Physical bases of dental material science

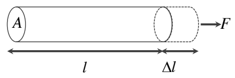
BIOMECHANICS

Dental tissue mechanics

1

Basics of tissue mechanics

Hookean elasticity

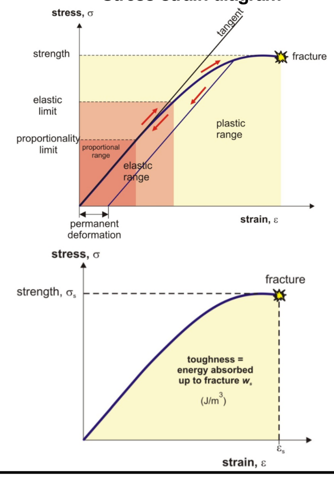


$$\frac{F}{A} = E\frac{\Delta l}{l}$$

F = force
A = cross-sectional area
l = rest length
Δl = extension

$F/A = \sigma$ = stress (N/m^2 = Pa)
$\Delta l/l = \varepsilon$ = strain (dimensionless)
E= σ / ε Young's modulus (Pa)

Stress-strain diagram



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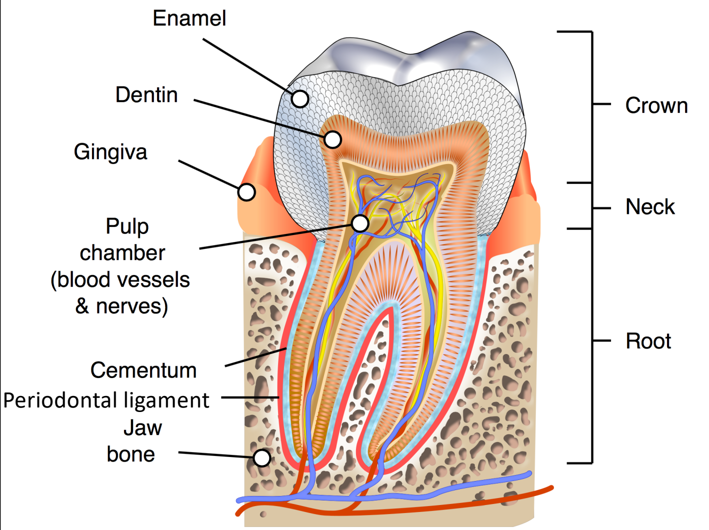

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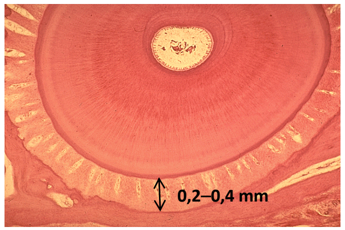
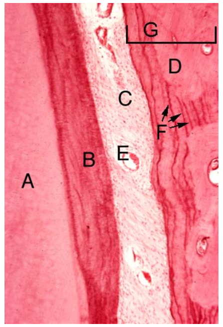
Periodontal ligament





≈ collagen

polimer

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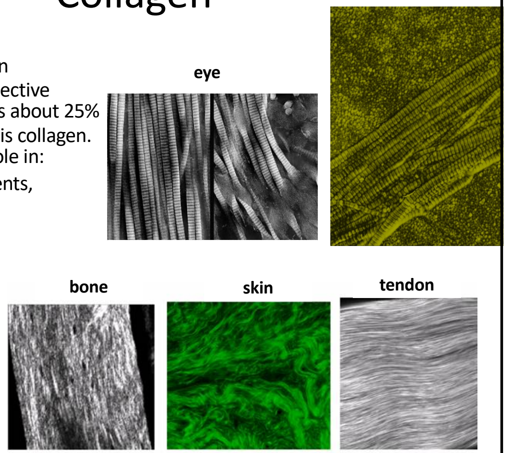
Collagen

Structural protein, main component of connective tissues, in mammals about 25% of the total protein is collagen. Has an important role in:

- tendons, ligaments,
- skin,
- cartilage,
- bone,
- tooth,
- blood vessels
- vitreous humor,
- cornea,
- etc.



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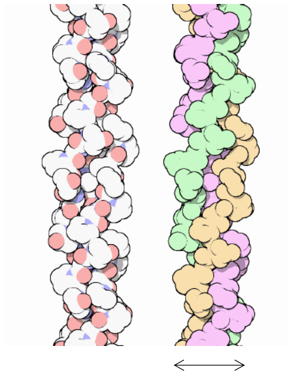
The collagen molecule



- 1400 aminoacids/chain
- glicin (1/3), prolin (1/10), hidroxiprolin, ...
- 3 chains → triple helix

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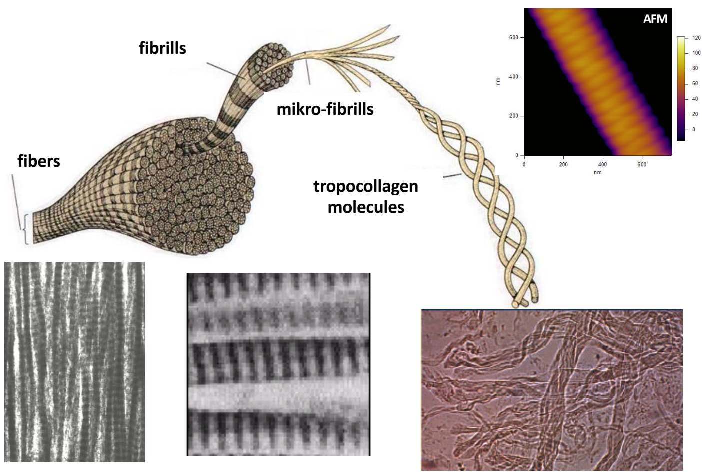
The structure of collagen



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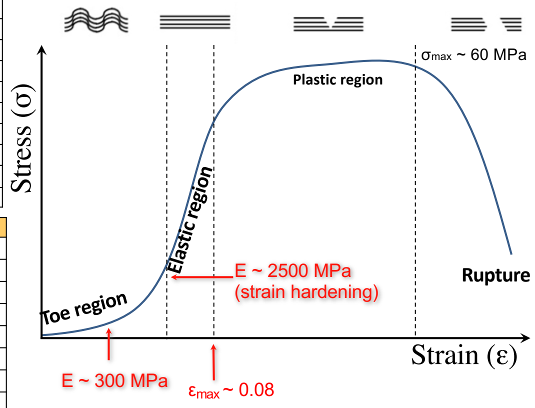
Stretch diagram of collagen

material	E (GPa)
enamel	≈ 100
dentin	≈ 15
steel	200-230
amalgam	50-60
gold	79
glass	60-90
ceramics	60-130
porcelain	60-110
PMMA	2,4-3,8
silicon	≈ 0,0003

material	$\sigma_{sz,\ szakító}$ (MPa)
enamel	≈ 10
dentin	≈ 110
amalgam	30-55
gold	108
Ni-Cr alloys	400-900
glass	≈ 70
ceramics	5-400
porcelain	≈ 25
PMMA	≈ 50



Moderately elastic and tough, but soft

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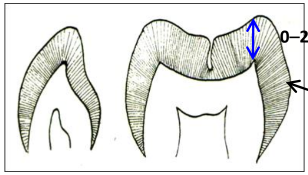
Enamel

ceramics

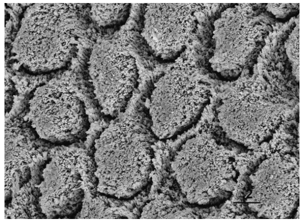


0–2,5 mm

≈ 92% hydroxyapatite (HAP)

enamel prisms

cross section



longitudinal section

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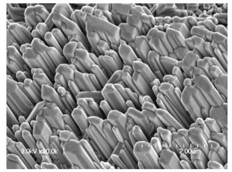
Hydroxyapatite

$Ca_{10}(PO_4)_6(OH)_2$



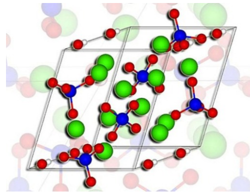
hexagonal ionic cristal

in dentin and bone

20-60 nm x 6 nm crystals

in enamel:

500-1000 nm x 30 nm crystals



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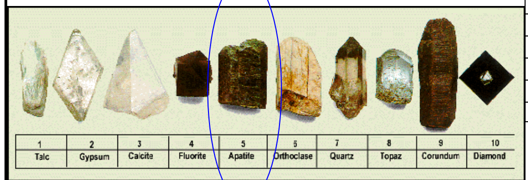
Properties of hydroxyapatite

material	*HV* (MPa)
enamel	≈ 3400
dentin	≈ 600
amalgam	≈ 1000
gold	
gold alloys	600-250
Pd-Ag alloys	1400-1900
Co-Cr alloys	≈ 4000
Ni-Cr alloys	3000-4000
glass	
porceelain	4500-7000
akrylate	≈ 200

Mohs scale:



HAP: $HV \approx$ 6 GPa $E \approx$ 140 GPa $\sigma_S \approx 60$ MPa (bending)

≈ 500 MPa (compression)

enamel: $HV \approx$ 3-6 GPa $E \approx$ 90-100 GPa $\sigma_S \approx 50$ MPa (tension)

≈ 400 MPa (compression)

Rigid, hard, strong but brittle!

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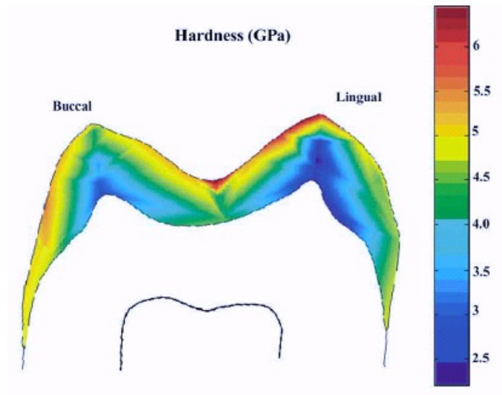
Hardness distribution of enamel crown



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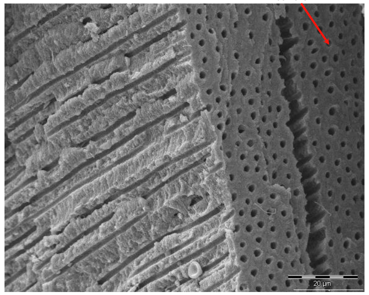
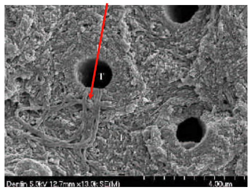
Dentin

composite

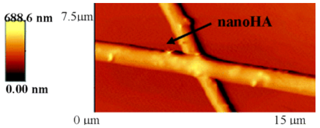
moderately hard, very strong and tough



about 1/3 organic + water
(collagen fibers)



about 2/3 inorganic
(HAP crystals on collagen fibers)



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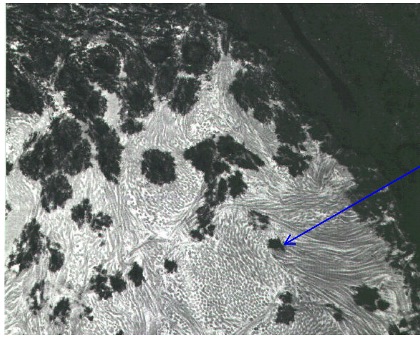
Cementum

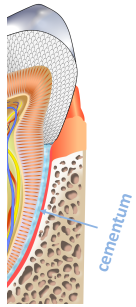
composite



≈ 50% organic + water (collagen!)

≈ 50% HAP

HAP crystals



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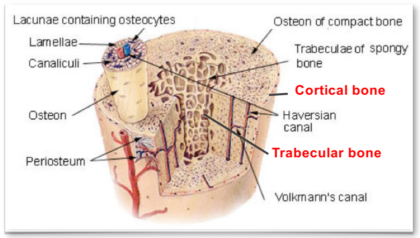
Bone

Due to the different structure of bone tissue along the cross section of long bones, the **Young's modulus distribution is anisotropic**. Denser cortical bone has greater Young's modulus vs. the trabecular bone..
Young's-modulus: 5-20 GPa
Decalcified bone (acid treatment): flexible
Removal of organic compounds (heating): brittle



30 % Organic matrix: collagen

70 % Inorganic salt: Hydroxylapatite

composite

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Properties of dental biomaterials

	PDL (≈ collagen)	dentin (≈1/3 collagen, 2/3 apatite)	enamel (≈ apatite)
Young's modulus (*E*) (GPa)	0,3–2,5	10–20	90–100
strength (σ_{max}) (MPa)	60	110 (tensile) 300 (compress)	50 (tensile) 400 (compress)
toughness (kJ/m³)	1–10	0,5–5	0,1–1
hardness HV (GPa)	*too soft to measure*	0,5–1	3–6

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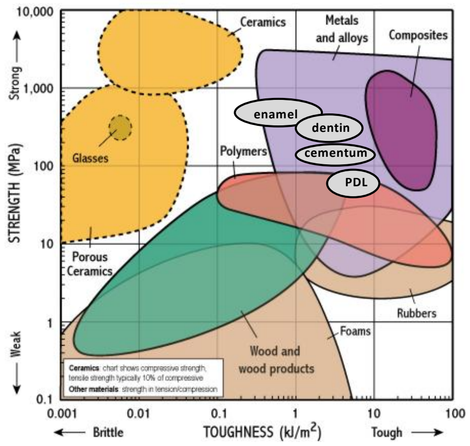

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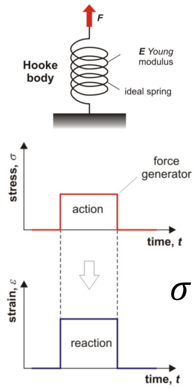
Viscoelasticity

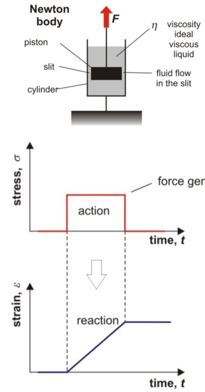
(mechanical model)

Elastic body



$$\sigma = E\varepsilon$$

Viscous body



viscosity

$$\sigma = \eta \frac{\Delta\varepsilon}{\Delta t}$$

strain rate

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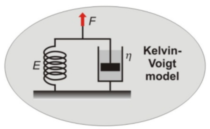
Viscoelasticity

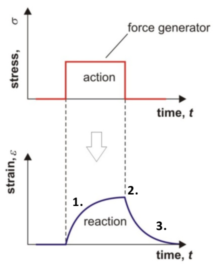
(mechanical model)



Viscoelasticity means to co-appearance of viscous and elastic behavior. A

model: parallel connection of spring and dashpot (Kelvin-Voight model)

Spring: ideal elastic (Hooke) body
Dashpot: ideal viscous (Newton) body



1. Upon stretch, the extension of the spring is slowed down by the dashpot.
2. Extension stops when the elastic spring force equals the external force.
3. When the external force is quenched, the contraction of the spring is slowed down by the dashpot.

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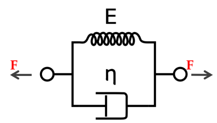
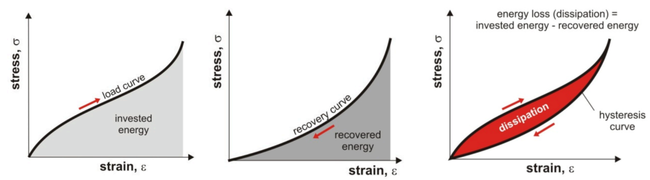
Visco-elasticity

(mechanical model)



model: parallel connection of a spring and a dashpot (Kelvin-body)



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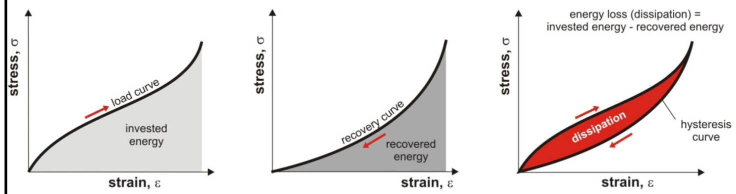
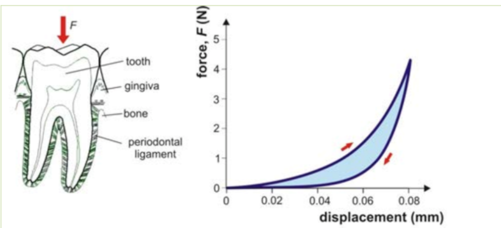
Energy dissipation in viscoelastic system



Periodontal ligament



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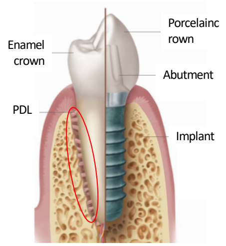
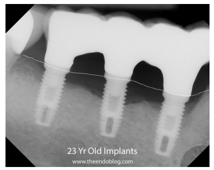
Example: Implants vs nastural tooth

PDL makes the difference!





Absence of PDL result in :

- **loss of masticatory force perception**
- **loss of visco-elastic (damper) effect**
- **loss of force sensory mechanisms**
- **No implant movement**

Implant is in direct contact with bone tissue

⇩

Increased compressive stress

⇩

Bone loss (0.2 mm / year)
Loss of gingival height

Implants ⇔ Root Canal Treatment

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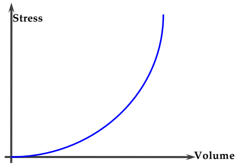
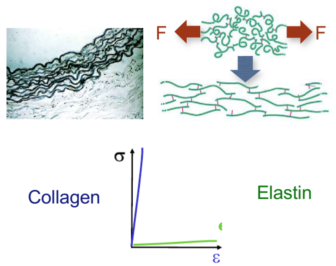
Biomechanics of elastic arteries

Non-liear elasticity
Strain is not linearly proportional to stress.



Determinants of vascular elasticity:
Elastin
Collagen
Smooth muscle

Implications of vascular easticity:
Storage of potential (elastic) energy
Dampening of pressure pulses
Constant flow rate



Collagen: E = 300 MPa .... 2 500 MPa; $\sigma_{sz} \approx 60$ MPa; $\varepsilon_{sz} \approx 0{,}08$ → strength

Elastin: E = 0,1 MPa .... 0,4 MPa; $\sigma_{sz} \approx 0{,}6$ MPa; $\varepsilon_{sz} \approx 3$ → elasticity

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Physical bases of dental material science

BIOMECHANICS

Molecular nanomechanics

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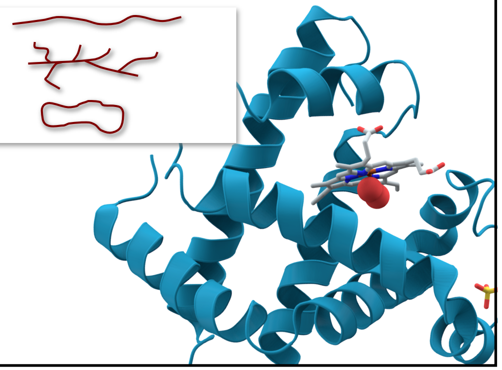
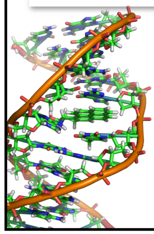
Biomolecules are polymers

Common feature: **Linear primary structure (protein, DNA)**
Strong bonds between monomers (covalent)
Weaker interactions between distant region of polymer chain

1. Linear
DNA, protein, cellulose
2. Branched
glycogen
3. Circular
mt DNA





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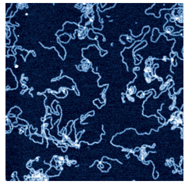
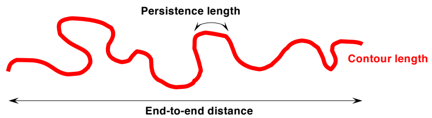
What is the shape of biopolymers?

Parameters to describe the shape of polymer



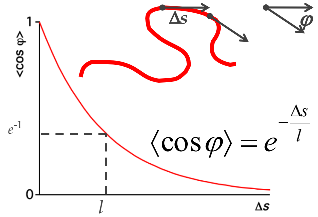
AFM image of dsDNA



Contour length (L): Full length of the chain

End-to-end distance (R): Distance between chain termini.

Persistence length (*l*) : describe the persistence of chain orientation.



$$\langle \cos\varphi \rangle = e^{-\frac{\Delta s}{l}}$$

Shorter persistence length polymers are more flexible.

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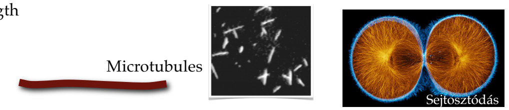
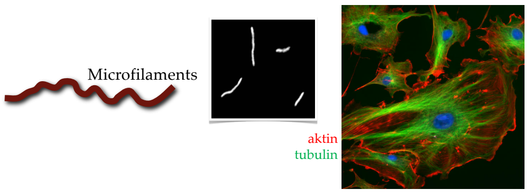
Biopolymer classification based on flexibility

l = persistence length
L = contour length

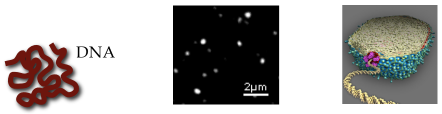
RIGID
$l >> L$



SEMIFLEXIBLE
$l \approx L$



FLEXIBLE
$l << L$



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Are biopolymers elastic?

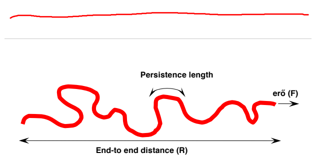
Yes, but Hooke's law is not valid! Non-linear elasticity.

Entropic elasticity

Thermal energy (k_BT) excites bending movements in the chain

The chain's disorder (entropy) increases

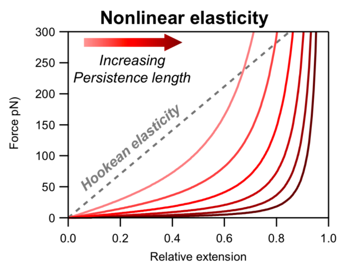
The chain shortens



Force is needed to stretch an entropic chain

$$F \sim \frac{k_B T}{l} \cdot \frac{R}{L} + \left(\frac{R}{L}\right)^a$$

F = force
l = **persistence length**
k_B = Boltzmann constant
T = absolute temperature
L = contour length
R = end-to-end distance
R/L = relative extension



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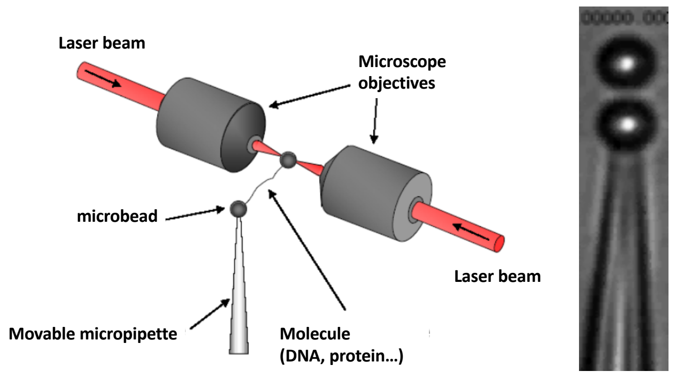
How to stretch single molecules?
Optical tweezers



http://glass.phys.uniroma1.it/dileonardo/Applet.php?applet=TrapForcesApplet

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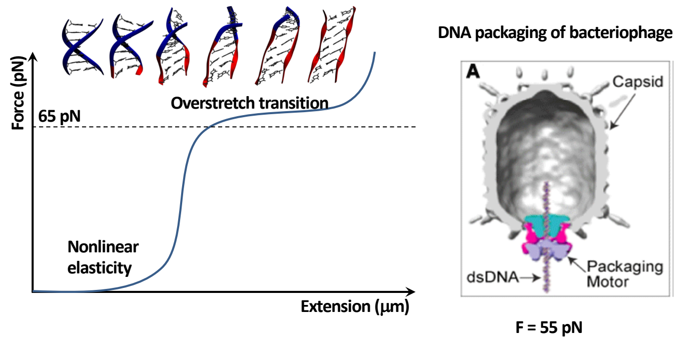
Stretching dsDNA with optical tweezers



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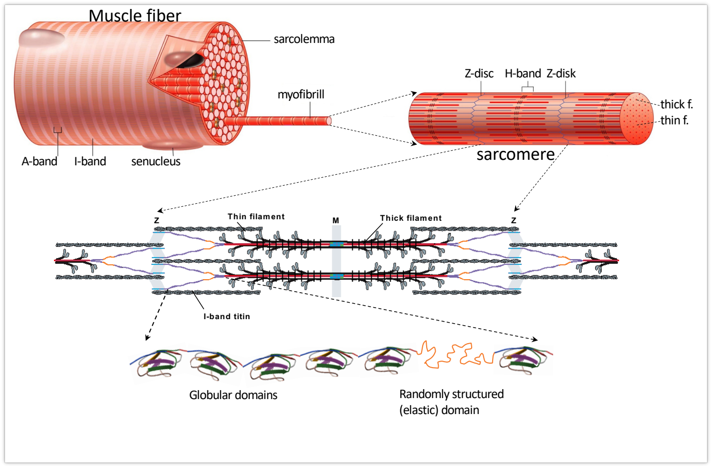
Titin: elastic filament of the sarcomere



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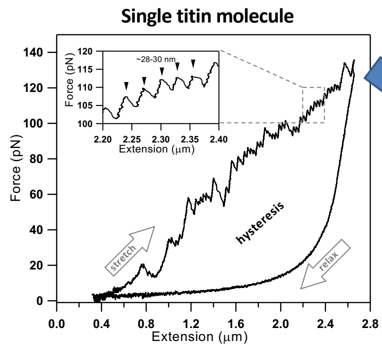
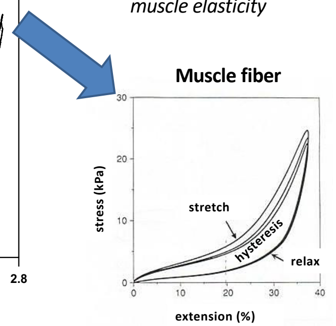
Titin is the main determinant of muscle elasticity



From molecule to tissue

Titin's molecular elasticity explains muscle elasticity



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