Material Properties

Corso Materiali intelligenti e Biomimetici
2/03/2018

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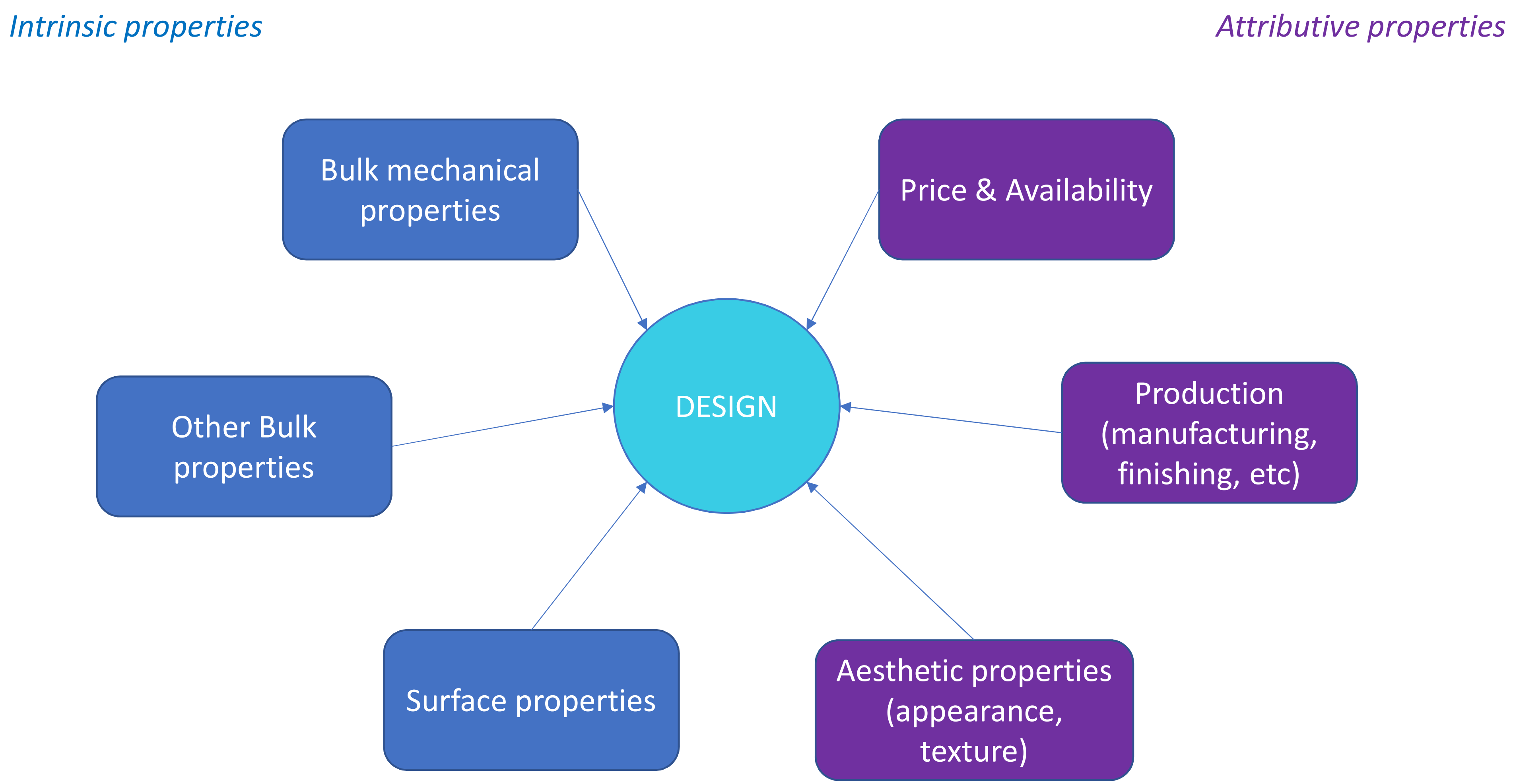

Intrinsic properties
Attributive properties
Bulk mechanical properties
Price & Availability
DESIGN
Other Bulk properties
Production (manufacturing, finishing, etc)
Surface properties
Aesthetic properties (appearance, texture)

Bulk vs. Surface Properties

- Mechanical
  - *elastic modulus & viscoelastic properties*
- Thermal
  - *Thermal expansion coefficient*

    $\varepsilon_{thermal} = \alpha\ (T_{final} - T_{initial})$
- Optical
  - *refractive index*

    $n = c_{vacuum}/c_{material}$
  - *transparency*

    $I = I_0\, exp(-\mu \rho x)$

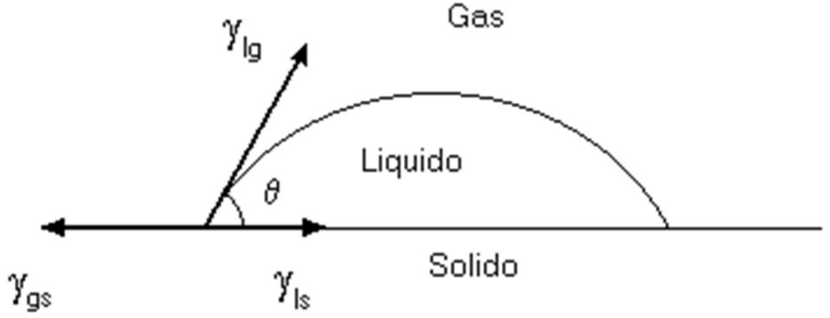
- Roughness
- Chemistry
- Wettability
- Surface energy
- Mechanical

How to measure surface properties

- Contact angles -> wettability (directly), surface energy (indirectly)
- Electron spectroscopy for chemical analysis (ESCA) -> chemical properties
- Atomic force microscopy -> topography, mechanics (up to 0.1 nm)
- Nanoindentation -> mechanics (um)

Mechanical Surface Properties (bracketing the last two items)

Contact angle

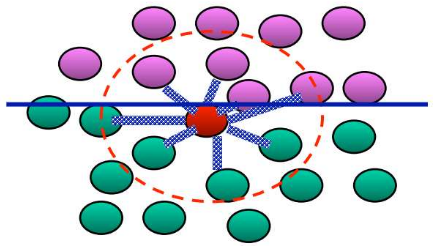


$$\gamma_{gs} = \gamma_{ls} + \gamma_{lg}\cos\theta$$

Superficial tension of a solid in a specific environment

Superficial tension between solid-liquid

Superficial tension of liquid in a specific environment

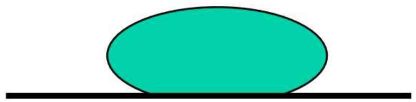


Solido. Adesione

Liquido. Coesione

Adesione > Coesione
Liquido bagna

$0 < \theta < 90°$



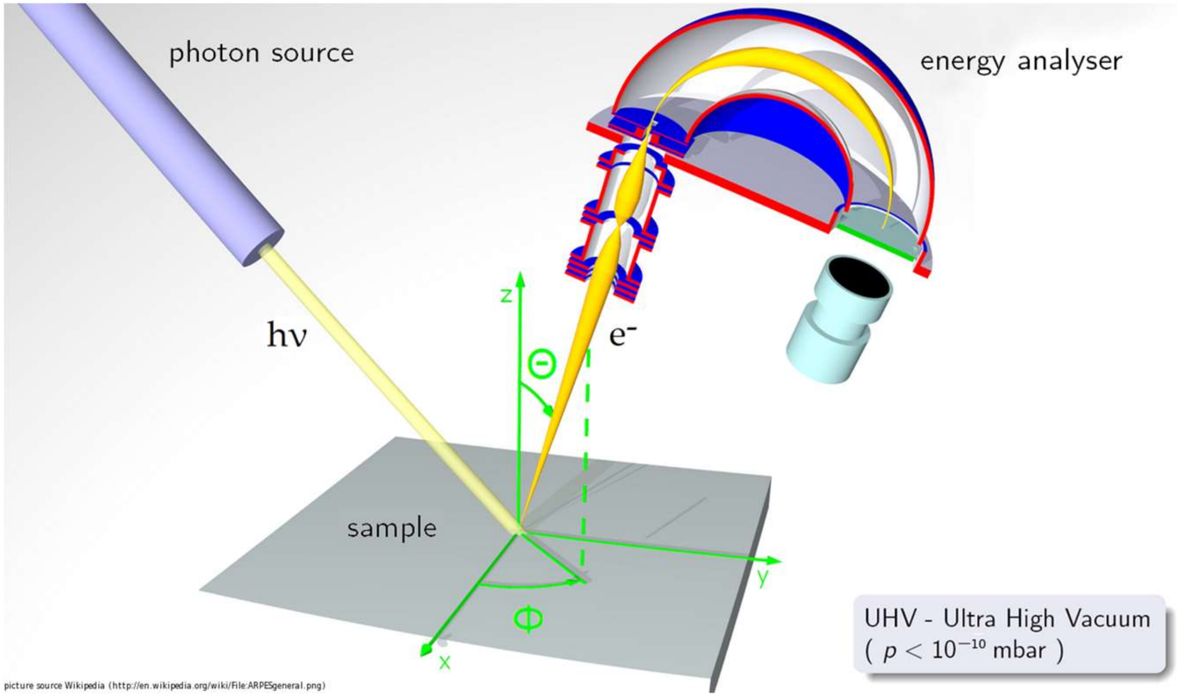
Adesione < Coesione
Liquido non bagna

$90° < \theta < 180°$

ESCA

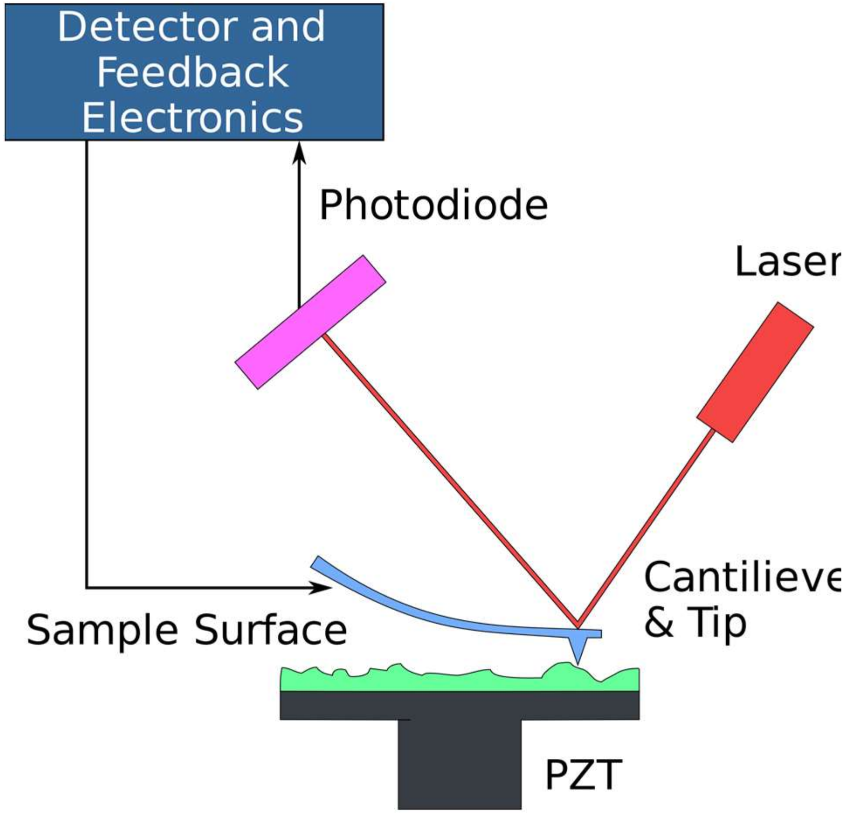
This technique is based on the **Photoelectric Effect:** when a material is irradiated with x-rays, photoelectrons are subsequently ejected from atoms in the near surface (*1-10 nm)*.

$E_b = h\nu - E_k$



information about: elemental composition, concentrations and chemical environments (i.e. oxidation states) of surface and near surface atoms.

AFM



The tip is scanned laterally across the surface, and the vertical movements of the tip are recorded and used to construct a quantitative **3 dimensional topographic map**.

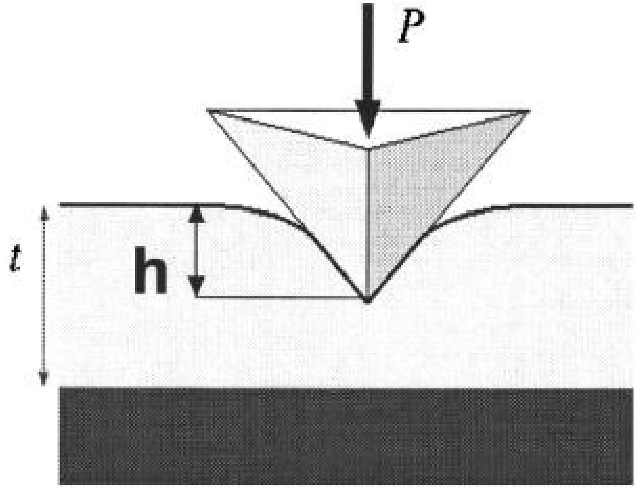
- lateral resolution: typically 5-15 nm
- vertical resolution: 0.1nm

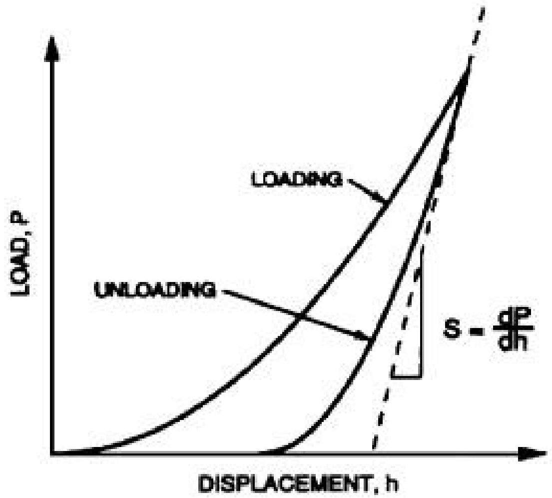
Other information:

- Surface roughness measurements
- Investigation of local mechanical properties

(i.e. stiffness, adhesion, friction)

Nanoidentation





The slope of the curve (dP/dh) upon unloading is indicative of the **stiffness S** of the contact. This value generally includes a *contribution from both the material being tested and the response of the tip itself.*

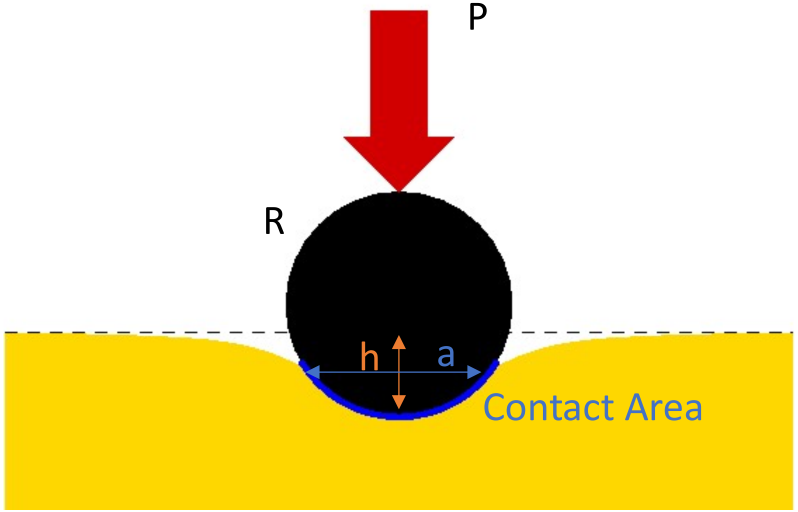
Reduced elastic modulus

$$E_r = \frac{1}{\beta}\frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A_p(h_c)}}$$

$$1/E_r = (1-\nu_i^2)/E_i + (1-\nu_s^2)/E_s\,.$$

Tip: known mechanical properties, typically very hard material (Ei>>Es)

Nanoidentation (1)

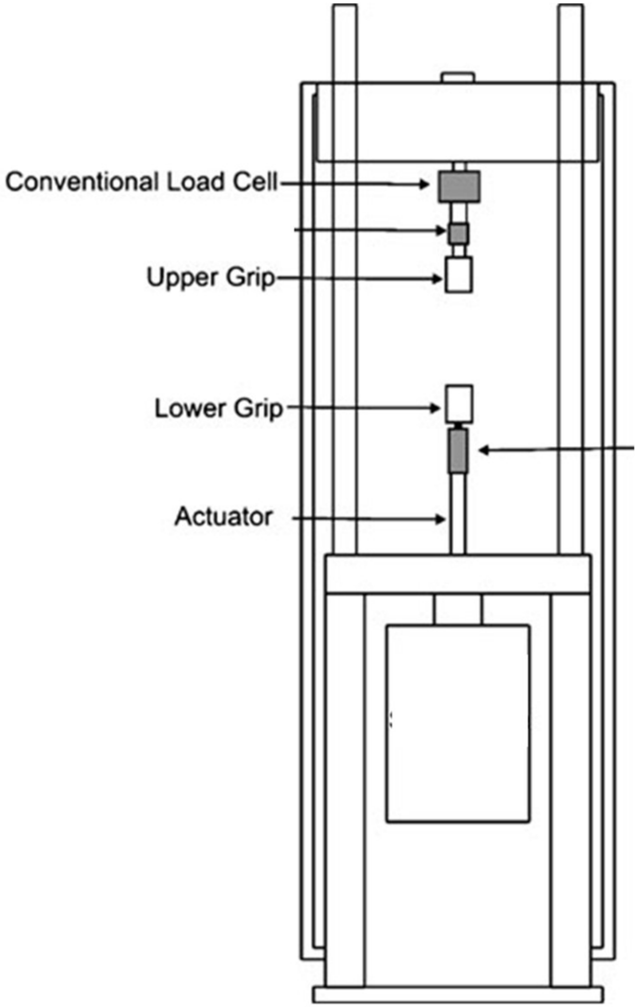


Hertzian Contact (sphere – half plane):

$$a = \sqrt{Rd}$$

$$P = \frac{4}{3} \, Er \, R^{1/2} d^{3/2}$$

Mechanical Bulk properties



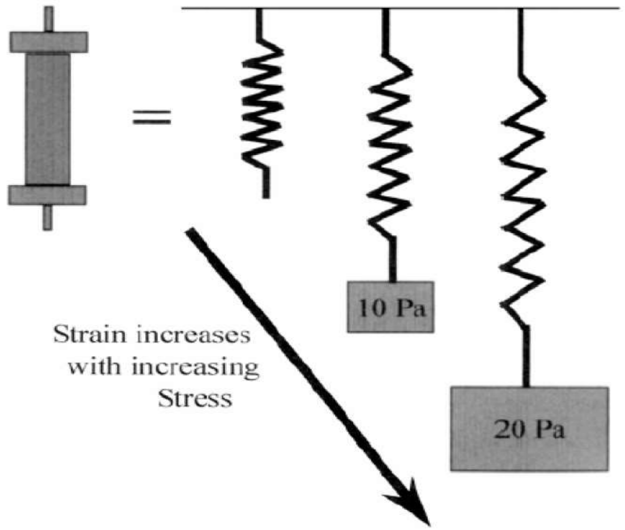
Standard testing machines:

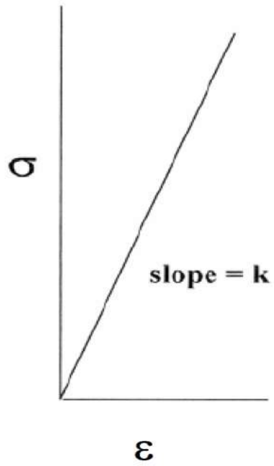
Compression and tensile tests

Main components:

- Load cell (different maximum loads)
- Actuator
- Sample holding system

Elastic Solids





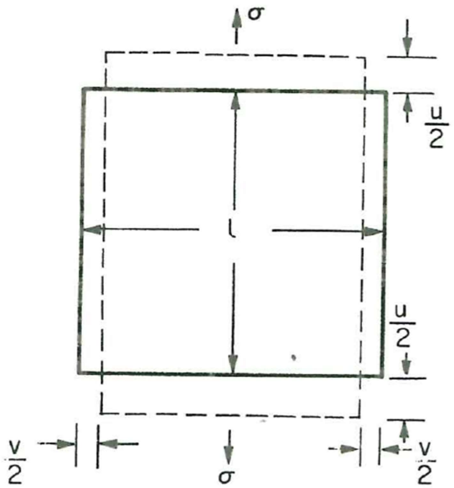
Stress is directly proportional to deformation:

$$\sigma = E \cdot \varepsilon$$

The **elastic modulus** (E) represents the resistance of a material to deformation (**stiffness**).
The reciprocal of E (J) is known as **compliance**.

$$J = \frac{1}{E}$$

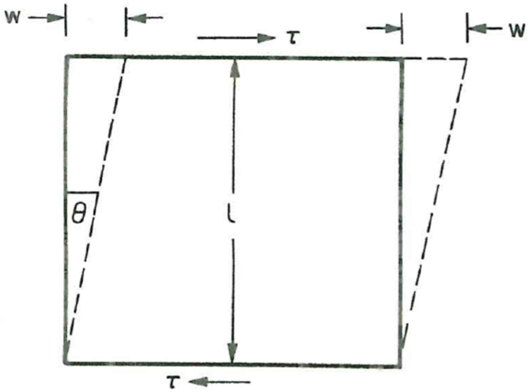
Elastic modulus vs. Shear modulus



Nominal tensile strain,
$\epsilon_n = \frac{u}{l}$

Nominal lateral strain,
$\epsilon_n = -\frac{v}{l}$

Poisson's ratio,
$\nu = -\frac{\text{lateral strain}}{\text{tensile strain}}$



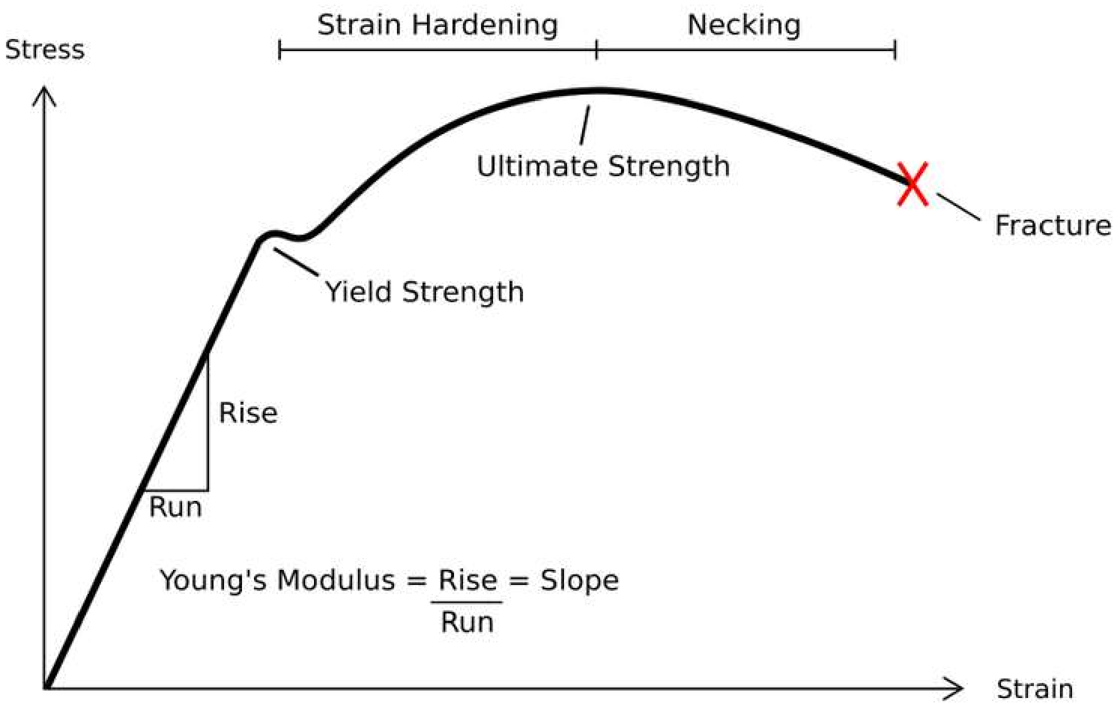
Engineering shear strain,
$\gamma = \frac{w}{l} = \tan\theta$

$$E = 2G(1-\nu)$$

Elastic modulus

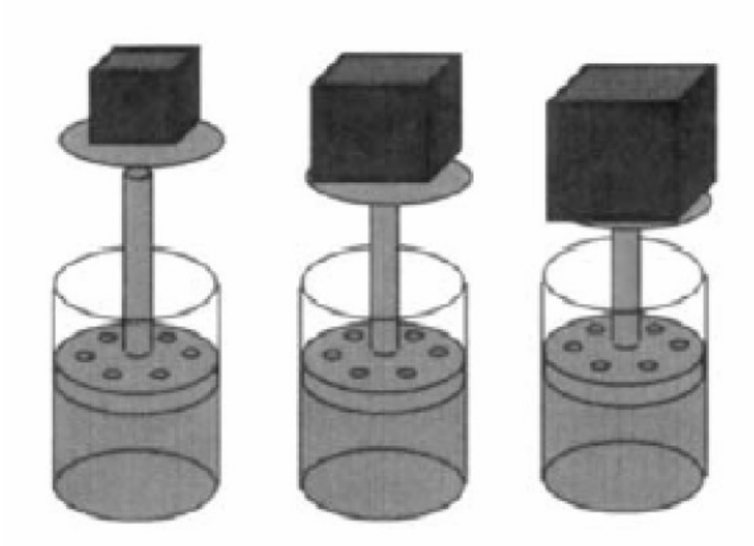
Shear modulus
G = τ /γ

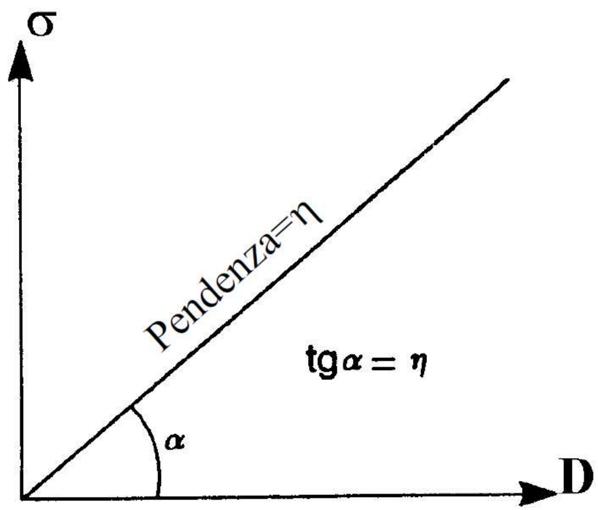
Elastic response



An elastic material has a linear response until a critical stress value (yield stress),
then it becames not linear until the failure of the sample.

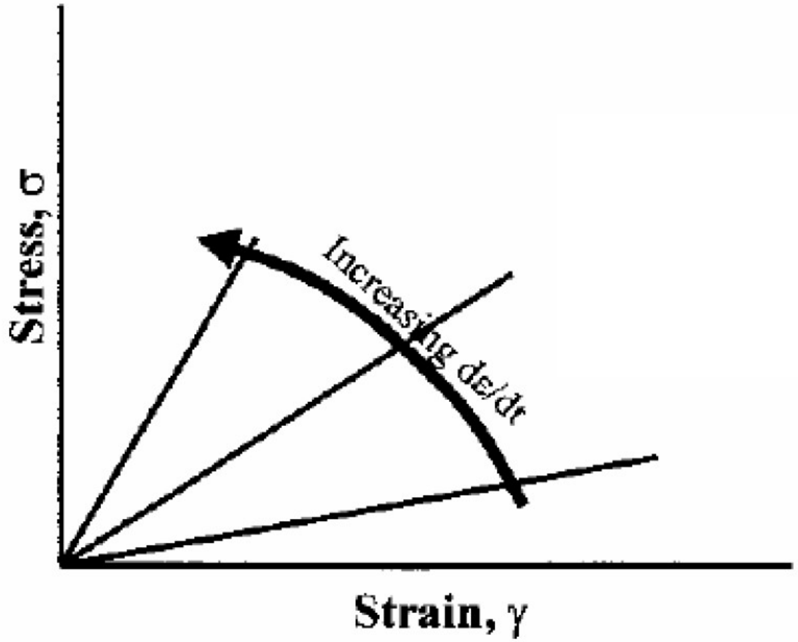
Viscous liquids





$$\sigma = \eta \cdot \frac{dV}{dy}$$

Viscoelastic materials

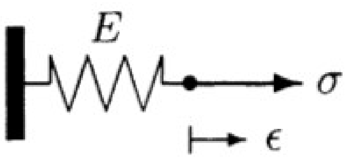


Time dependency:
The **apparent stiffness** of the material increases with increasing testing velocity

Lumped parameter models

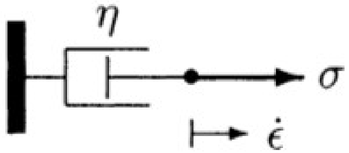
SPRING: ELASTIC SOLID

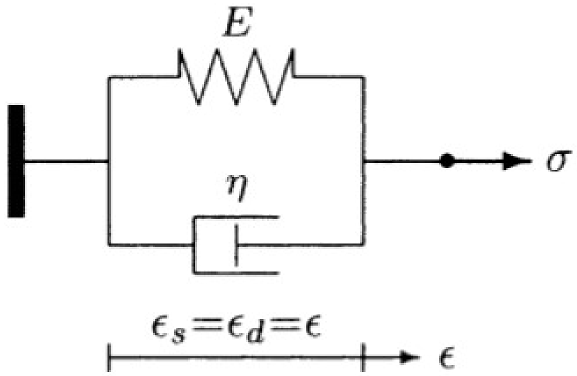
$$\sigma = E\,\epsilon$$



DASHPOT: VISCOUS FLUID

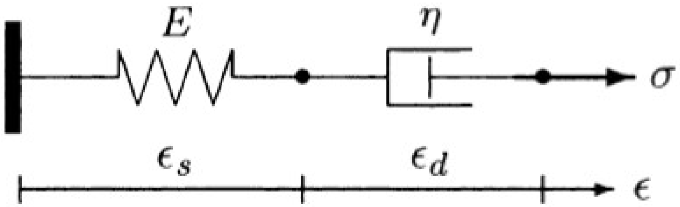
$$\sigma = \eta\,\dot{\epsilon}$$





$$\sigma = E\varepsilon + \eta\frac{\mathrm{d}\varepsilon}{\mathrm{d}t}.$$

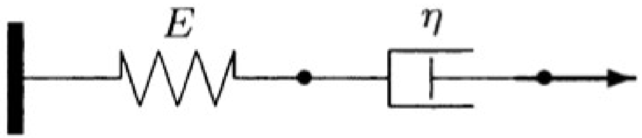
Kelvin–Voight model

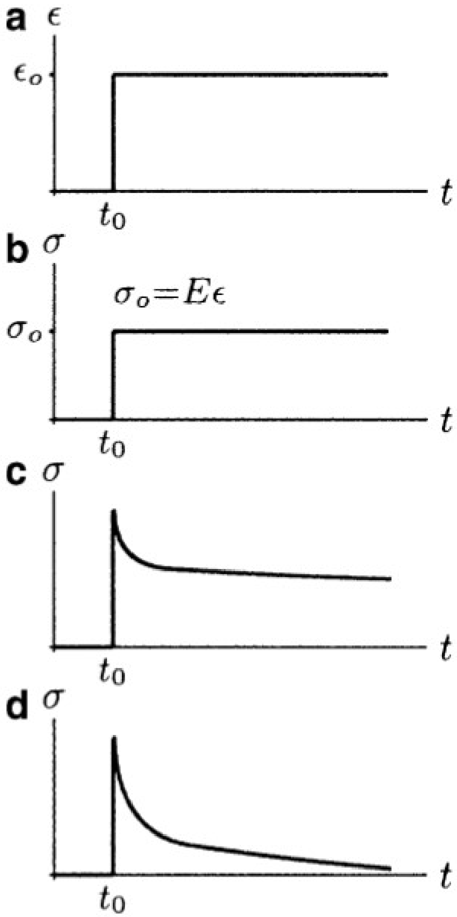


$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta}$$

Maxwell model

Stress Relaxation





Stress relaxation

Stimulus = **strain step ε_0** (a)

Response:

- (b) elastic material -> constant stress

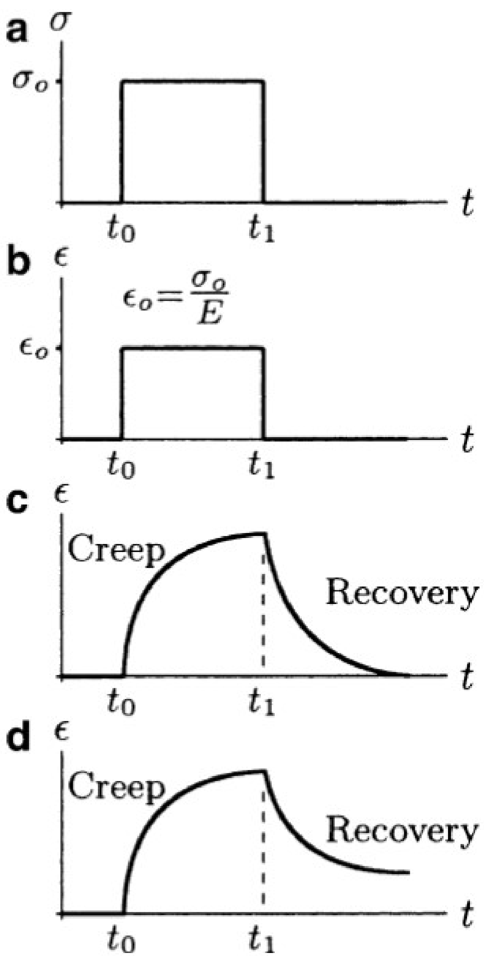
- (c) viscoelastic solid -> **initial high stress that will decrease over time**, but stress level will **never reduce to zero**

- (d) viscoelastic liquid -> initial high stress that will decrease over time, and the stress will **eventually reduce to zero**

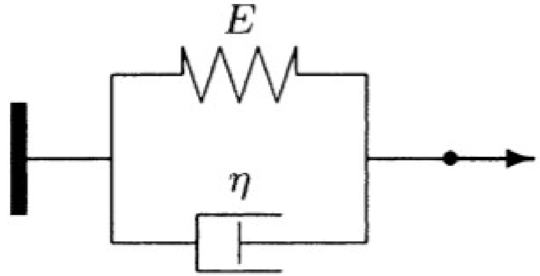
$$\sigma(t) = \varepsilon_0 E e^{-tE/\eta}$$

Relaxation time (τ_{SR}): The force drops to 1/e of its initial value

Creep



Creep and recovery



Stimulus = **stress step σ_0** (a)

Response:

- (b) elastic material -> **constant strain** at time t0. At time t1, the material will instantly and **completely recover the deformation**.

- (c) viscoelastic solid -> a **strain gradually increasing** between times t0 and t1. At time t1, gradual recovery will start. The *recovery will eventually be complete.*

- (d) viscoelastic liquid -> complete recovery will never be achieved and there will be a **residue of deformation** left in the material

$$\varepsilon(t) = \frac{\sigma_0}{E}(1 - e^{-tE/\eta})$$

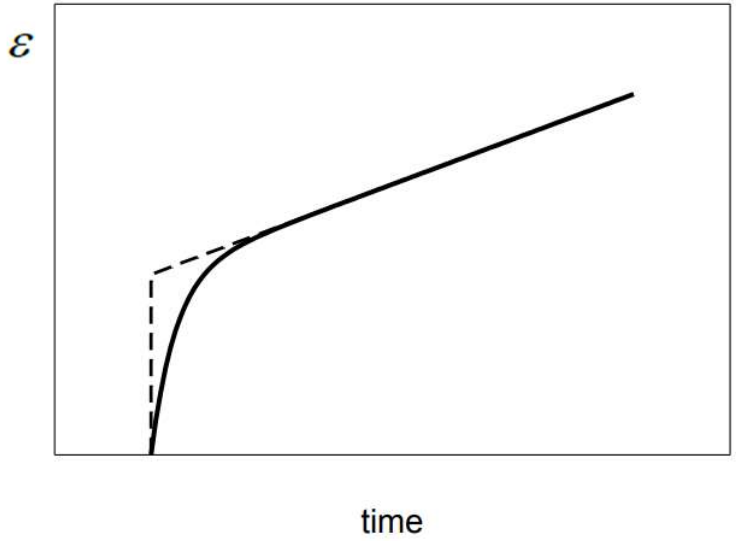
Retardation time (τ_C): The strain achives to 1/e of its final value

Creep and SR equations

- Creep -> Voigt

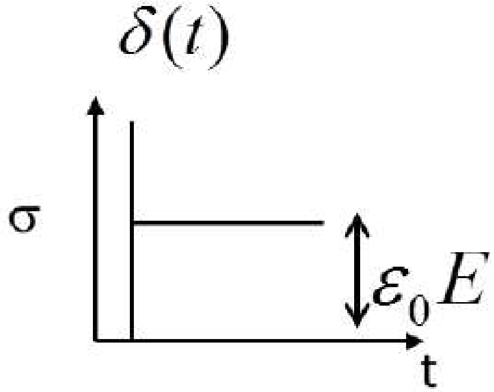
  because Maxwell does not describe correctly creep answer: the answer is more edgy and **does not describe the transition between short time** (elastic) **and long time behavior** (viscous)**.**
  Maxwell does not describe well all the situations in which the applied stimulus is a stress.

$$\varepsilon(t) = \sigma_0\left(\frac{t}{\eta} + \frac{1}{E}\right)$$



- SR -> Maxwell

$$\sigma(t) = \varepsilon_0 \eta . \delta(t) + \varepsilon_0 E$$



Deborah number

''Le montagne si scioglieranno davanti al Signore, Dio di Israele '' - Libro dei Giudici (5,-5)

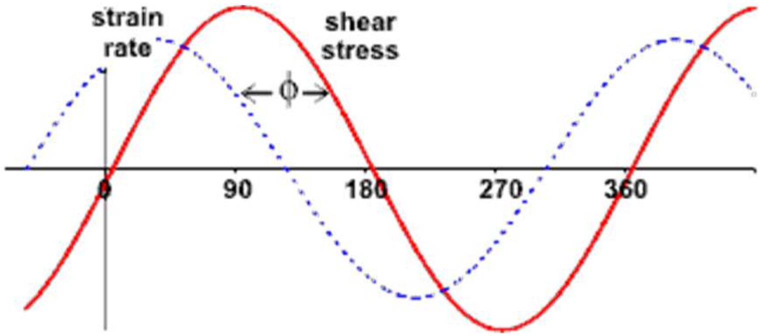
''But Deborah knew two things. First, that the mountains flow, as everything flows. But, secondly, that they flowed before the Lord, and not before man, for the simple reason that man in his short lifetime cannot see them flowing, while the time of observation of God is infinite.''
M.Reiner, The Deborah Number, Physics today, 62 (1964)

The perception of a material is dependent from **observation time**.

$$De = \frac{\tau}{t}$$

De >> 1 ($\tau_{SR} \gg t$)	Slow response (solid like materials)
De << 1 ($t \gg \tau_{SR}$)	Instantaneous response (liquid like materials)
De ≈ 1 ($\tau_{SR} \approx t$)	Intermediate response (viscoelastic materials)

DMA



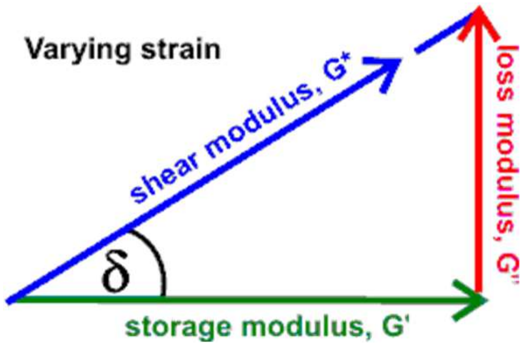
Stimulus = **strain sinusoid**

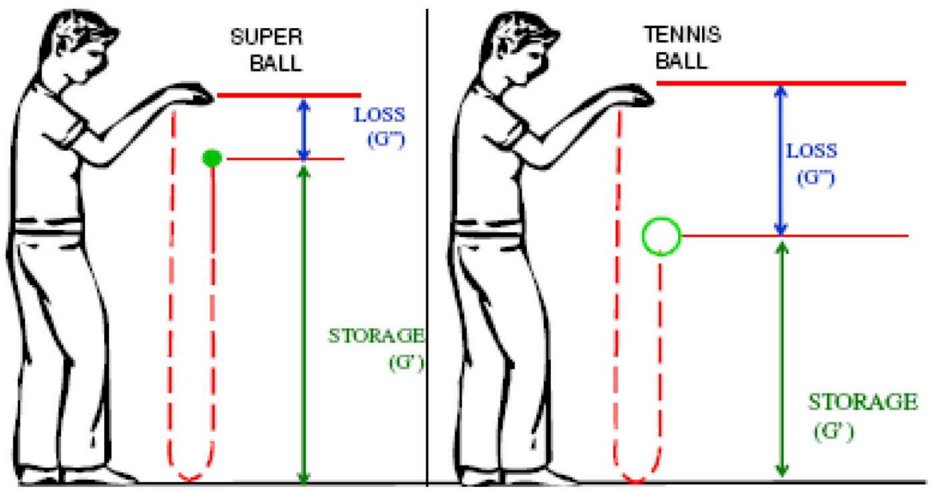
Response = stress sinusoid:

- ϕ= 0 for ideally elastic material (all energy stored in the material)
- ϕ= 90° for an ideally viscous liquid (all energy dissipated)

shear stress = shear strain ^{x} sin(ωt + ϕ)
shear stress = viscous stress - i ^{x} elastic stress

complex shear moduls
G* = G' + iG''





Esercizi

1) Data un barra di acciaio con E=200GPa, l=100mm, d=2mm compressa con una F=500N; calcolare: allungamento verticale e laterale (v=0.5)
2) Considerare un test di creep con s0=7kPa, d_eq=600um, d_inst=400um; h=8mm; ricavare i parametri concentrati del modello (E, tau)

Articoli (eps-dot, nano-eps dot)

- Qual è la differenza tra eps-dot e nano-eps dot?
- Come si trasformano le curve P-h in stress-strain (nano-eps dot)?
- Quali sono I vantaggi di questi due metodi rispetto metodi standard?