and strain is known as the *Young's modulus*, E :

$$\sigma = E \epsilon$$

- The equivalent constant of proportionality in the case of a shear stress being applied is known as the *shear modulus*, G :

$$\tau = G \gamma$$

- Similarly, we can define a *bulk modulus*, K , as the constant of proportionality relating pressure to the volume change caused by that pressure:

$$P = -K \frac{V_2 - V_1}{V_1} = -K \frac{\Delta V}{V_1}$$

where a pressure P causes a reduction in volume from an initial volume V_1 to a final volume V_2 .

In all three cases, the definitions of the different types of elastic modulus assume that:

- the cause of deformation (tensile stress, shear stress or pressure) is sufficiently small and the response (tensile strain, shear strain or volume change) is *proportional* to the cause.
- It also ensures that the response is *reversible*; when the stress or pressure is removed, **the material returns to its original dimensions.**

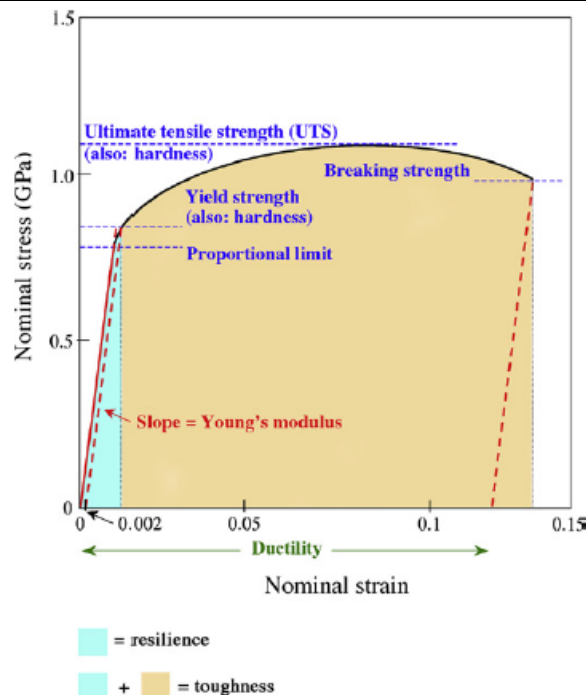


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

- Another constant that is commonly encountered in the context of the elastic deformation of materials is *Poisson's ratio, ν* .
- when we pull on a piece of material, it usually becomes thinner as well as longer. Poisson's ratio is defined as:

$$\nu = - \frac{\epsilon_{transverse}}{\epsilon_{longitudinal}}$$

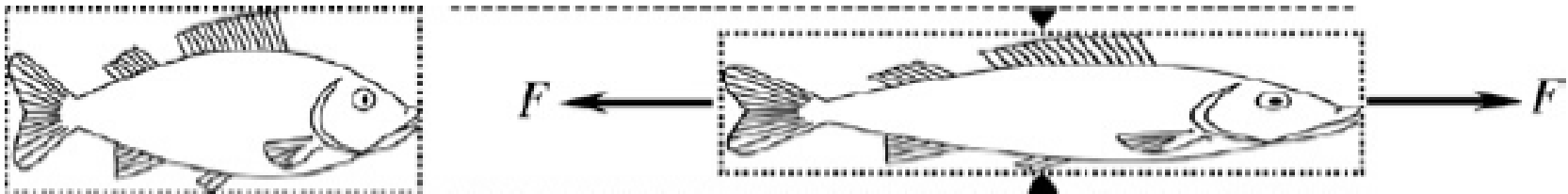


FIGURE I.1.3.4 Longitudinal elastic strain (in this case elongation) parallel to the direction of the applied load is accompanied by a transverse elastic strain (in this case contraction) perpendicular to the direction of the applied load. The negative of the ratio of transverse elastic strain to longitudinal elastic strain defines Poisson's ratio.

Plastic Deformation

- As the stress on a material increases, a point may be reached where the response is no longer linear.
- There is a permanent (irreversible) deformation and deformation that is not recovered on removing the stress. Irreversible deformation is known as *plastic deformation*.
- It occurs commonly in metals and polymers, and rarely in ceramics.

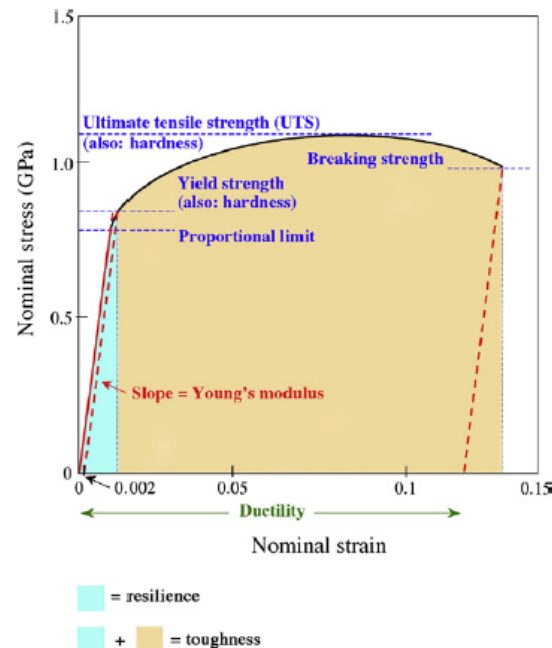


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

➤ Yield Strength and Ductility.

- The amount of plastic deformation associated with a given stress is found by drawing a line from the point of interest on the stress–strain curve, parallel to the initial linear segment of the curve, and marking the point where this constructed line intersects the horizontal (strain) axis.
- The horizontal distance from the origin to the point of intersection is a measure of the plastic strain. The value of plastic strain required to break the material defines the **ductility**
- The stress at which departure from a linear stress–strain relationship occurs is known as the **proportional limit**
- It is not always easy to ascertain the proportional limit accurately, and so a more practical determination of the condition for plastic deformation is provided by the **yield strength**, which is the stress at which *noticeable* plastic strain occurs.

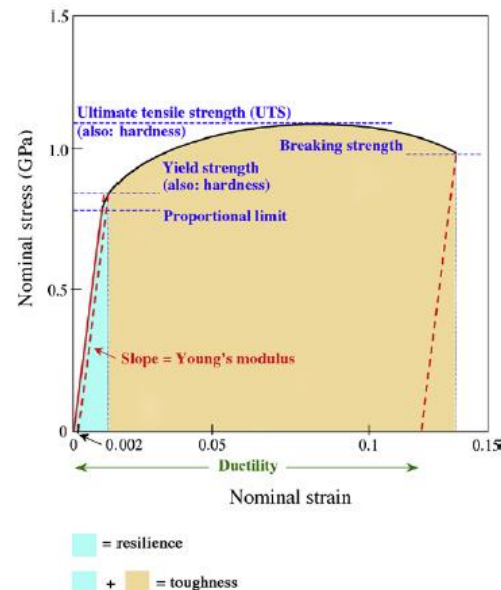


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

➤ Strength and Failure.

- For materials in which permanent deformation (and the attendant shape change) is acceptable, failure may be deemed to occur when a noticeable “neck” (constriction) develops in the material.
- The effect of the neck is to concentrate the load on a smaller area; therefore, the load that can be supported by the sample is decreased.
- On a nominal stress versus nominal strain plot, the stress required for additional deformation decreases.
- Therefore, the onset of necking corresponds to a maximum in the nominal stress versus nominal strain plot, defining the *ultimate tensile strength (UTS)* or simply the *tensile strength* of the material.

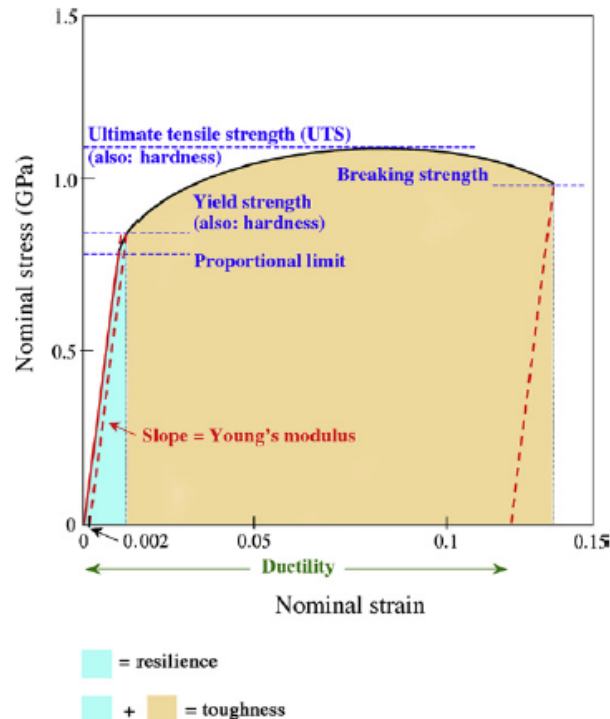


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

- On both nominal stress versus nominal strain and true stress versus true strain plots, a *breaking strength* can be defined at the point where the material actually breaks.

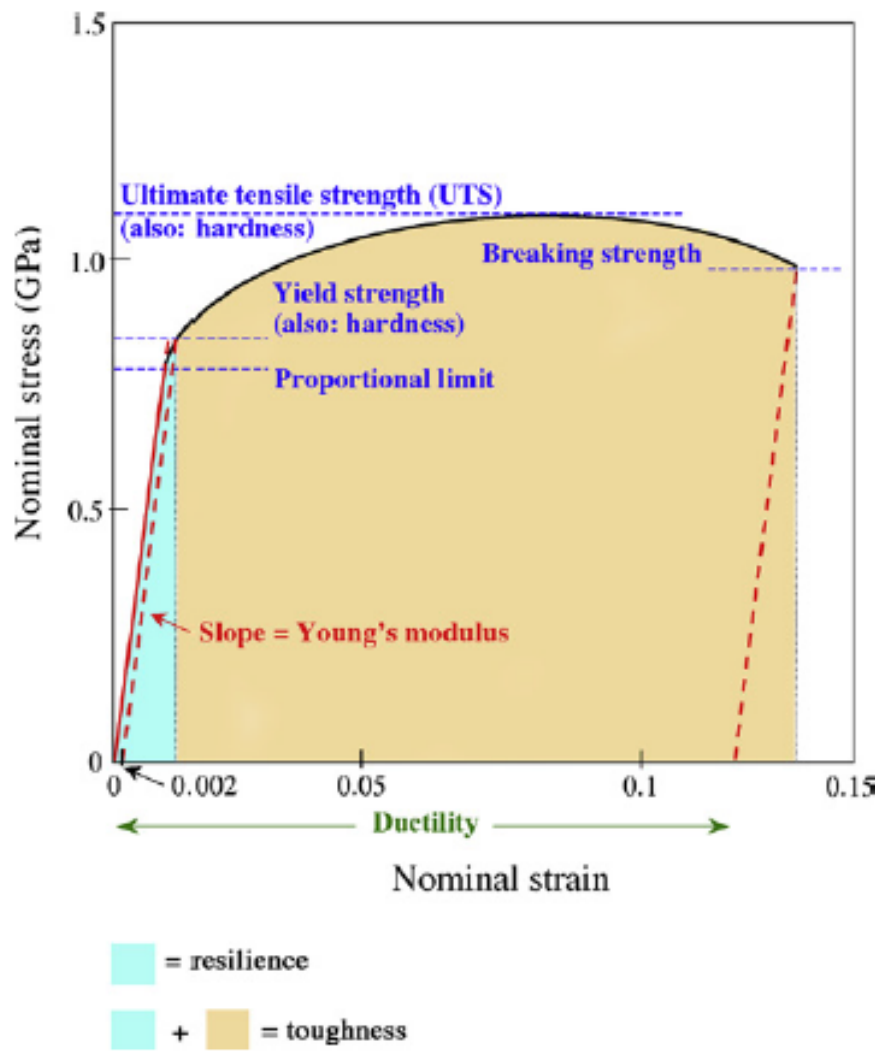


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

➤ Hardness

- hardness provides a measure of how successfully a material resists plastic deformation, which in turn is characterized by both yield strength and tensile strength.
- It is therefore possible to empirically develop calibration charts that can be used to convert hardness measurements into both yield strength and tensile strength values

➤ Resilience

- *Resilience* is a measure of the *elastic energy* that can be stored in a unit volume of stressed material.
- It corresponds to the area underneath a stress versus strain plot, extending from zero strain up to the strain at which the sample yields

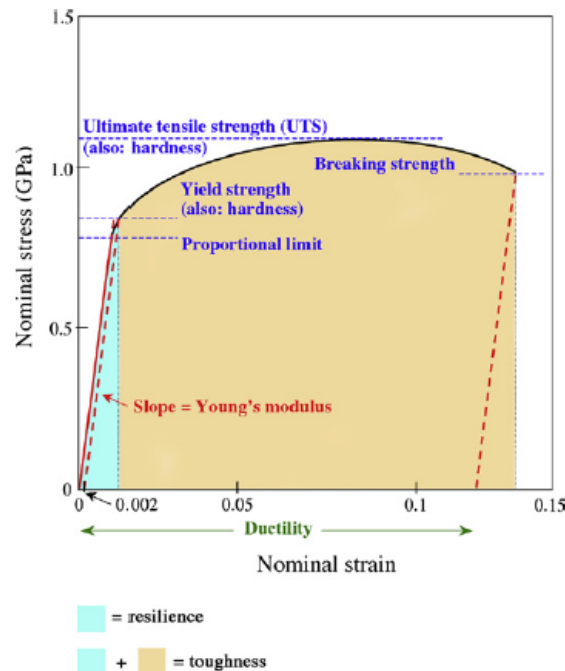


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

➤ **Toughness and Fracture Toughness**

- **Toughness** is a measure of the energy required to deform a unit volume of material to its breaking point. Therefore, the definition is similar to that used for resilience, except that we now take into account the entire area under the stress versus strain plot, extending from zero strain up to the strain at which the sample breaks.

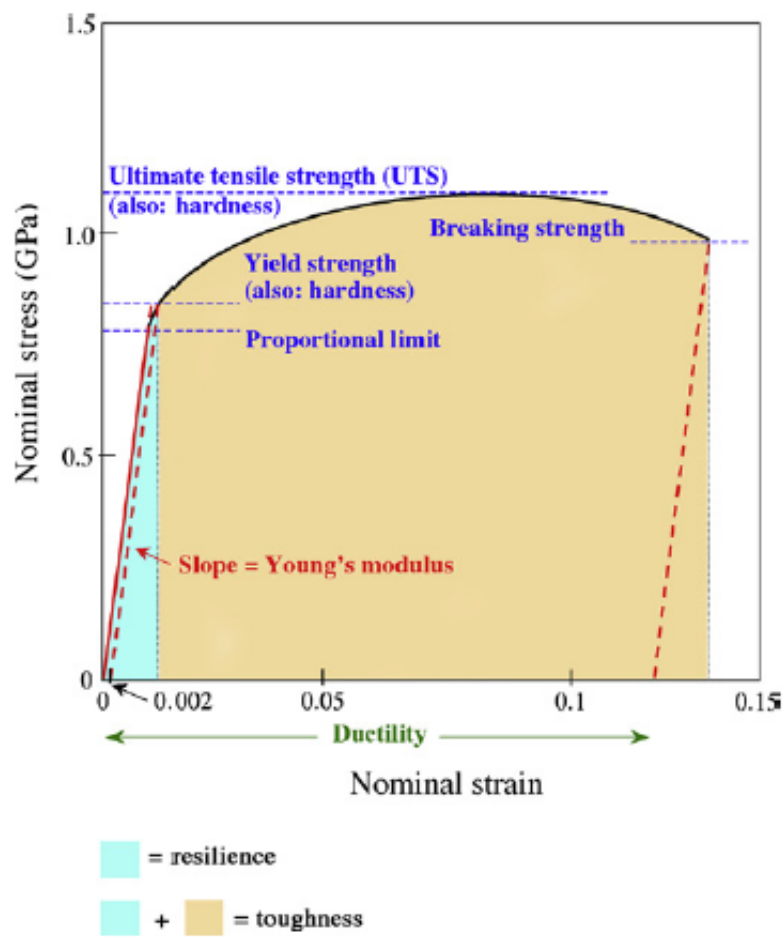


FIGURE I.1.3.3 Schematic nominal stress versus nominal strain plot for a ductile metal, emphasizing the features that relate to specific mechanical properties.

- *Fracture toughness* is a measure of how successfully a material resists the propagation of cracks.

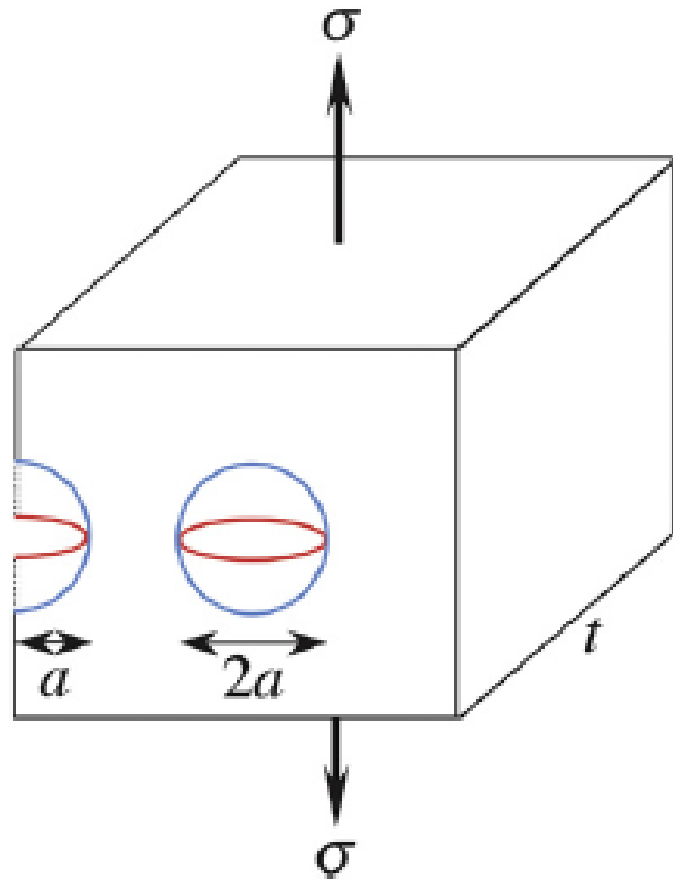


FIGURE I.1.3.8 Sample geometry used in defining the fracture toughness of a material. Examples of both a surface crack and an internal crack are shown. The cracks are assumed to be cylindrical (blue circles) for ease of mathematical description; a flattened profile (red ellipses) would be more realistic.

OTHER BULK PROPERTIES

- The bulk properties of a material are not limited to performance in mechanical tests. Other types of bulk properties that may have to be taken into account during the selection of a biomaterial include:
 - ✓ thermal properties
 - ✓ optical properties
 - ✓ electrical properties
 - ✓ magnetic properties

Thermal Properties

- Thermal conductivity becomes a significant consideration if an implanted material contributes to an unnatural flow of heat through the surrounding tissue.
 - ✧ For example, metal rods selected for their combination of stiffness, strength, fracture toughness, and biocompatibility can promote heat loss and cause the patient to feel colder than normal.

Optical Properties

- In the context of biomaterials, the most significant bulk optical properties are color, refractive index, and transparency; all three are important in the selection of materials for intraocular lenses or fluids.
 - The color of a transparent material is controlled by composition, and therefore demands a high degree of quality control to avoid impurities that could adversely affect color
 - the effectiveness of a material as a lens is directly related to its refractive index
 - *Transparency* is a qualitative term that describes the ability of a material to transmit light without attenuating (absorbing or scattering) it