# Bone:  Structure and Function

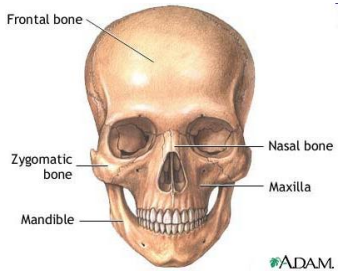
Dr. Warren Macdonald

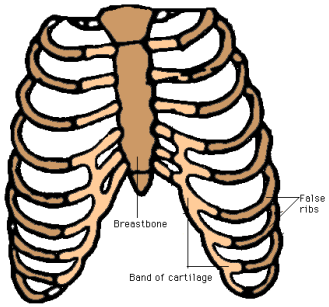
# Bone

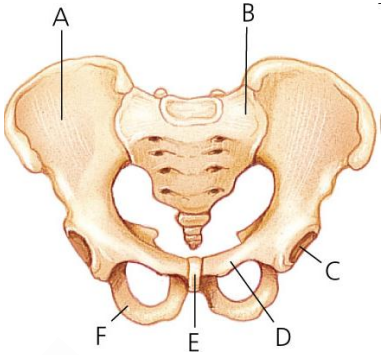
- Structure
- Function
- Mechanical properties

# Types of bones

- Flat bones
  - Skull
  - Ribs, sternum
  - Scapula
  - Pelvis
- Long bones
  - Arms
  - Legs

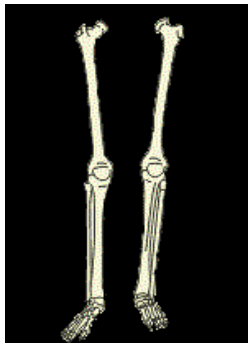


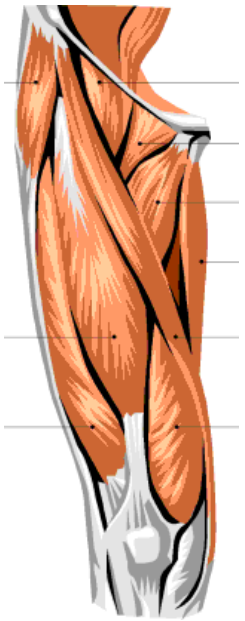



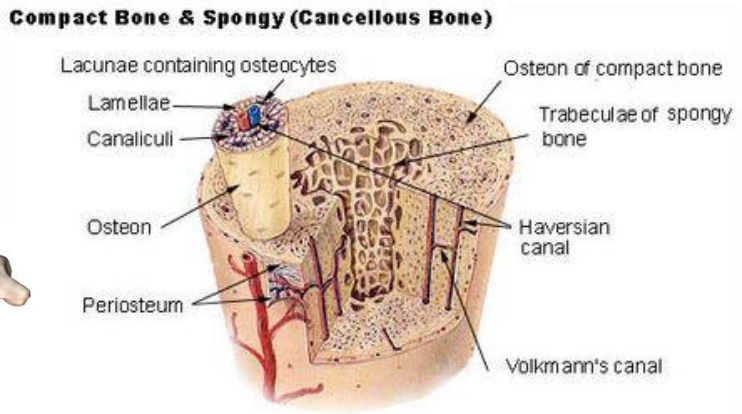



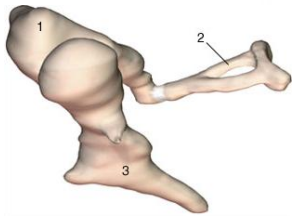

# Functions of Bone

- Support load
- Protect organs
- Provide attachment for muscles
- Store calcium
- Produce cells
- Hearing







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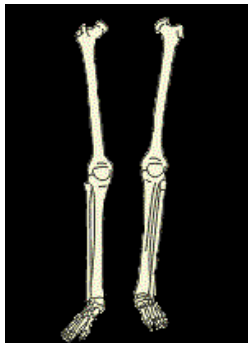
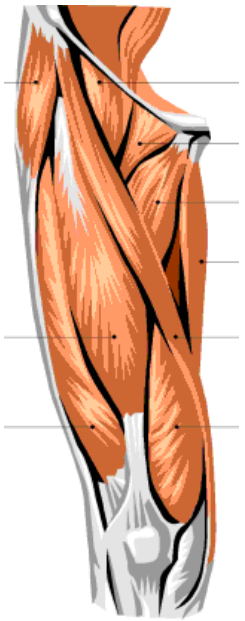
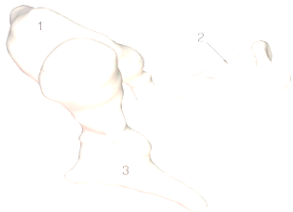
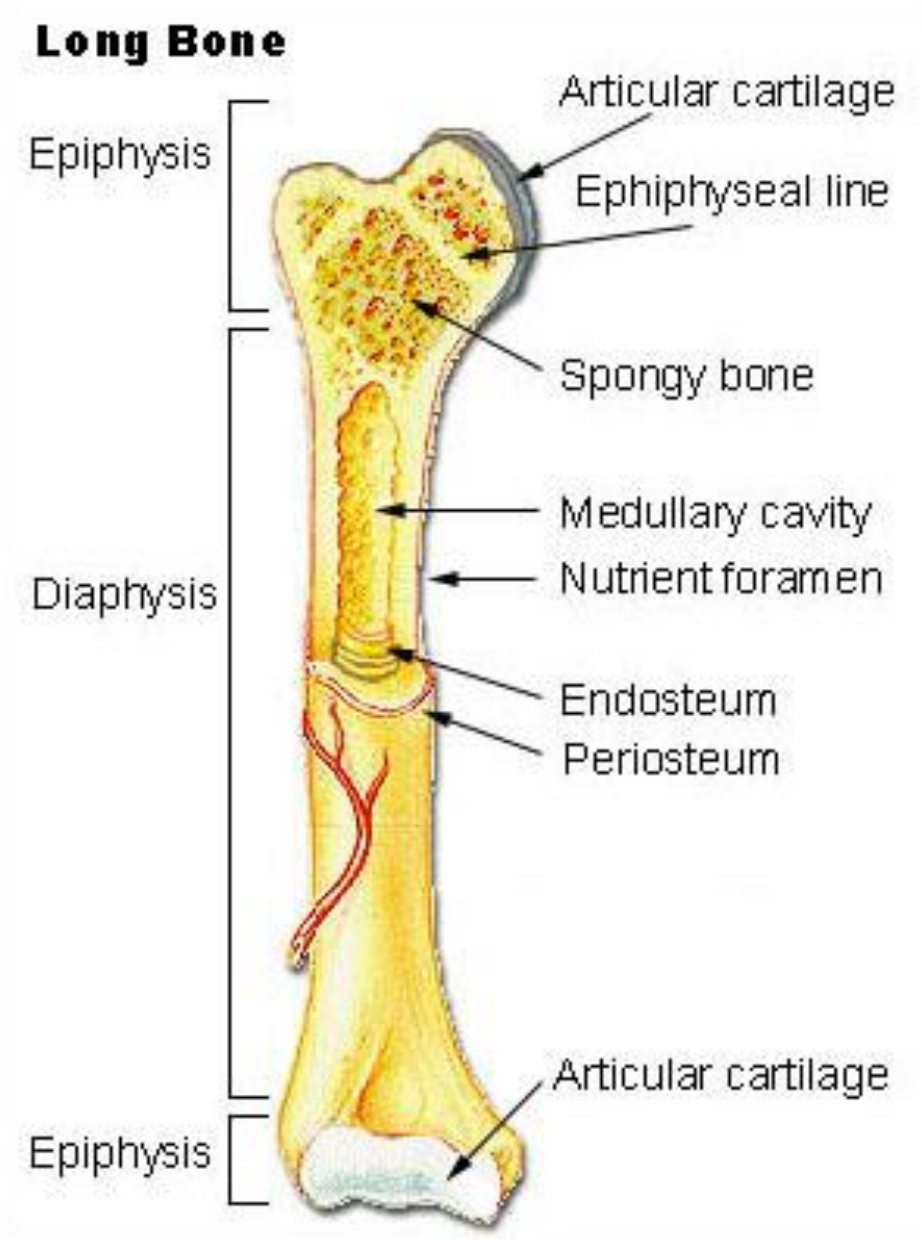




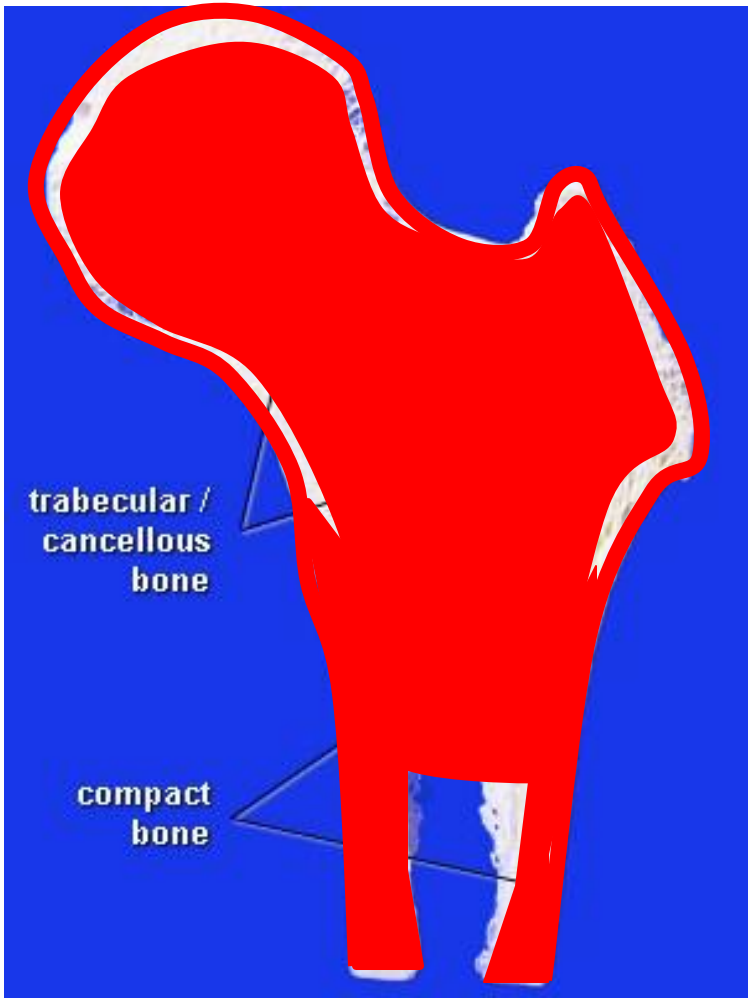
# Terminology

- diaphysis
- epiphysis
- metaphysis
- articular cartilage
- periosteum
- endosteum
- medullary canal

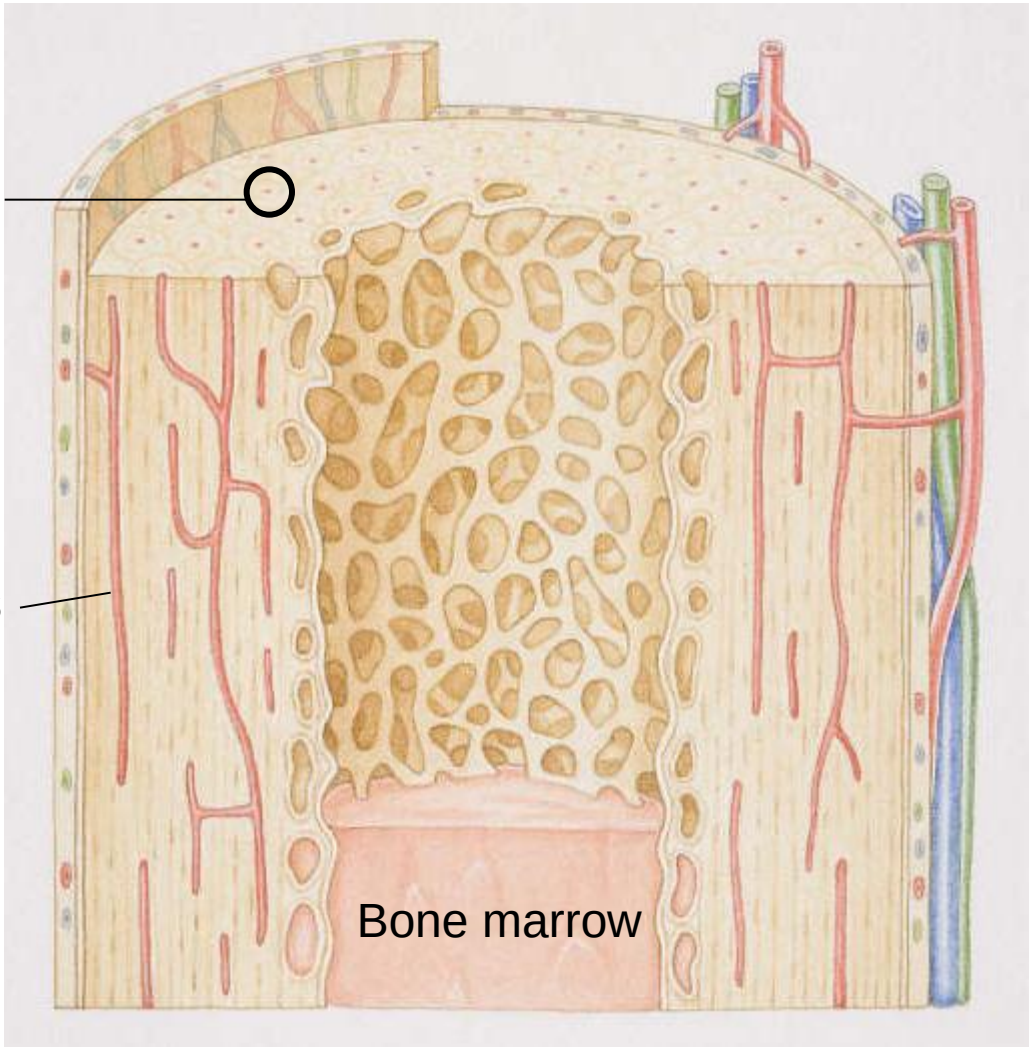


# Structure of bone

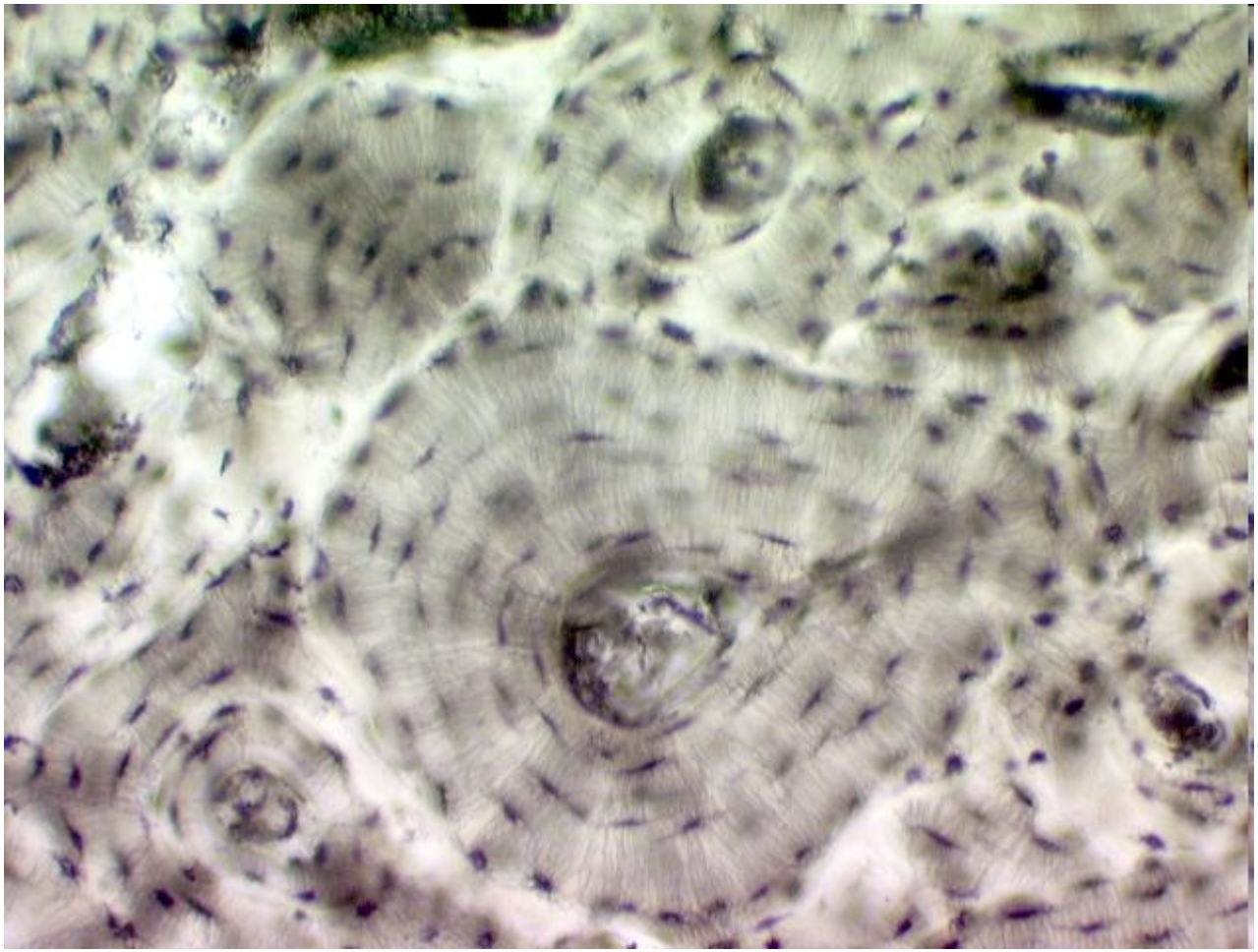
- Cortical bone
  - Compact bone
- Trabecular bone
  - Spongy bone
  - Cancellous bone



# Cortical bone

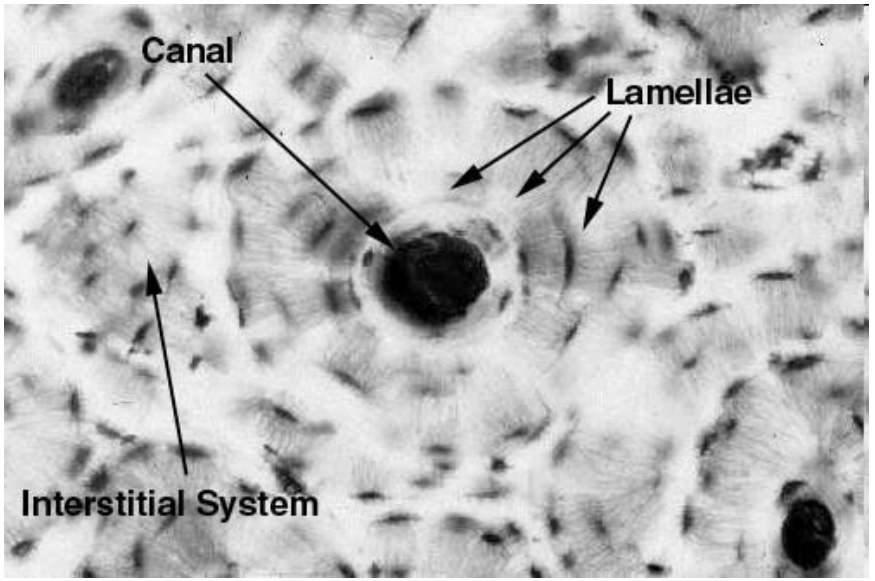


# Osteon



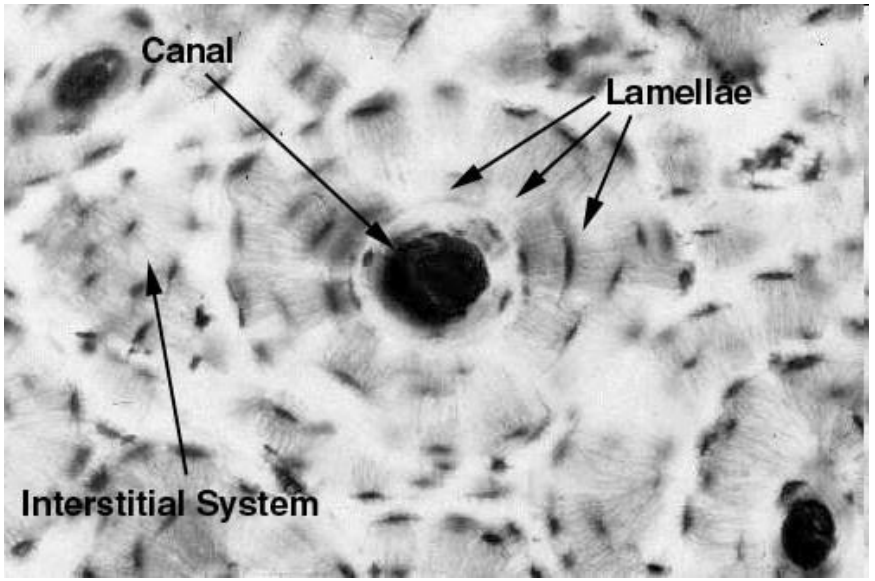
# Osteon

- Lamellae – concentric rings of bone tissue
  - 4-20 lamellae/osteon
  - 3-7 μm width



# Osteon

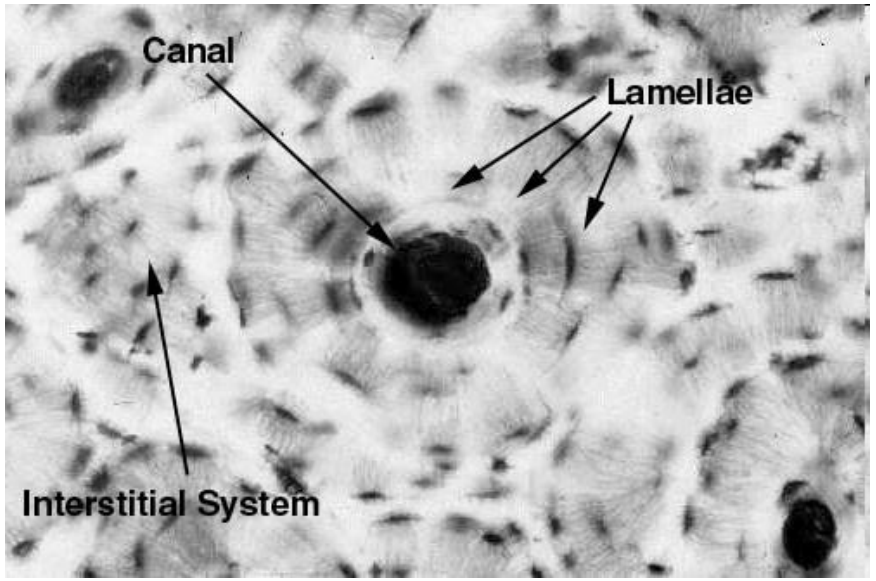
- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon



# Osteon

- Lamellae – concentric rings of bone tissue
- Cement line – outer ring of osteon
- Haversian canal – blood vessels

  50-100 μm in diameter



# Osteon

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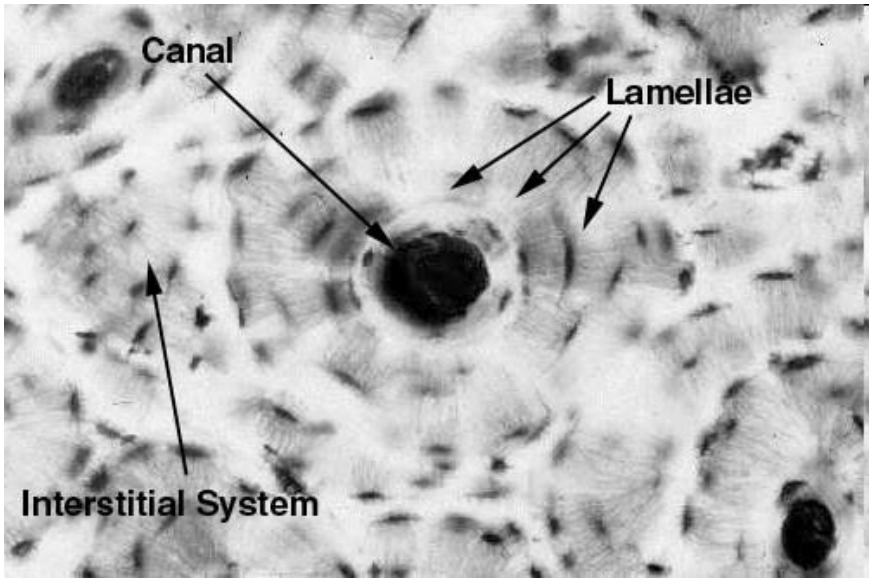
- Haversian canal – blood vessels
- Lacunae - holes for osteocytes



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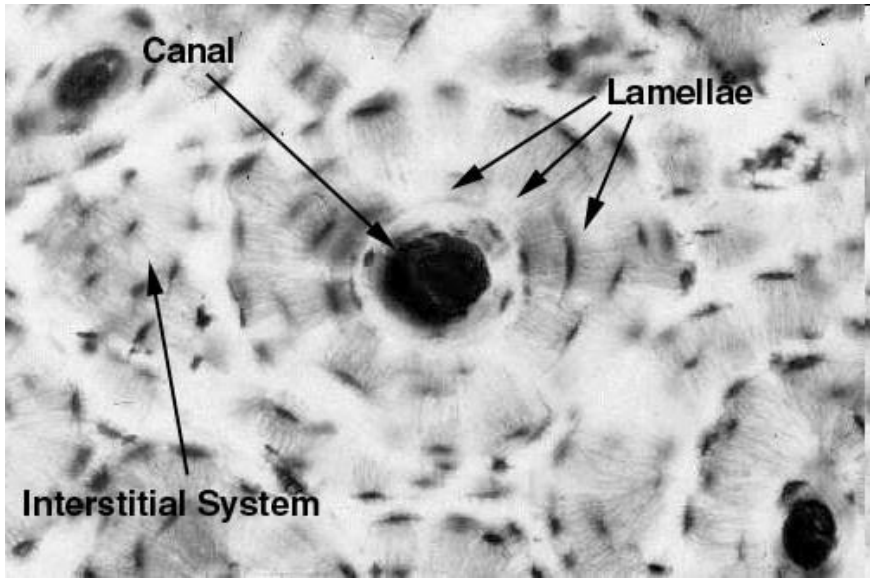
- Canaliculi- osteocyte communication



# Osteon

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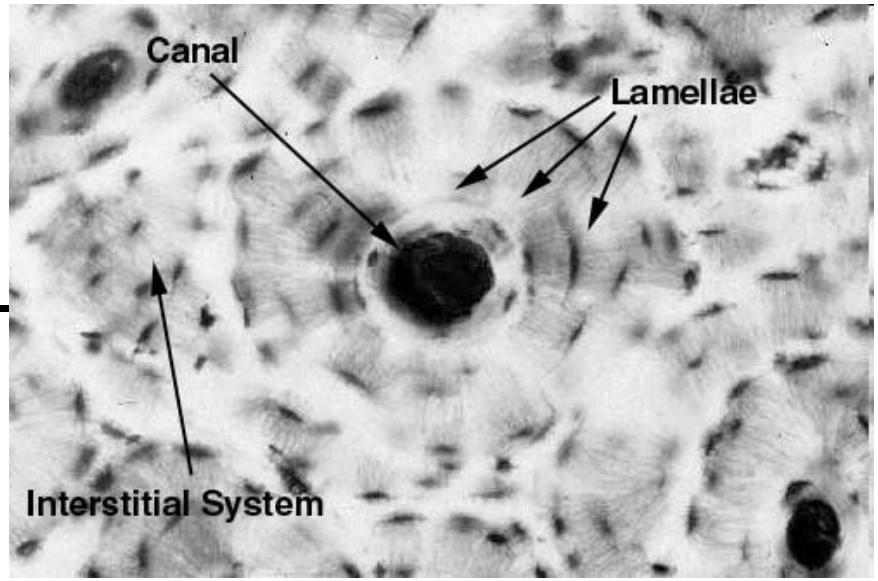
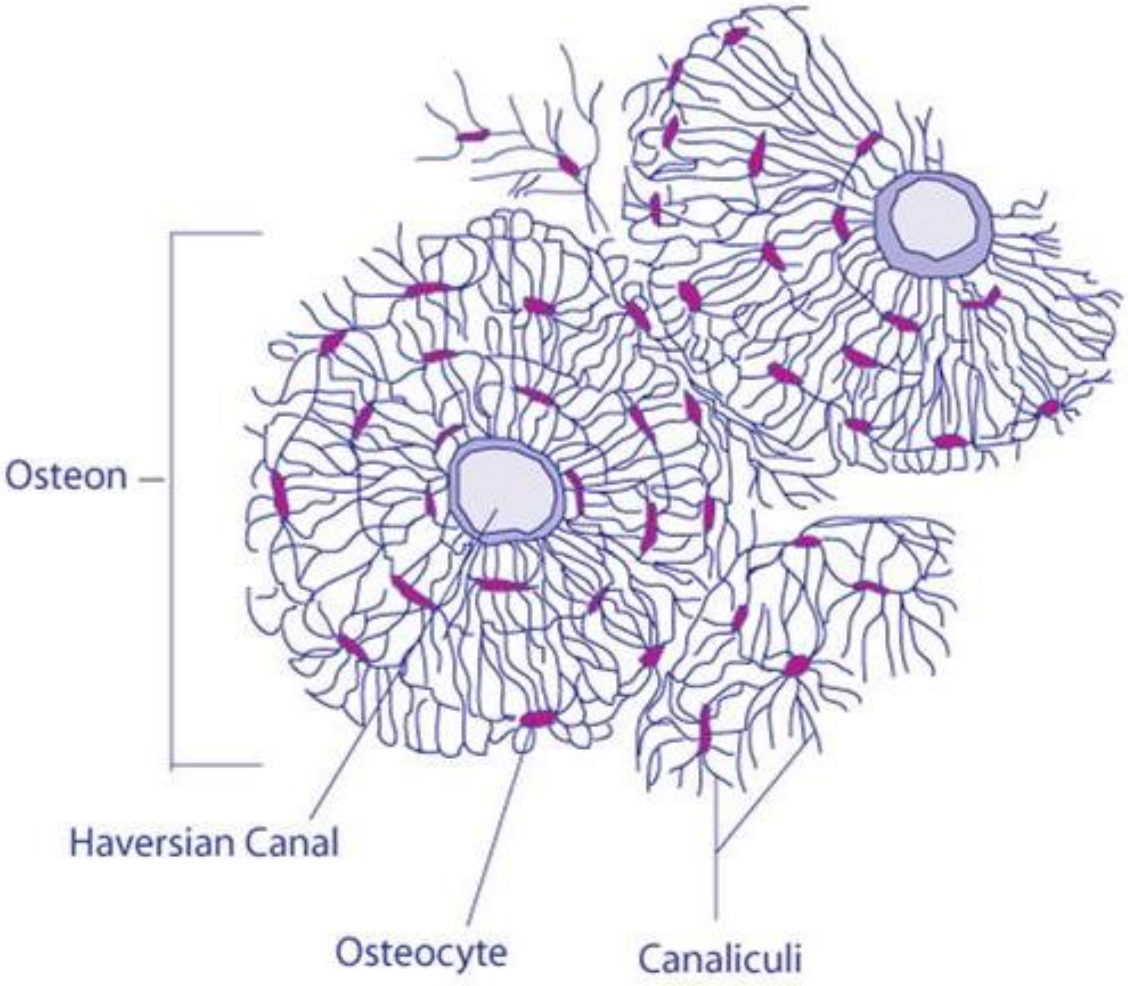
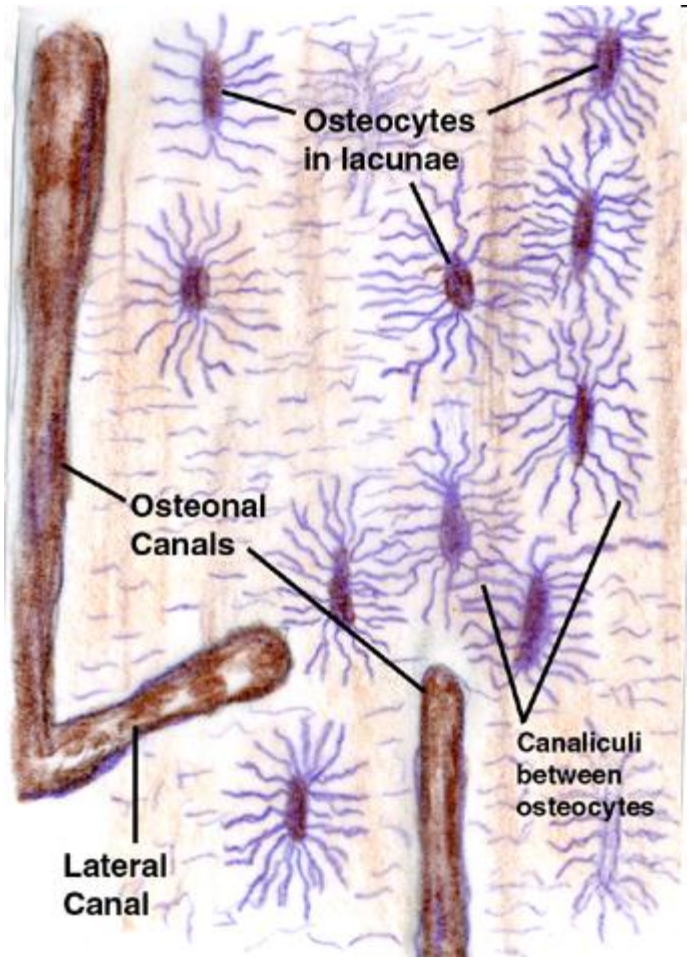
- Cement line – outer ring of osteon
- Haversian canal – blood vessels
- Lacunae - holes for osteocytes
- Canaliculi- osteocyte communication
- Volkmann's canal – transverse blood vessels



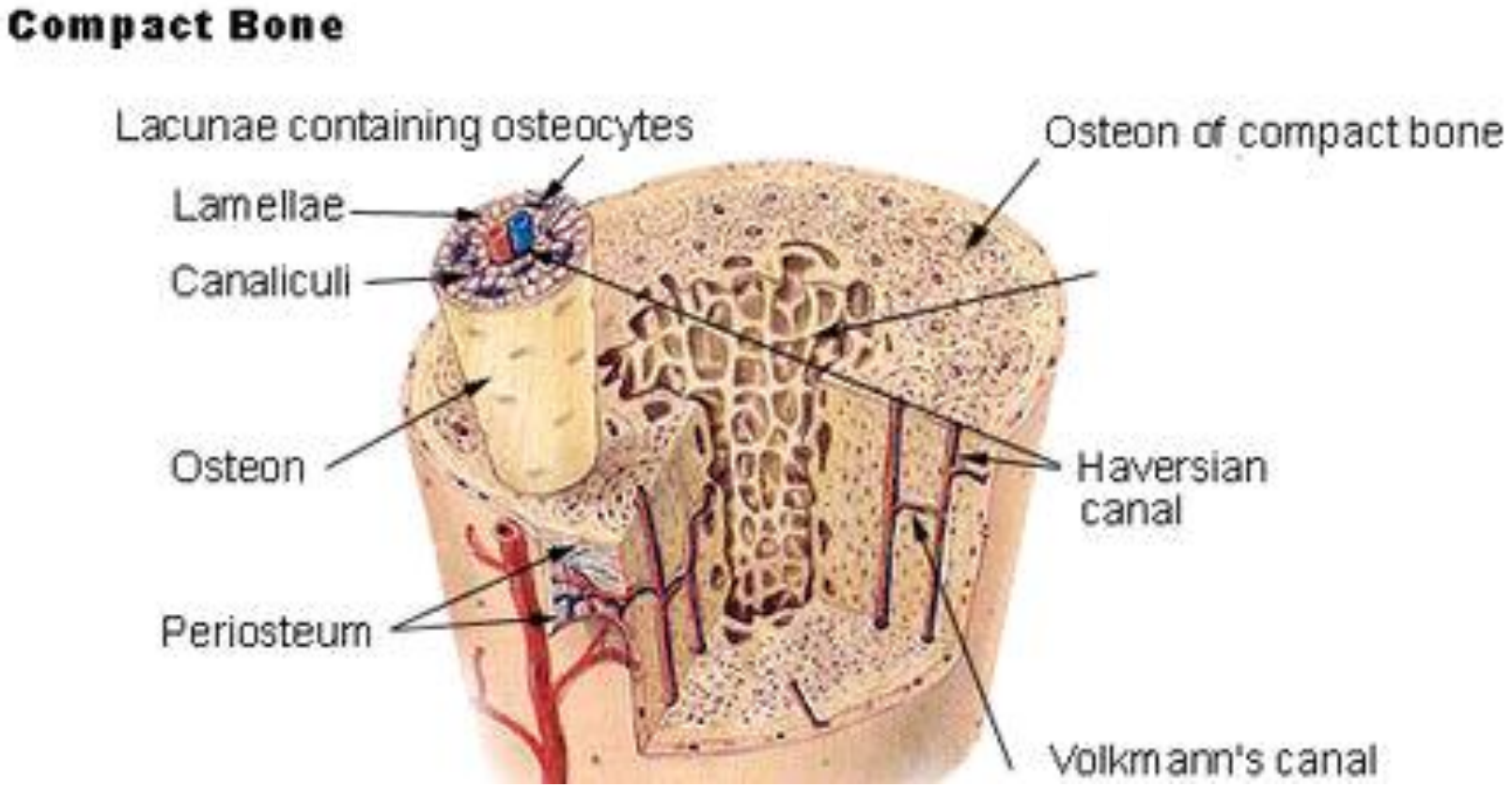
# Cross section



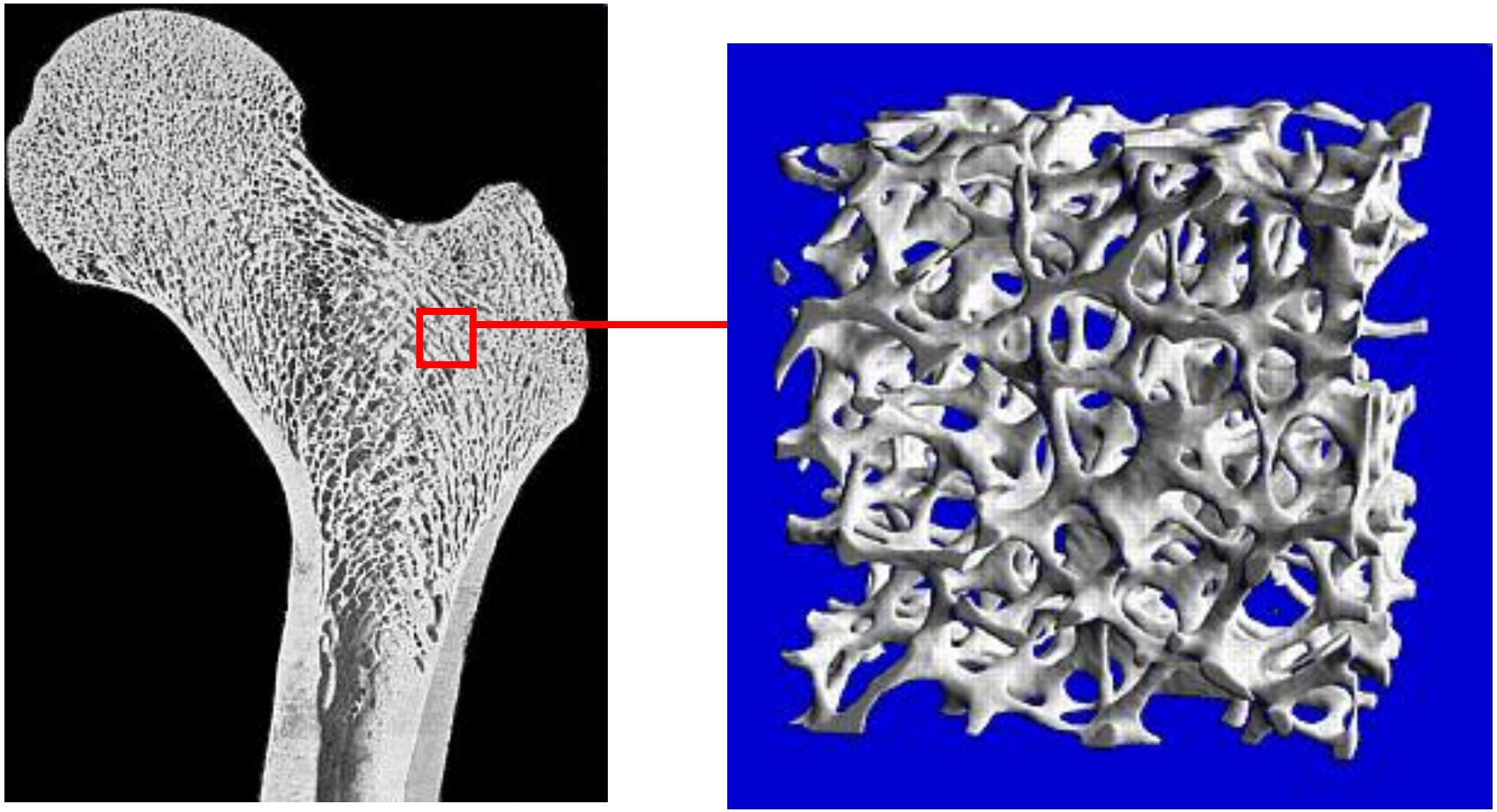

# Longitudinal



# Cortical bone



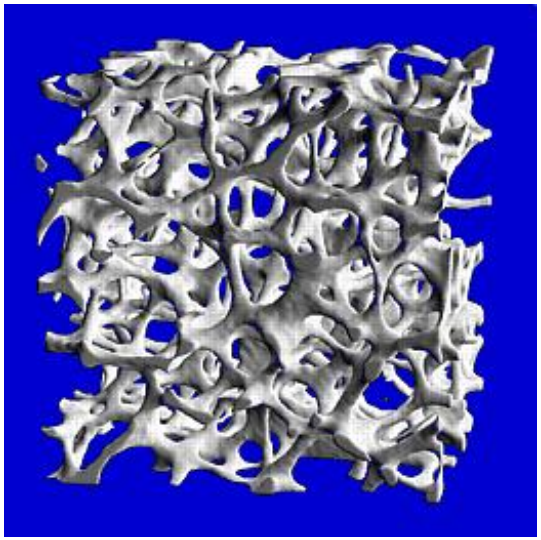
# Trabecular bone



- Found in epiphysis and metaphysis of long bones

# Trabecular bone

- Structure
  - Low density, high surface area
  - Surrounded by red marrow
  - Highly vascular
- Quantifiable
  - Bone volume/total volume
  - Trabecular thickness
  - Trabecular spacing
  - Trabecular shape (rod, plate)
  - Anisotropy



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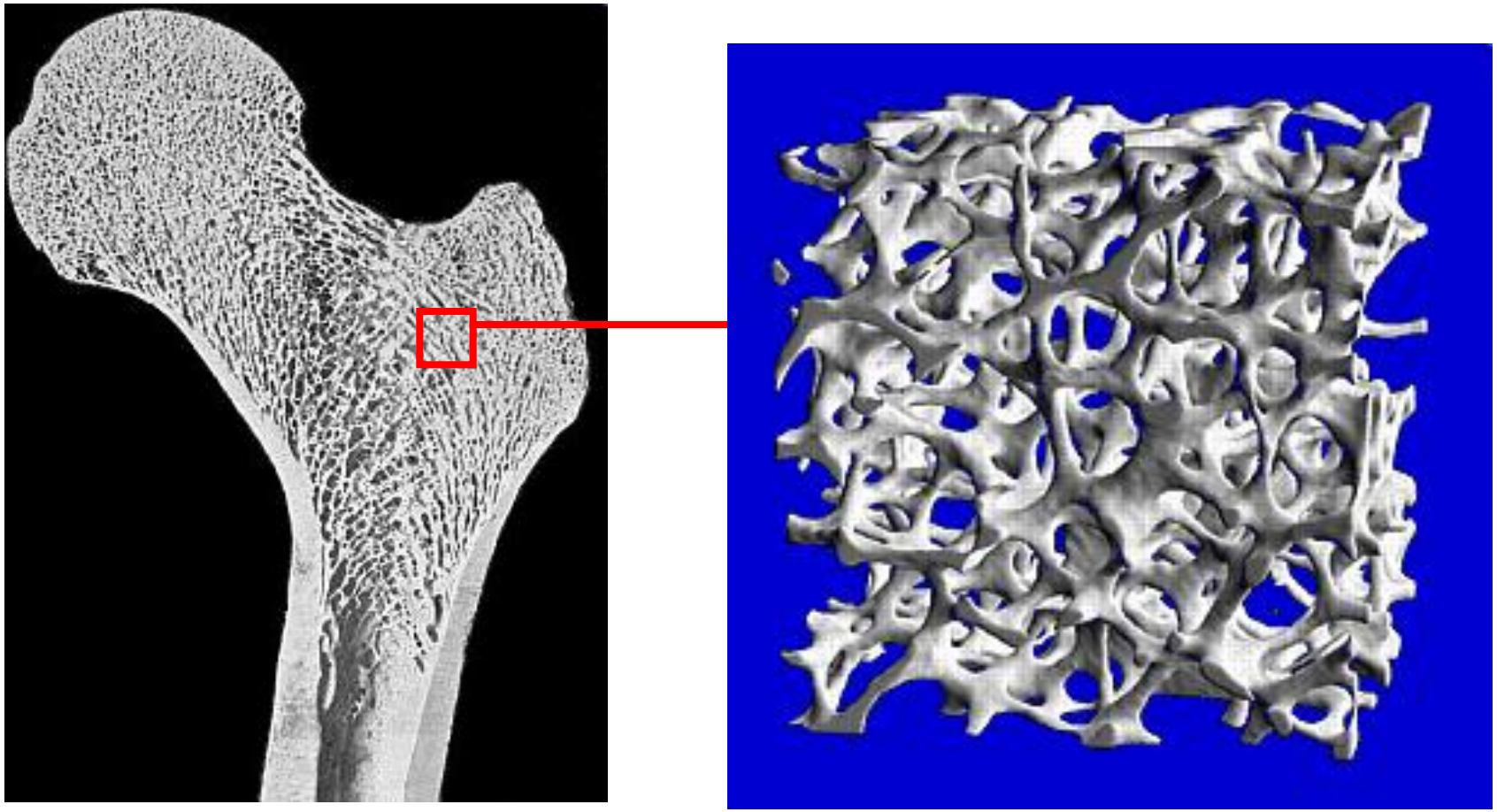


# Bone structure

- Apparent density ($\rho_{app}$)

  = bone mass/total volume
- Cortical bone density: 1.86 ± 0.06 g/cm$^3$

  10% porosity (volume of spaces/volume bone)
- Trabecular bone density: 0.3 ± 0.09 g/cm$^3$

  50-90% porosity
- Tissue density ($\rho_{tiss}$)

  = bone mass/bone volume = 2.0 g/cm$^3$

# Bone content

- Organic components (osteoid)
  - 90% collagen

# Bone content

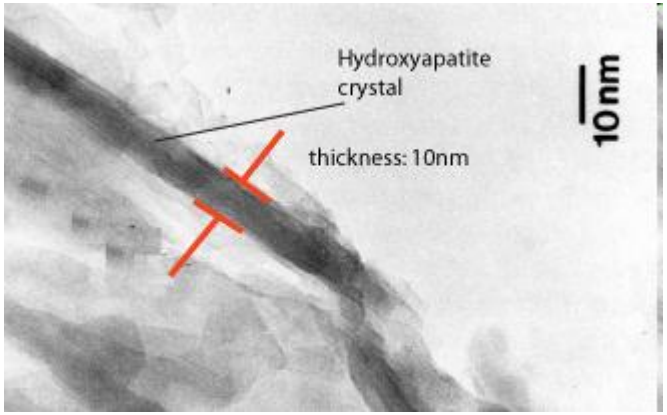
- Organic components (osteoid)
  - 90% collagen I
  - 10% GAGs, glycoproteins

Organic components = 50% bone volume

25% bone by weight

# Bone content

- Organic components (osteoid)
- Mineral
  - Hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$
  - Crystals 2-5 nm thick, 15 nm wide, 20-50 nm long
  - Ca/P ratio changes
  - $PO_4$ sometimes carbonate



# Bone content

- Organic components (osteoid)
- Mineral components

Organic components = 50% bone volume
25% bone weight

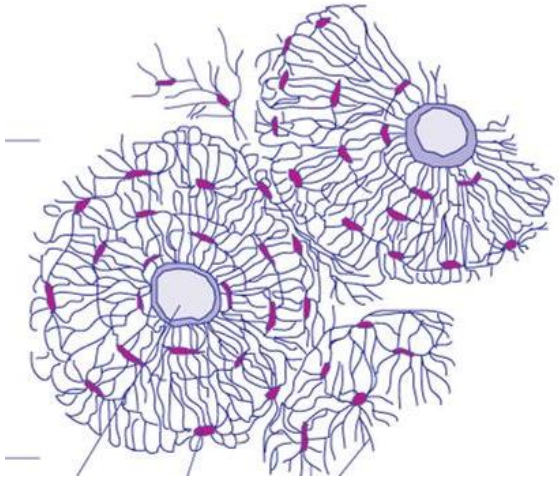
Mineral components = 50% bone volume
75% bone weight

# Bone content

- Organic components (osteoid)
  - Tensile strength
- Mineral components
  - Compressive strength

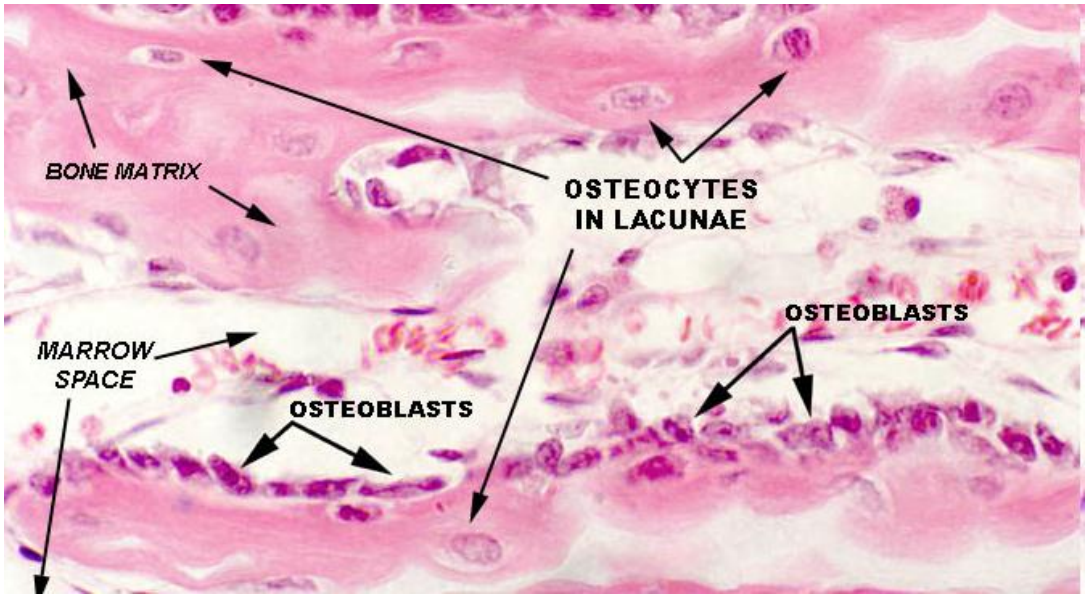
# Bone cells

- Osteocytes
  - Sit within bone matrix
  - Communicate with canaliculi
  - Live for 25 years
  - Function = mechano-sensing, maintenance



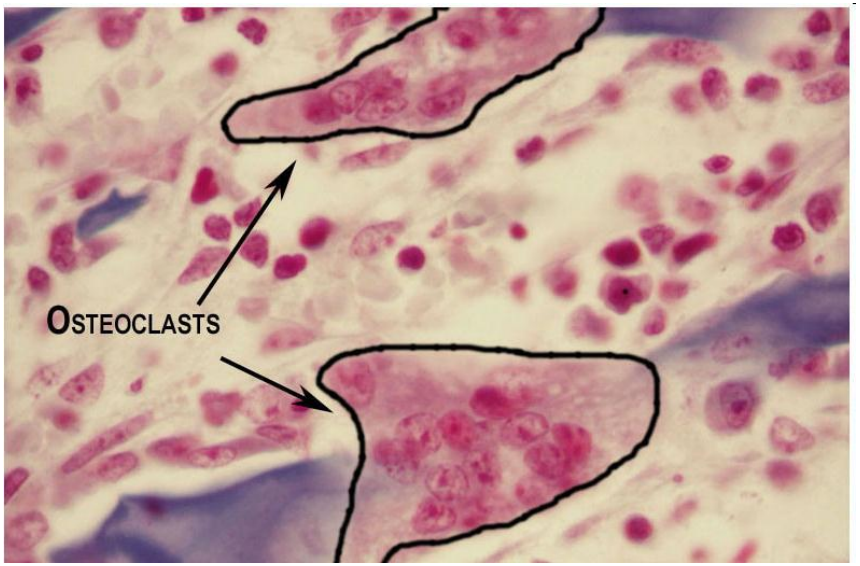
# Bone cells

- Osteocytes
- Osteoblasts
  - Lay down bone
  - Make collagen fibers and proteoglycans
  - Deposit apatite
  - Can become osteocyte



# Bone cells

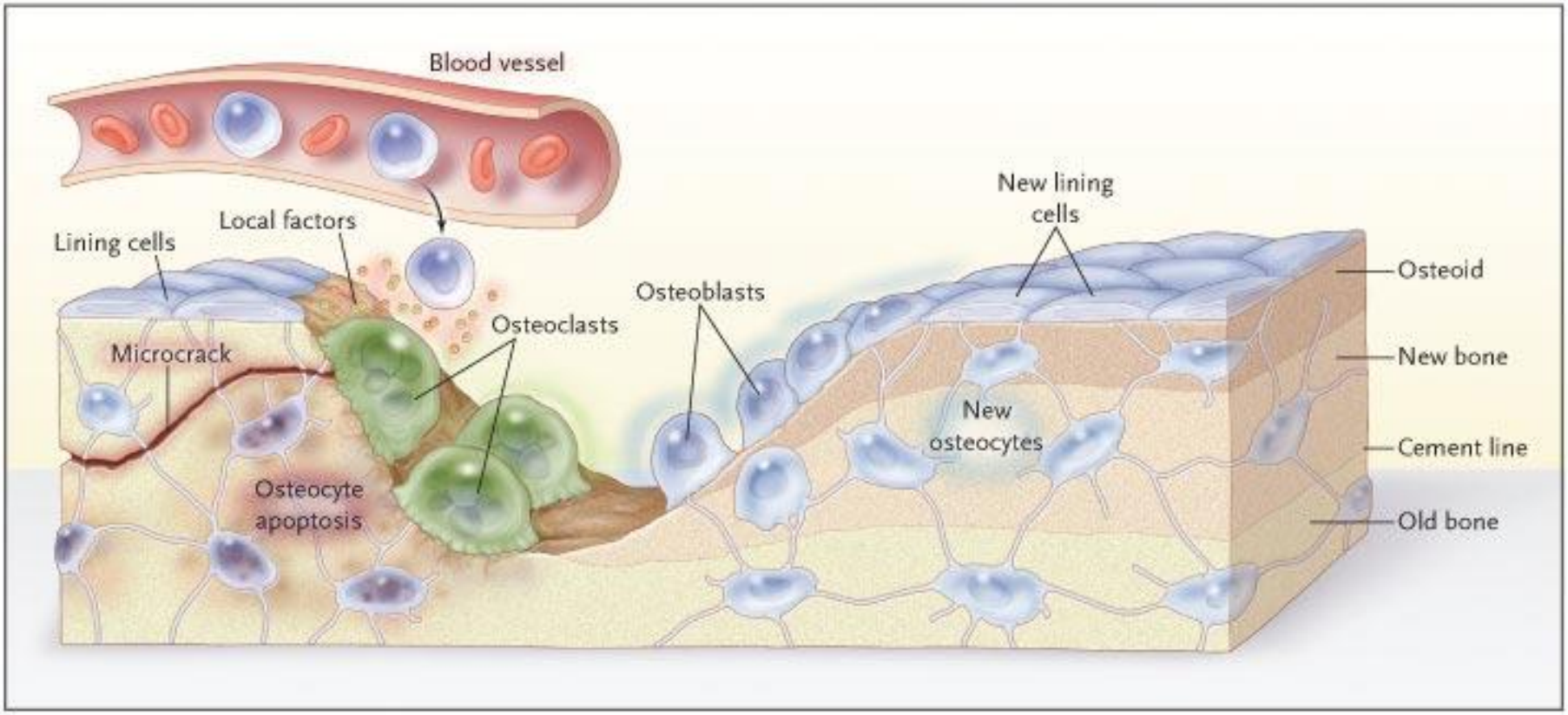
- Osteocytes
- Osteoblasts
- Osteoclasts
  - Remove bone
  - Multinucleated, larger than osteoblasts
  - Secrete $H^+$ to dissolve mineral
  - Secrete collagenase to clear protein



# Bone turnover

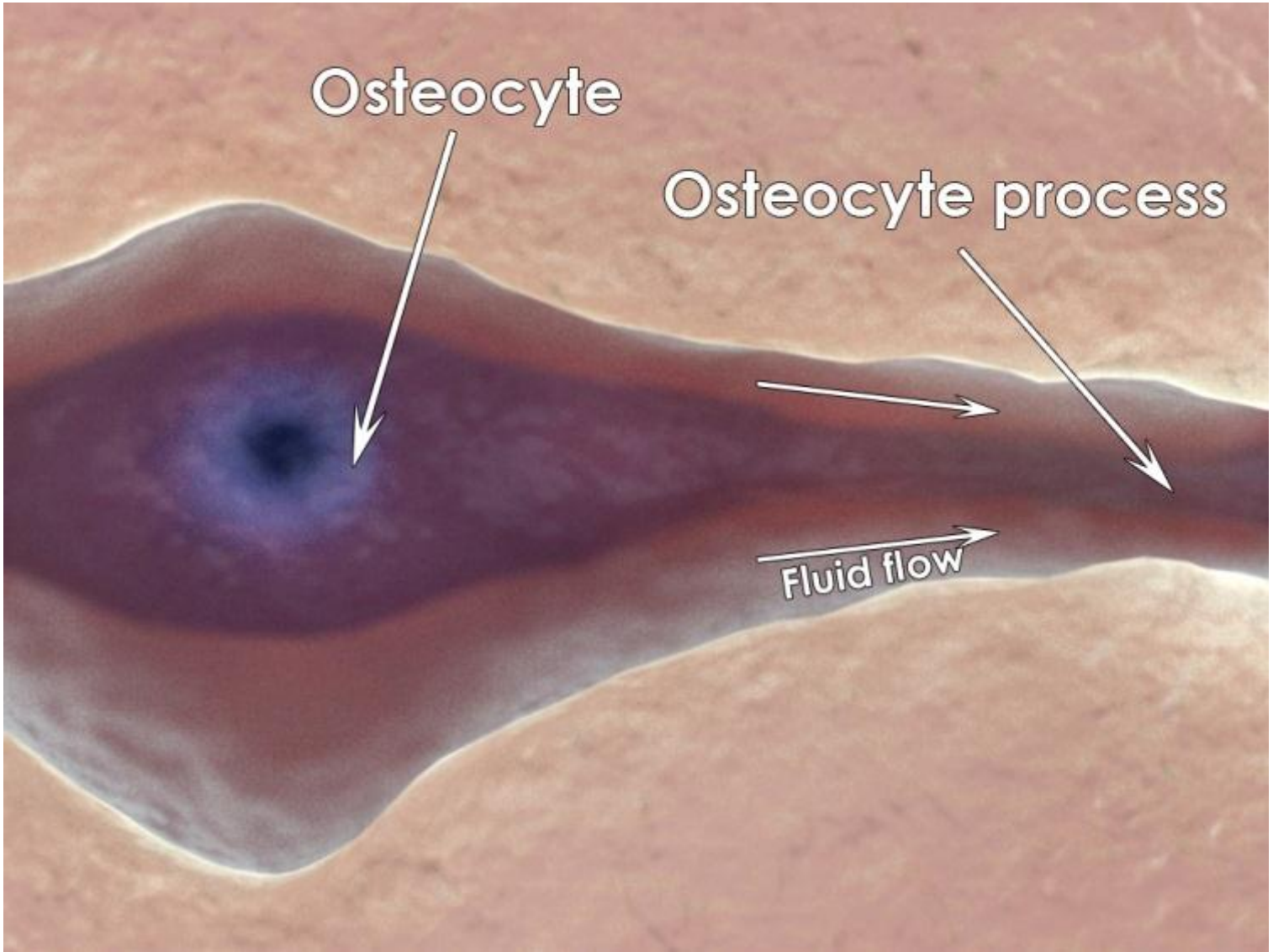
- All bone in your body is replaced in 3 years
- Basic multicellular units (BMUs)
  - Bone lining cells
  - Osteoclasts
  - Osteoblasts

# BMU

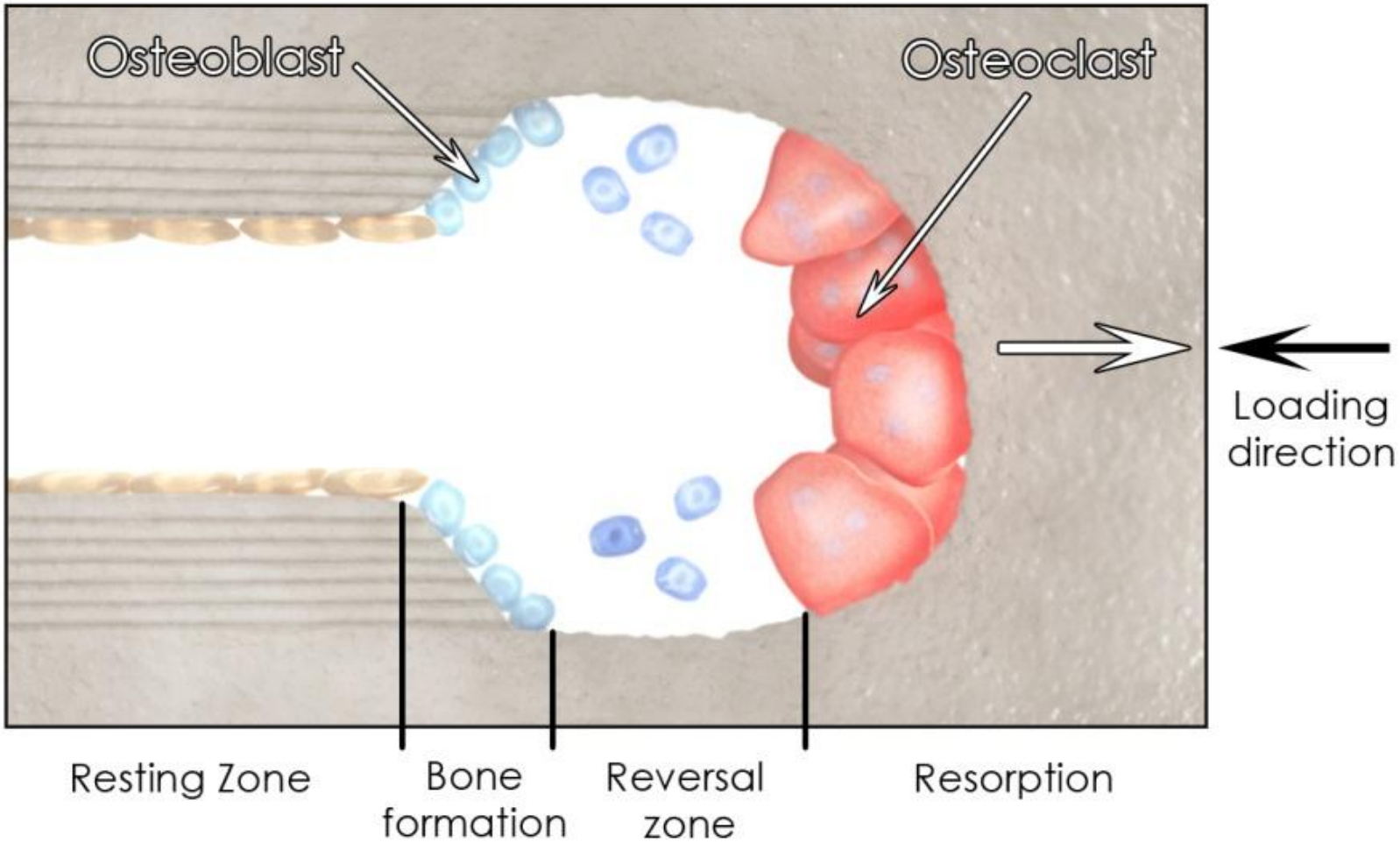

Blood vessel
Lining cells
Local factors
Microcrack
Osteocyte apoptosis
Osteoclasts
Osteoblasts
New lining cells
New osteocytes
Osteoid
New bone
Cement line
Old bone

# Osteocytes

# Mechanotransduction



# Aligned remodelling



# BMU

- Origination – damage or mechanical stimuli triggers start of process
- Bone lining cells recruit osteoclasts
- Osteoclasts resorb bone – create resorption pit
- Osteoclasts die (apoptosis)
- Osteoblasts fill pit with osteoid
- Mineralization of matrix
- Maturation of matrix

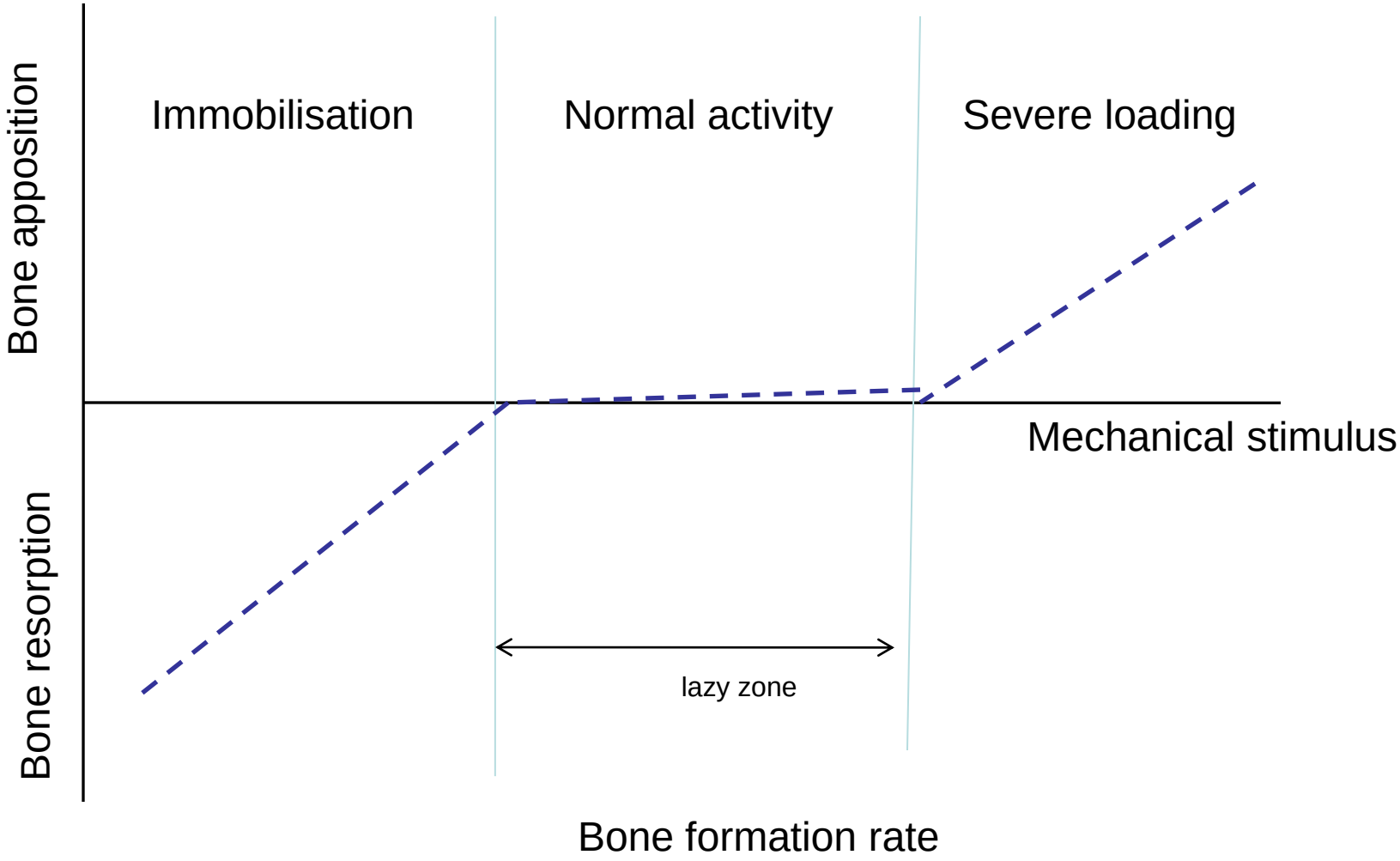
# BMU Time line

- Activation – 3 days
  - Sense damage, recruit osteoclasts
- Resorption – 30 days
  - Osteoclasts to dig a pit
- Formation – 90 days
  - Osteoblasts lay down osteiod
- Mineralization – 6 months
  - 60% occurs within 24 hours

# Bone turnover

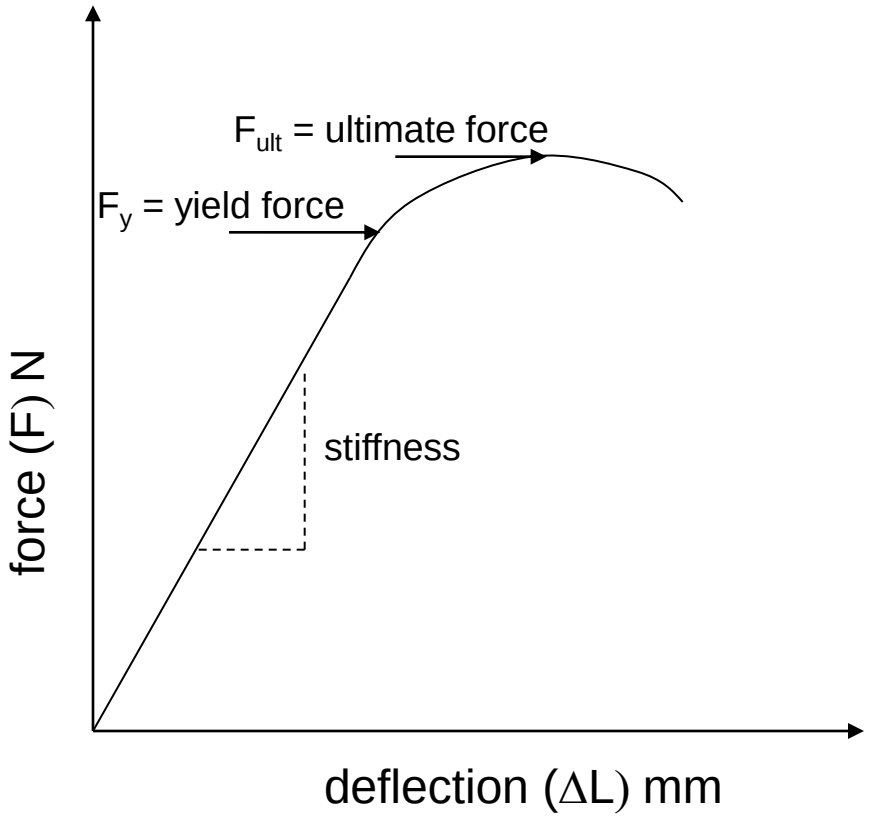
- Trabecular bone
  - On the surface
- Cortical bone
  - Within an osteon

# Bone Maintenance



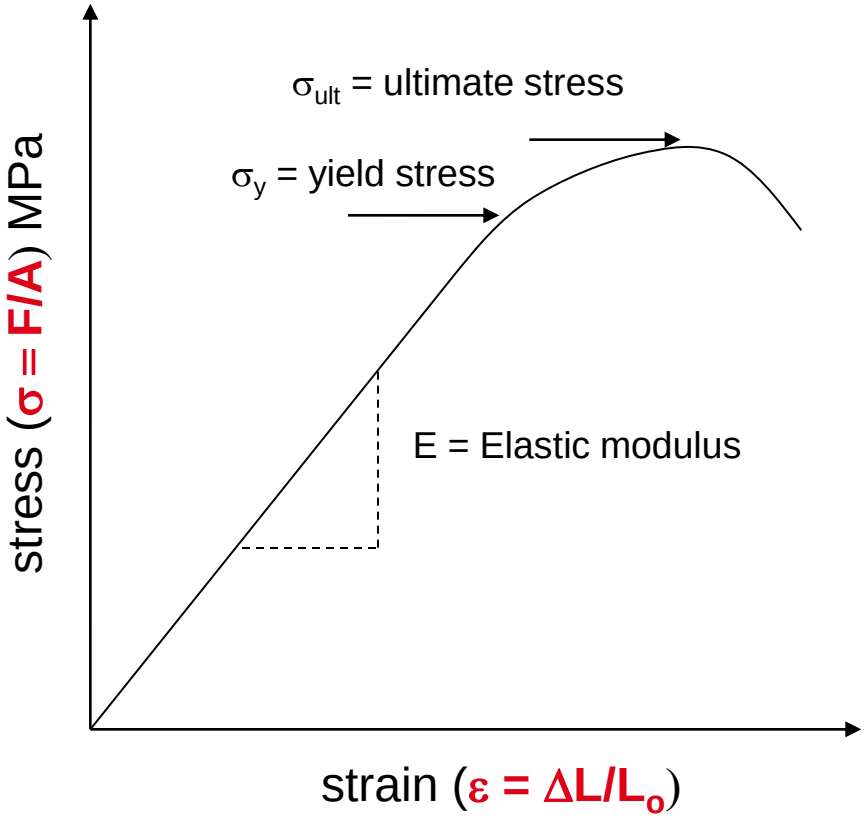
# Bone mechanics

- Force/displacement



# Bone mechanics

- Stress/strain curve



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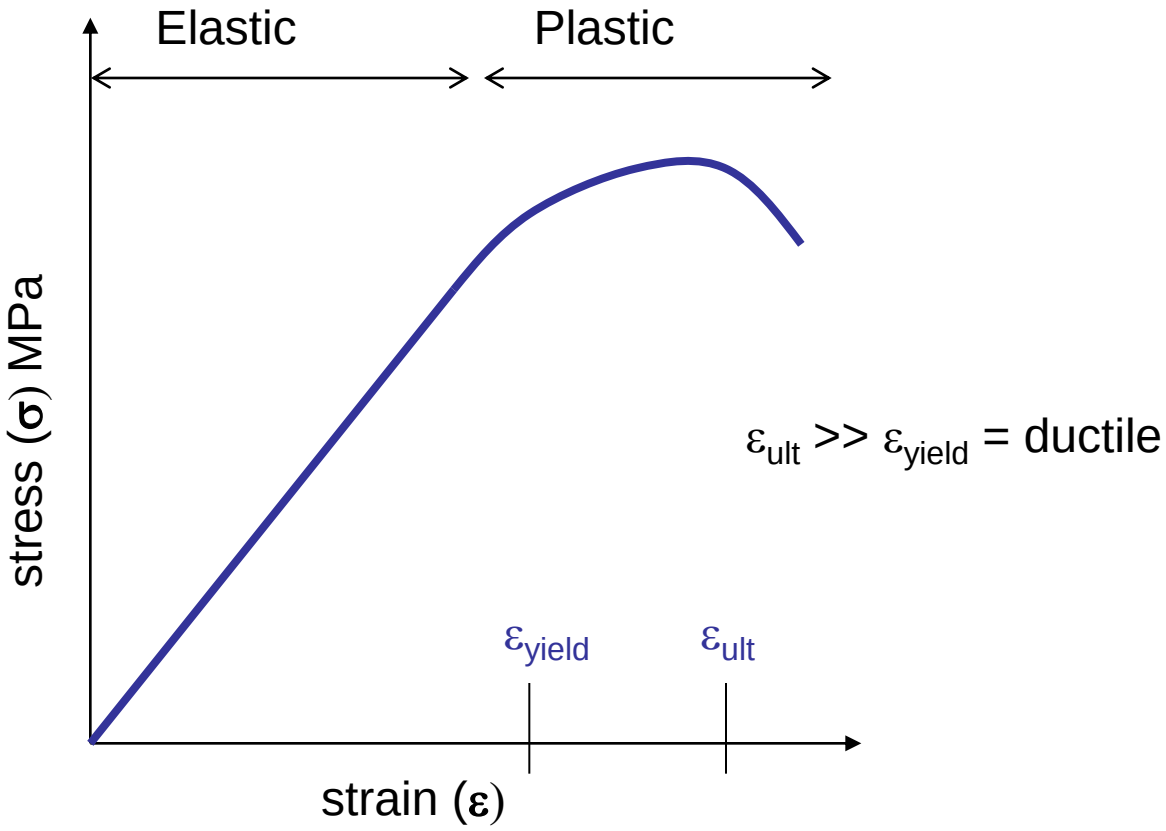

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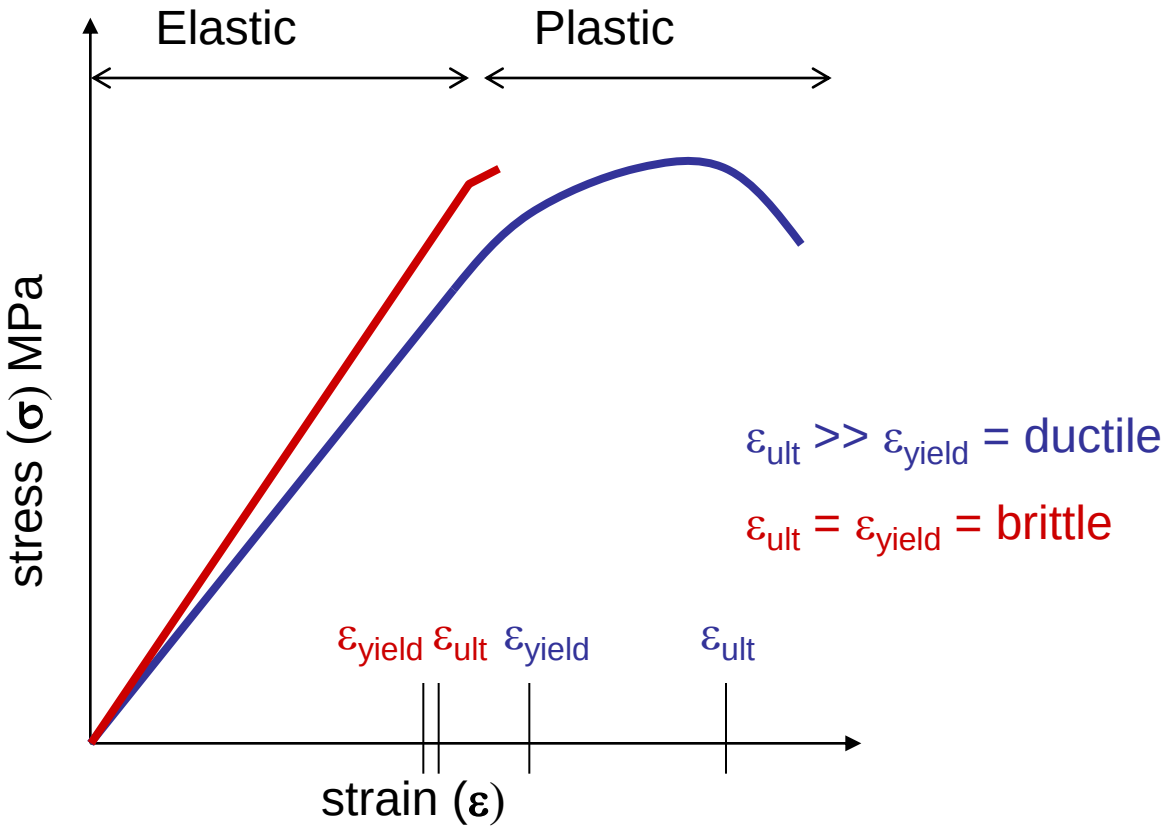
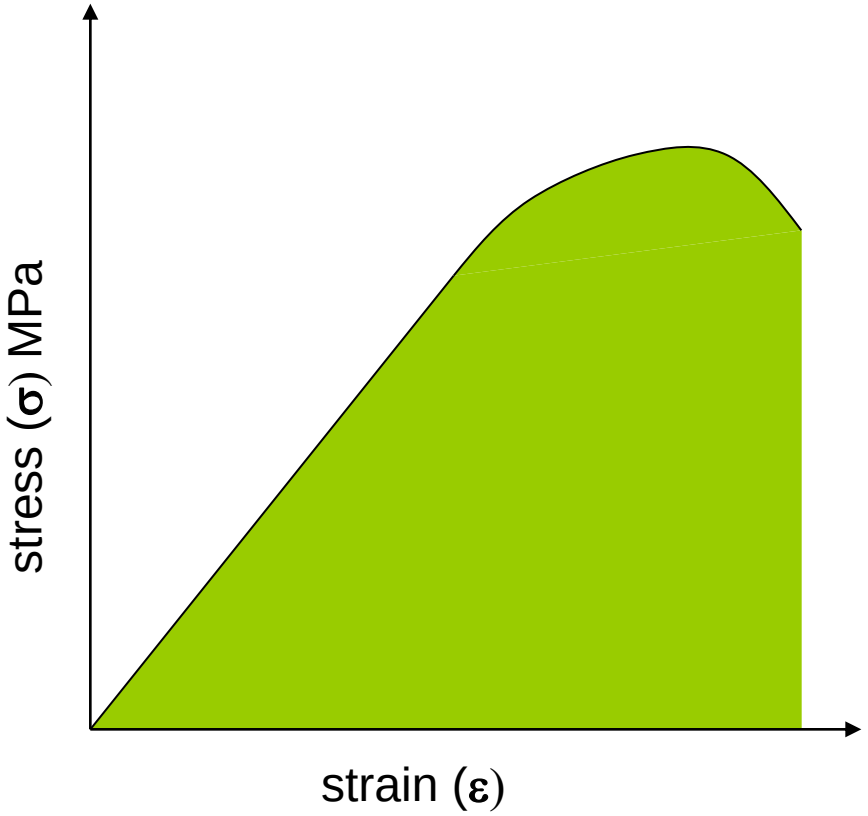
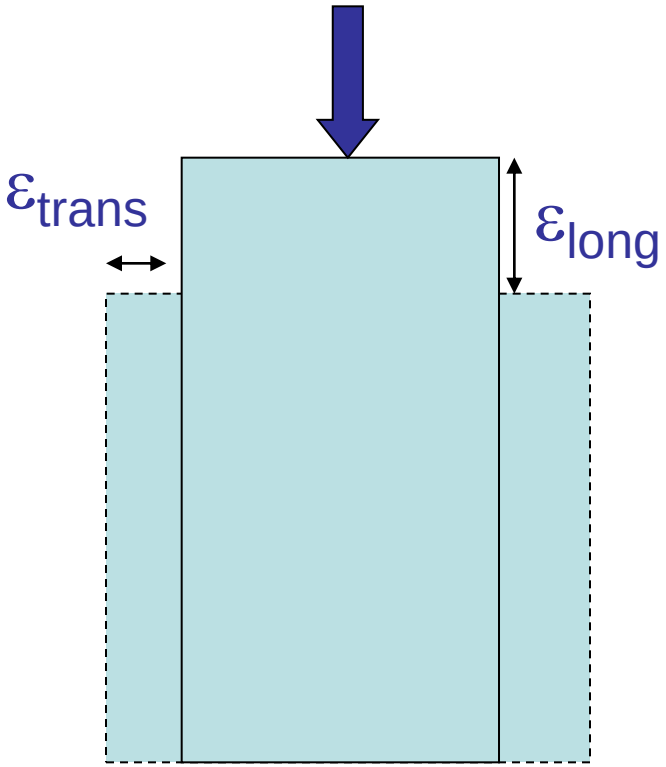


# Bone mechanics

- Absorbed energy = area under curve



# Bone biomechanics




Poisson's ratio

$\nu = \varepsilon_{trans} / \varepsilon_{long}$

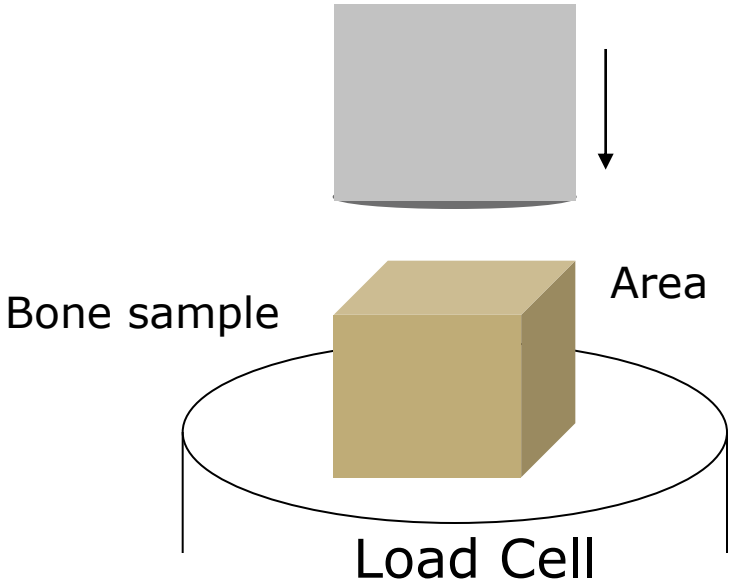
$\nu_{bone} = 0.3$

$\varepsilon = \delta L / L_{init}$

# Bone biomechanics

Determining bone strength

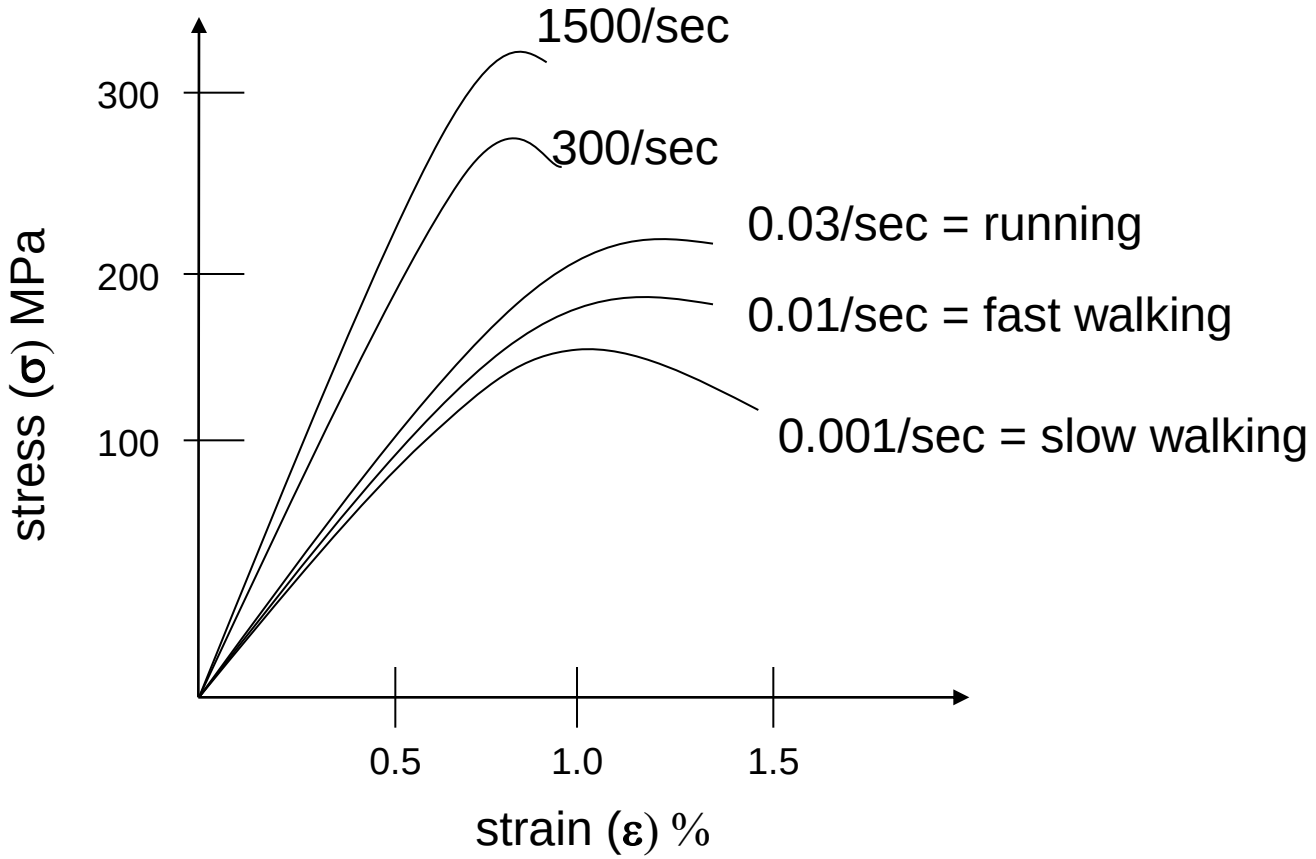
- Load machined samples of bone
- Tension, compression, shear, bending



# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate



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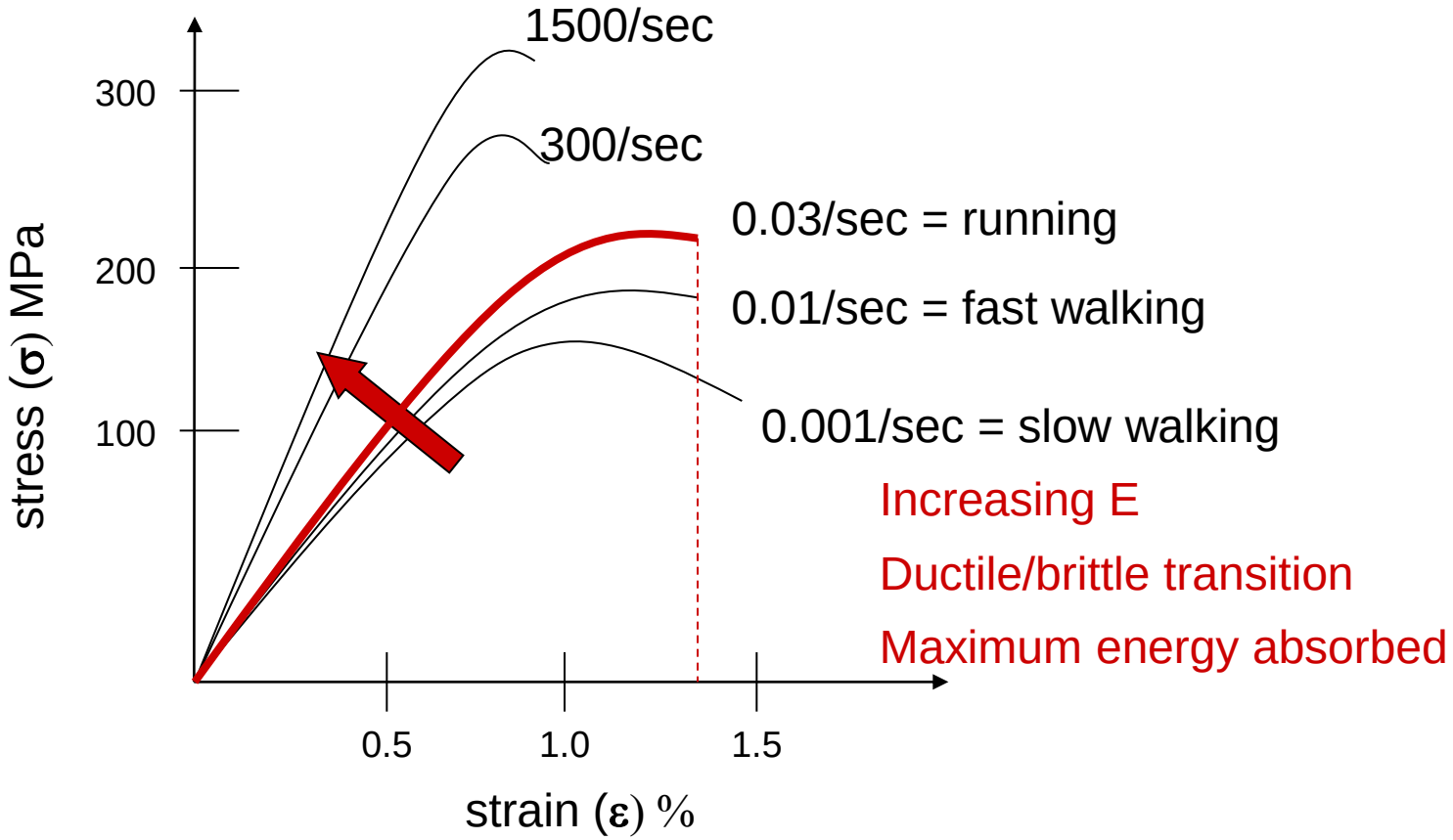


# Bone biomechanics

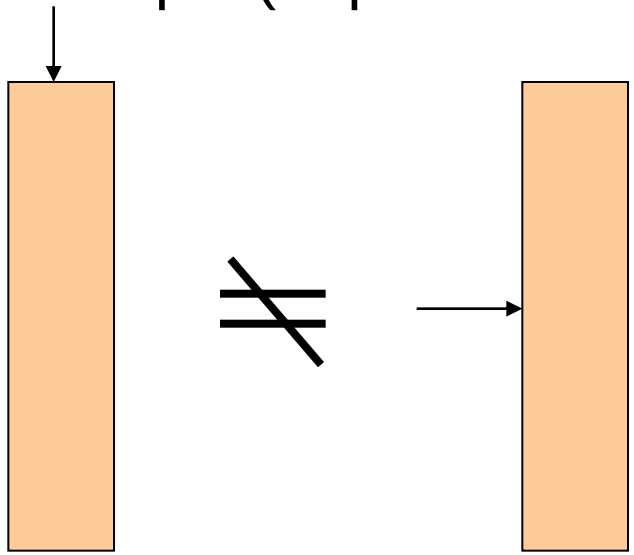
Factors that affect mechanical properties:

1. Loading rate
   - Viscous behaviour = E increases with load rate
   - Bones adapted for strain rates during strenuous activity (absorb maximum energy)

# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)



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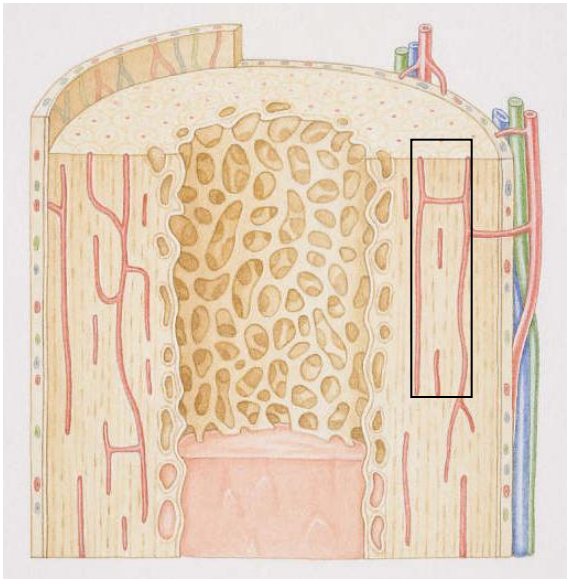

longitudinal

| Longitudinal | Ultimate strength ($\sigma$) MPa | Modulus (E) MPa |
|---|---|---|
| Compression | 193 | 17 |

# Bone biomechanics

Factors that affect mechanical properties:

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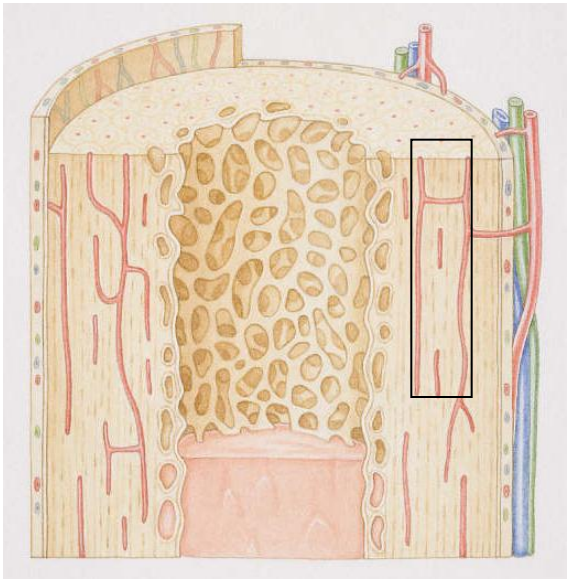

longitudinal

| Longitudinal | Ultimate strength ($\sigma$) MPa | Modulus (E) MPa |
|---|---|---|
| Compression | 193 | 17 |
| Tension | 133 | 17 |

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Factors that affect mechanical properties:

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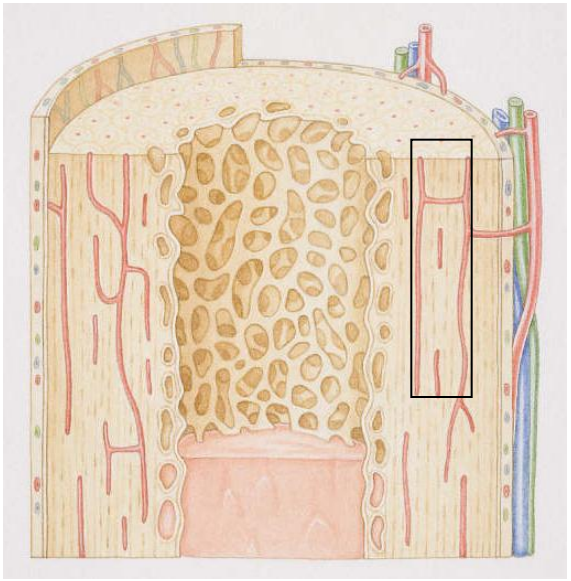

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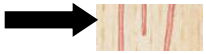
|---|---|---|
| Compression | 193 | 17 |
| Tension | 133 | 17 |
| Shear | 68 | 3.3 |

# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)



transverse

| | Ultimate strength ($\sigma$) MPa | Modulus (E) MPa |
|---|---|---|
| Longitudinal | | |
| Compression | 193 | 17 |
| Tension | 133 | 17 |
| Shear | 68 | 3.3 |
| Transverse | | |
| Compression | 133 | 11.5 |

# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)

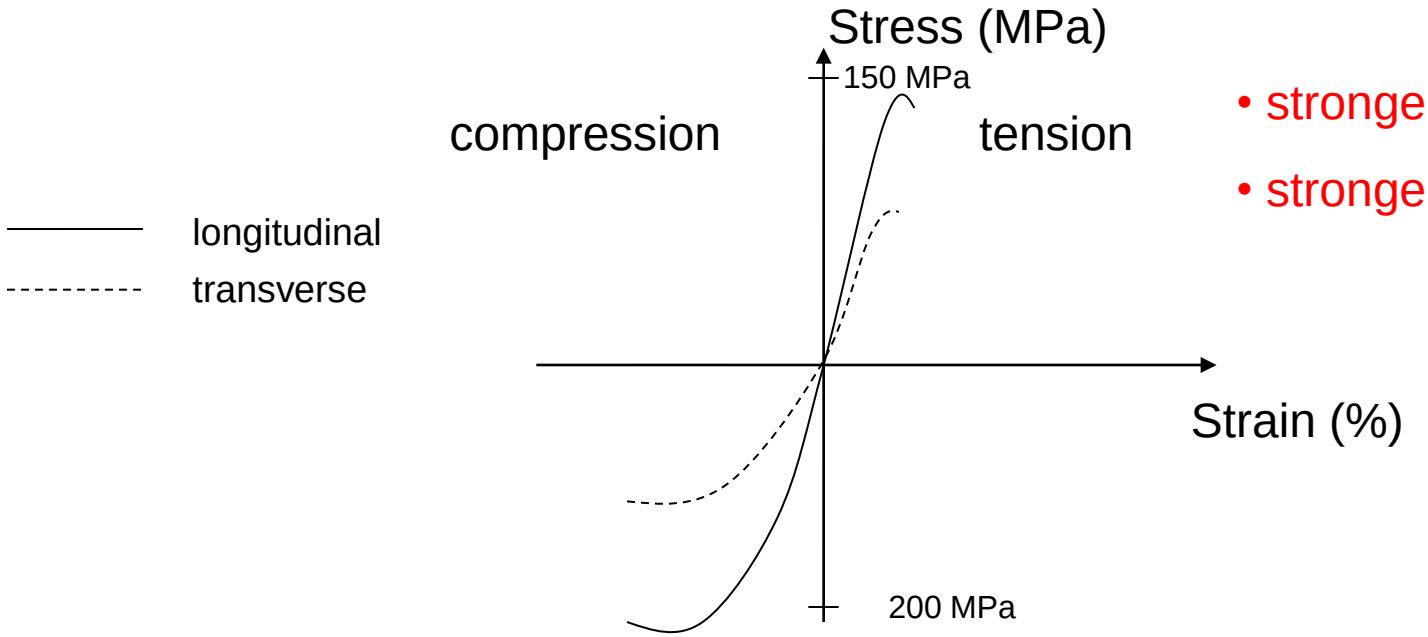
transverse

| | Ultimate strength ($\sigma$) MPa | Modulus (E) MPa |
|---|---|---|
| Longitudinal | | |
| Compression | 193 | 17 |
| Tension | 133 | 17 |
| Shear | 68 | 3.3 |
| Transverse | | |
| Compression | 133 | 11.5 |
| Tension | 51 | 11.5 |

# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)




- stronger in compression
- stronger longitudinally

# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)
   - Required constants

     $E_l$, $E_t$, G, $\nu_l$, $\nu_t$,

# Bone biomechanics

Failure of bone:

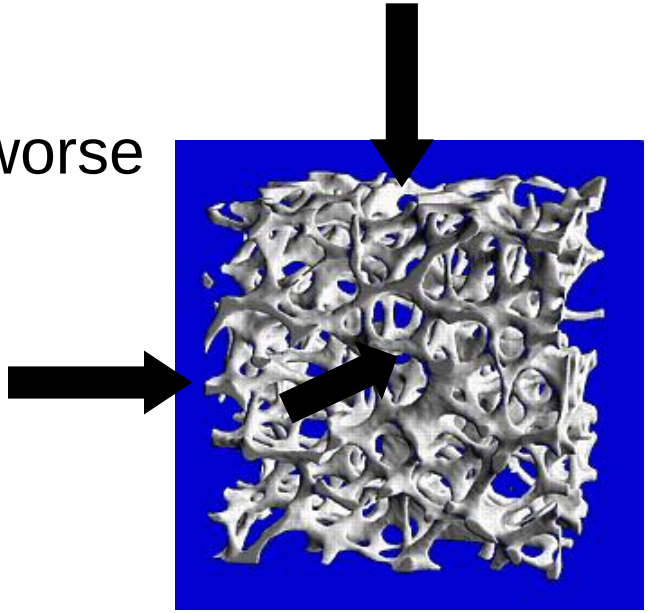
1. Tends to occur in shear (so a
2. Orientation
   - Under bending or compression, at 45° to long axis (butterfly fragment)
   - Under torsion – spiral fracture

# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
   - Anisotropic (depends on direction)
   - Required constants

     $E_l$, $E_t$, $G$, $\nu_l$, $\nu_t$,
   - Trabecular bone even worse
   - $E_1$, $E_2$, $E_3$,
   - $G_{12}$, $G_{23}$, $G_{13}$,
   - $\nu_{12}$, $\nu_{23}$, $\nu_{31}$



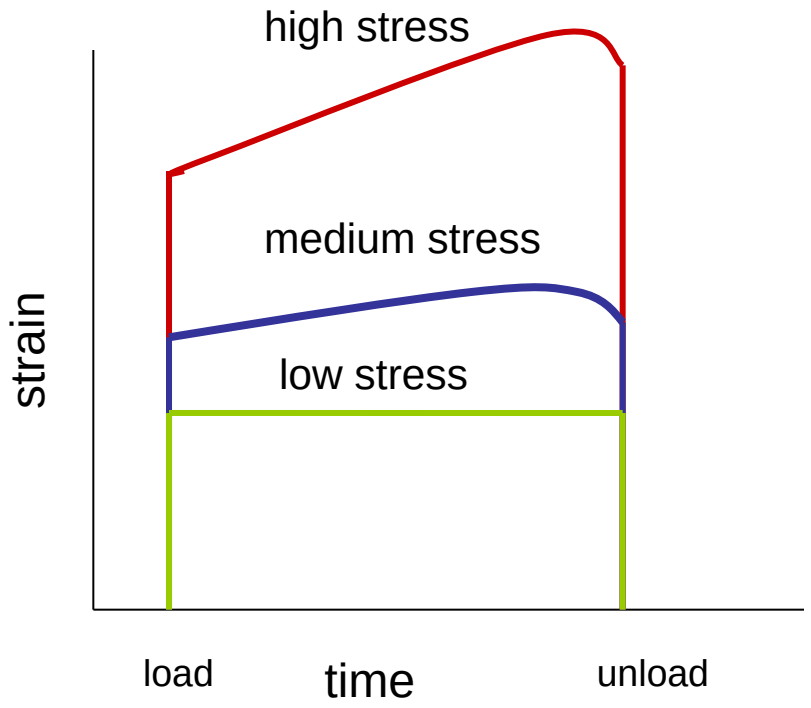
# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
3. Creep

   - strain changes with constant load

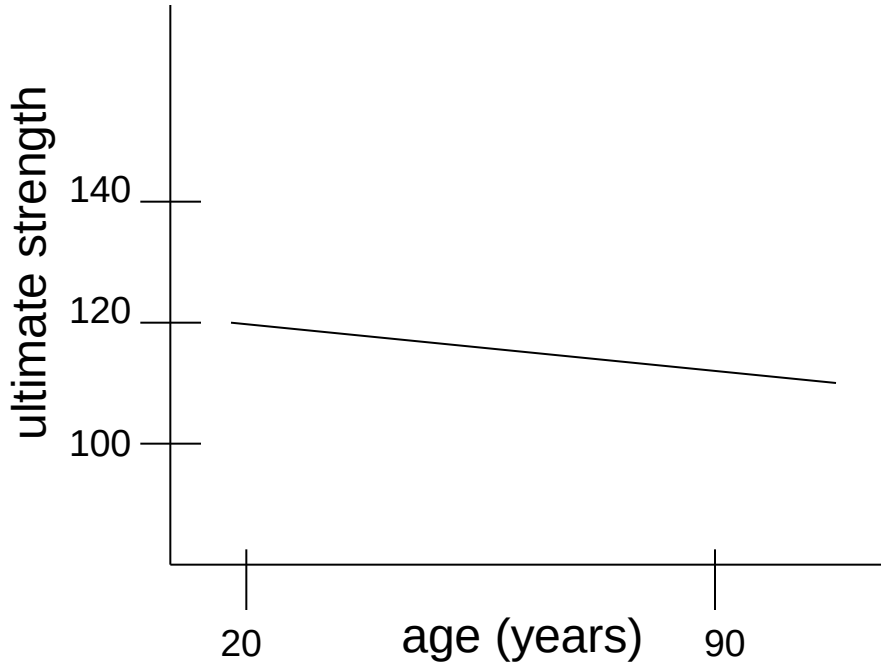
   = viscoplastic



# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
3. Creep
4. Age
   - less stiff
   - less strong
   - more brittle

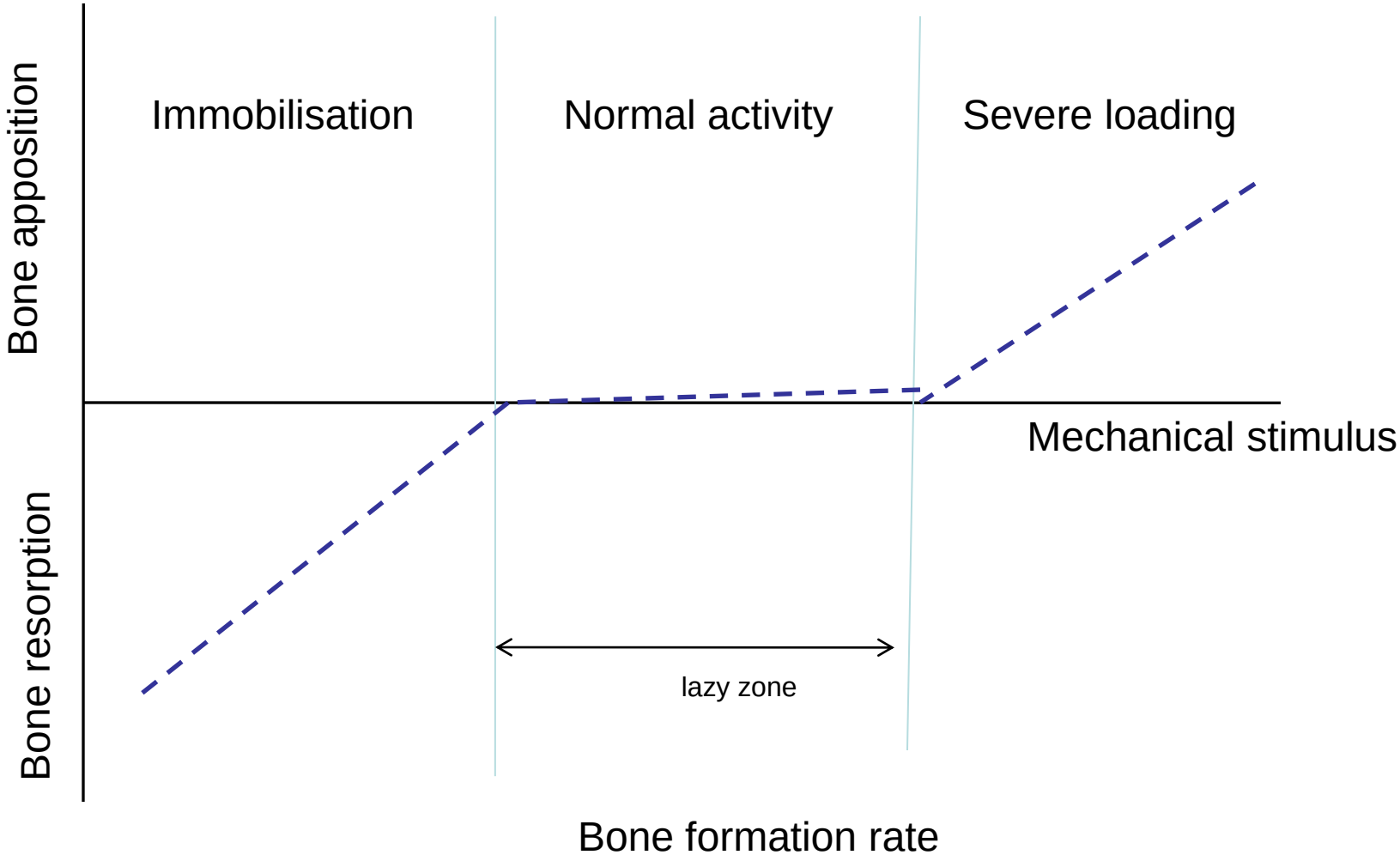


# Bone biomechanics

Factors that affect mechanical properties:

1. Loading rate
2. Orientation
3. Creep
4. Age
   - less stiff: elastic modulus decreases
     30 yr = 17 GPa, 90 yr = 15.6 GPa
   - less strong: ultimate strength decrease
     2% / decade
   - more brittle: energy absorption decreases
     7% / decade

# Bone Maintenance

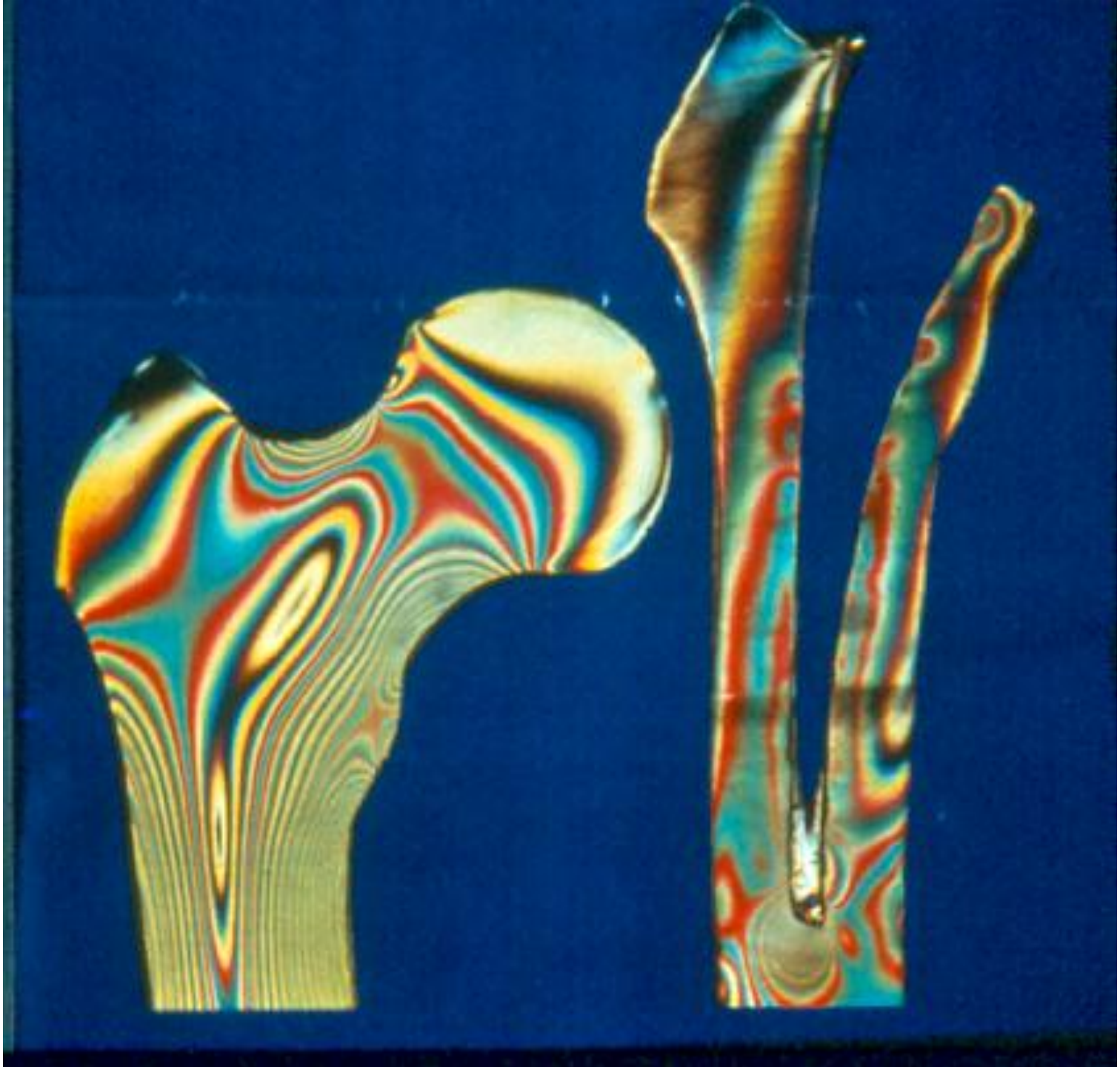


# Loading Conditions

Bone - a biomechanical tissue

- needs strain to maintain
- 1000 to 4000 μstrain (0.1 to 0.4%)

Lanyon et al, 1970 on



# Stress-shielding

"It is suggested that if the fixation of a fully coated implant of this sort remains sound, gross atrophy of the upper femoral shaft develops after five years."

Brown & Ring, 1985. JBJS 67-B(2): 218 - 221

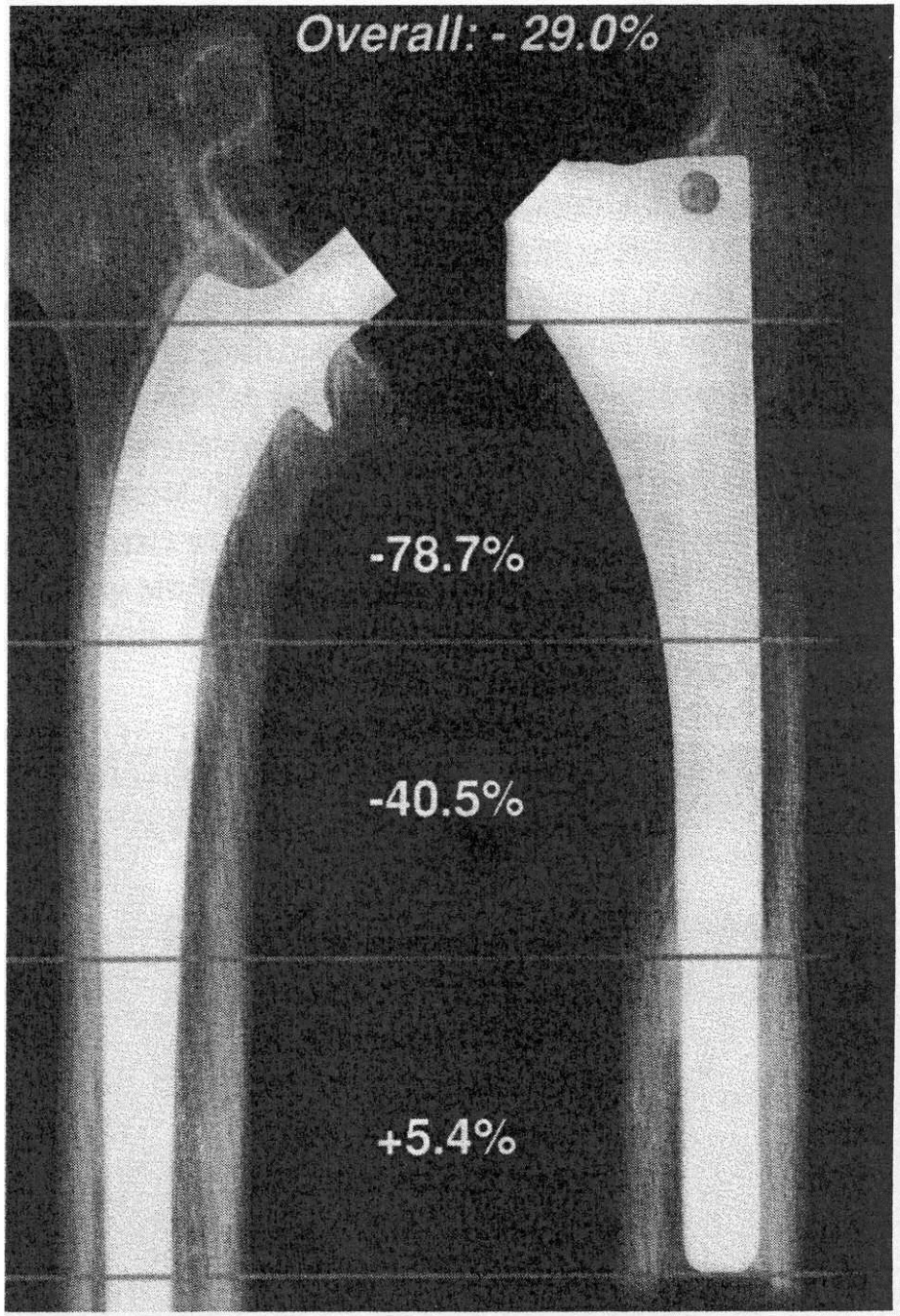



**Fig. 11.** Case 2. Dual-energy x-ray absorptiometry analy-

# Stress Shielding

McCarthy, CK; Steinberg, G G et al . 1991

JBJS 73-B (5): 774 - 778 (40% to 49%)

Engh, CA; McGovern, TF; Bobyn, J D; Harris, WH. 1992

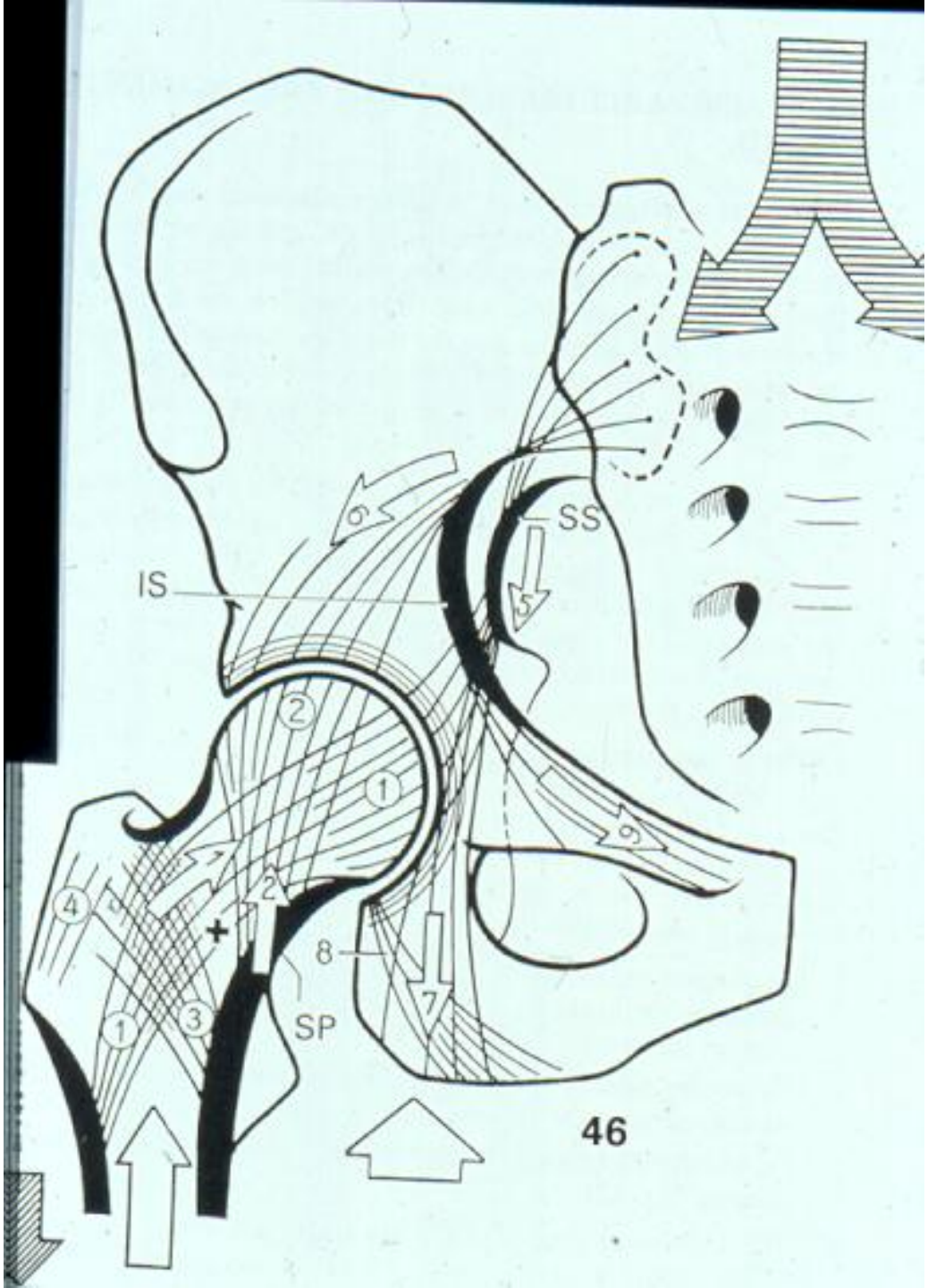
JBJS 74-A (7): 1009 - 1020 (45%)

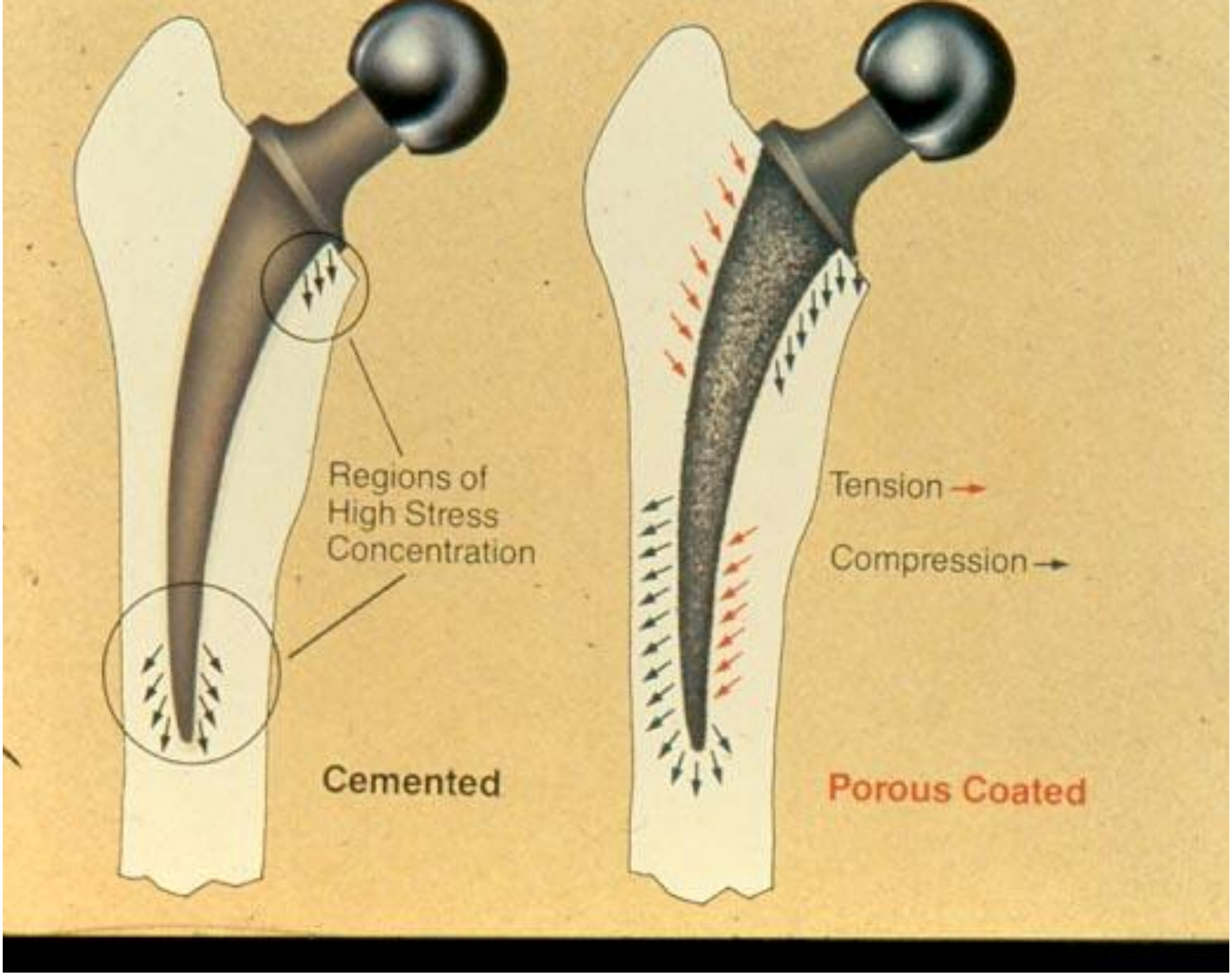
Rosenthall, L; Bobyn, J D; & Brooks, C E. 1999

J Arthroplasty 14(1): 71 - 76

Engh, CA; Sychterz, C; & Engh C. 1999

J Arthroplasty 14(5): 637 - 644


SS
IS
SP
8
46


Regions of
High Stress
Concentration
Cemented
Tension
Compression
Porous Coated

# Summary

- Function
- Structure
  - Cortical
  - Trabecular
- Contents
  - Mineral
  - Protein
- Material properties
  - Viscoelastic
  - Anisotropic
  - Viscoplastic