Bone Anatomy and Physiology

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References and Acknowledgments

BOOKS

- Viceconti M. *Multiscale Modeling of the Skeletal System*. 2012
- Cowin S. *Bone Mechanics Handbook*. 2001
- Currey J. *Bones: Structure and Mechanics*. 2006
- Carter D. – Beaupre G. *Skeletal Function and Form*. 2001

WEB (mainly for Figures)

- Various websites through Google Image search

JOURNAL ARTICLES

- Clark B. *Normal Bone Anatomy and Physiology*. Clin J Am Soc Nephrol 3: S131–S139, 2008

Studying the Bone

Biology

Biomechanics

Imaging

Bone

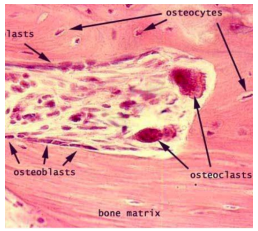
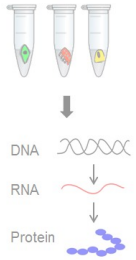
Bone Quality Assessment

Bone Fracture and Fixation

Multi-Scale Approach to Bone Study

	BODY LEVEL	ORGAN LEVEL	TISSUE LEVEL	CELLULAR LEVEL	MOLECULAR LEVEL
Biology					
Biomechanics					
Imaging					

Multi-Scale Approach to Bone Study

	BODY LEVEL	ORGAN LEVEL	TISSUE LEVEL	CELLULAR LEVEL	MOLECULAR LEVEL
Biology					
Biomechanics	[m - cm]	[cm - mm]	[mm - µm]	[µm]	[nm]
Imaging					

The Body Level

Biology

BODY LEVEL

[m - cm]

ORGAN LEVEL

[cm - mm]

TISSUE LEVEL

[mm - µm]

CELLULAR LEVEL

[µm]

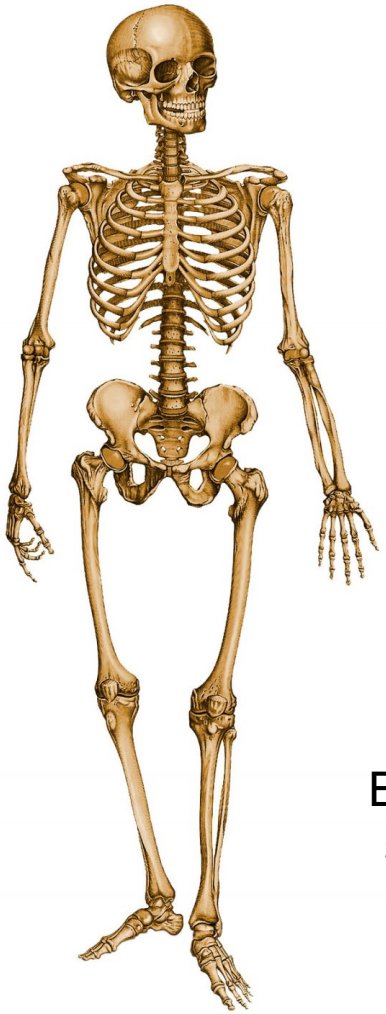
The Adult Skeleton

- The **adult** skeleton is made of 206 bones
- The functions of the skeleton are:

Protection
The cranium protects the brain, the rib cage protects heart and lungs

Shape
Without the skeleton, the body would be flabby and shapeless

Support
The vertebrae support the head



Movement
The bones and joints work with muscles to enable us to walk, run and sprint

Blood Production
Red blood cells are made in the ribs and limb bones

Calcium Storage
Bone is the largest supply of calcium

The Organ Level

Biology

BODY LEVEL

[m - cm]

ORGAN LEVEL

[cm - mm]

TISSUE LEVEL

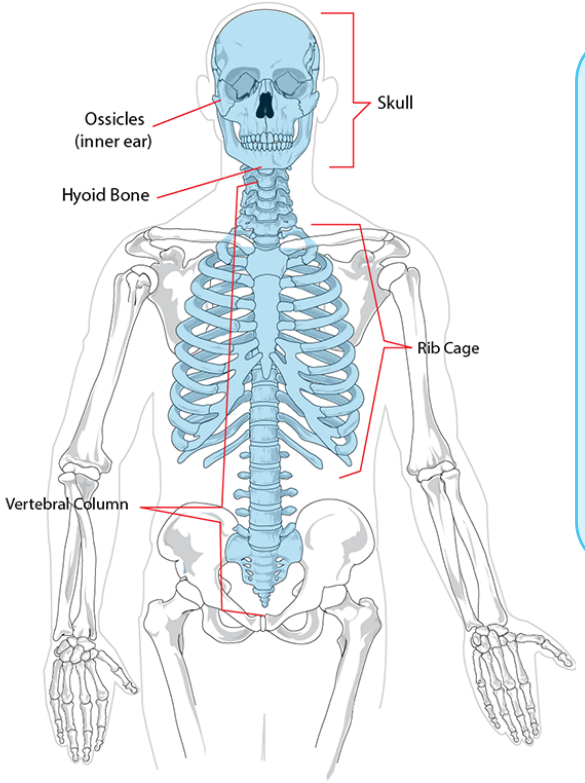
[mm - µm]

CELLULAR LEVEL

[µm]

Bone Classification 1: Axial vs. Appendicular

Axial

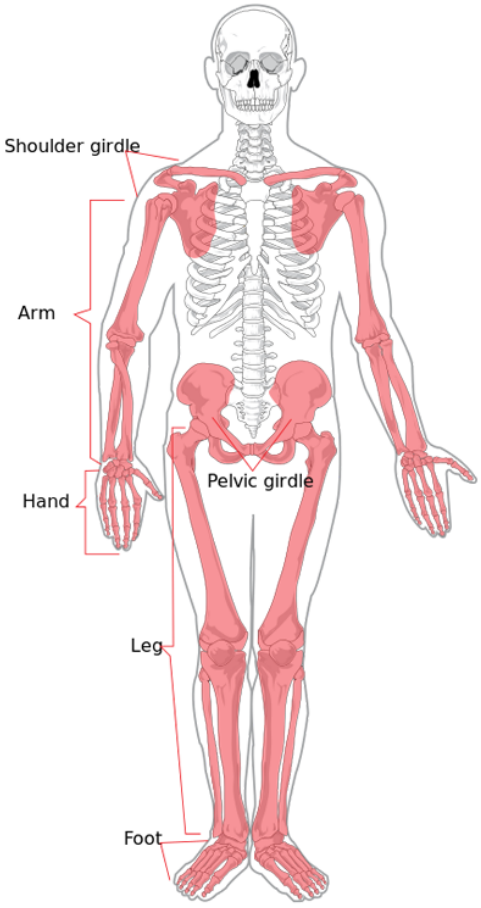


Axial	Feature	Appendicular
Cancellous	Main bone tissue	Cortical
Viscera	Adjacent soft tissue	Muscle
Thin	Cortices	Thick
Hematopoietic	Marrow	Fatty
High	Turnover	Low
	Main function:	
Mechanical	Cortical	Mechanical
Metabolic	Cancellous[a]	Mechanical

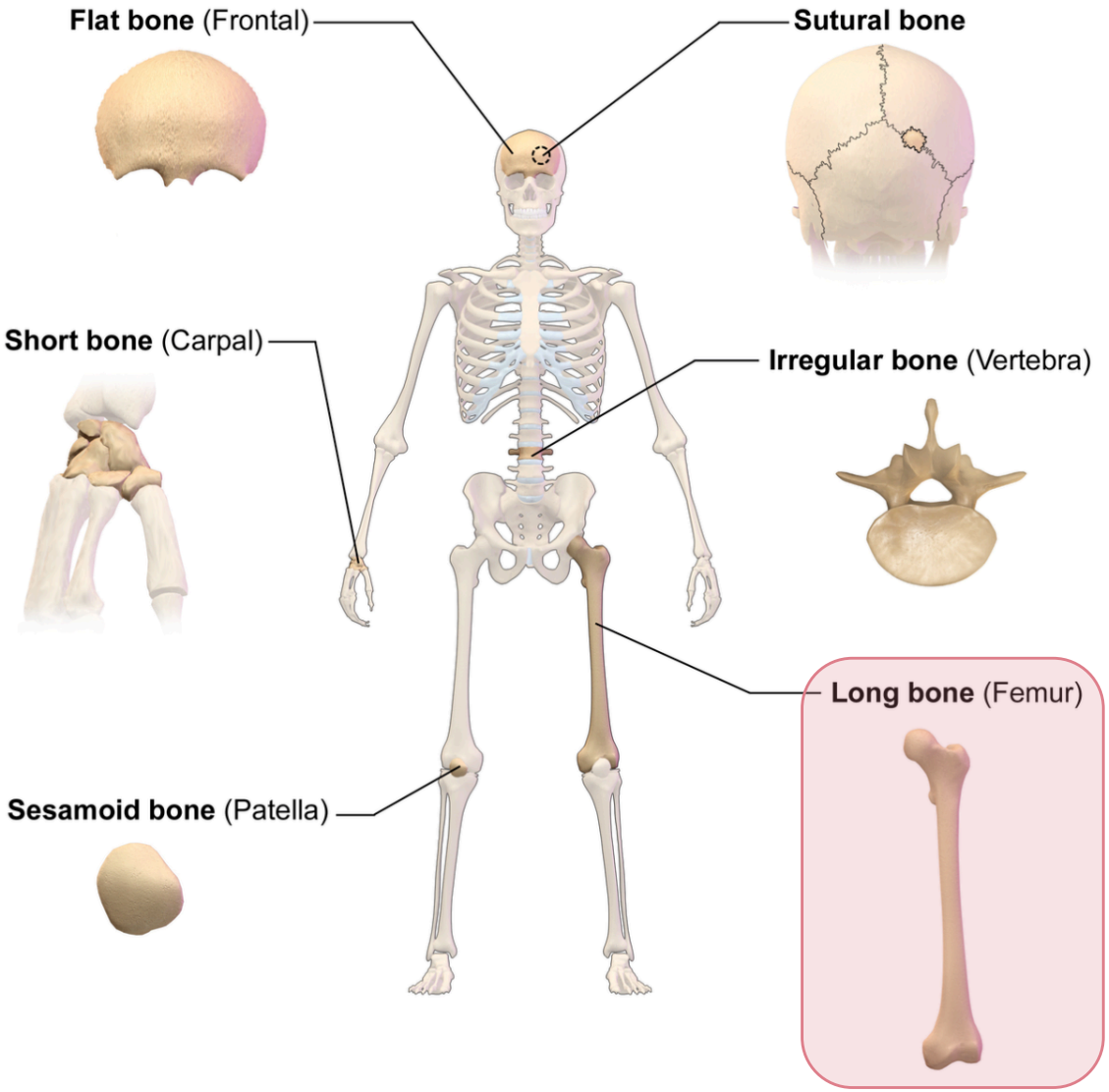
[a] Metabolic activity such as uptake and release of calcium occurs in all cancellous bone in red marrow sites throughout the skeleton.

Cowin, 2001

Appendicular



Bone Classification 2: Based on Shape



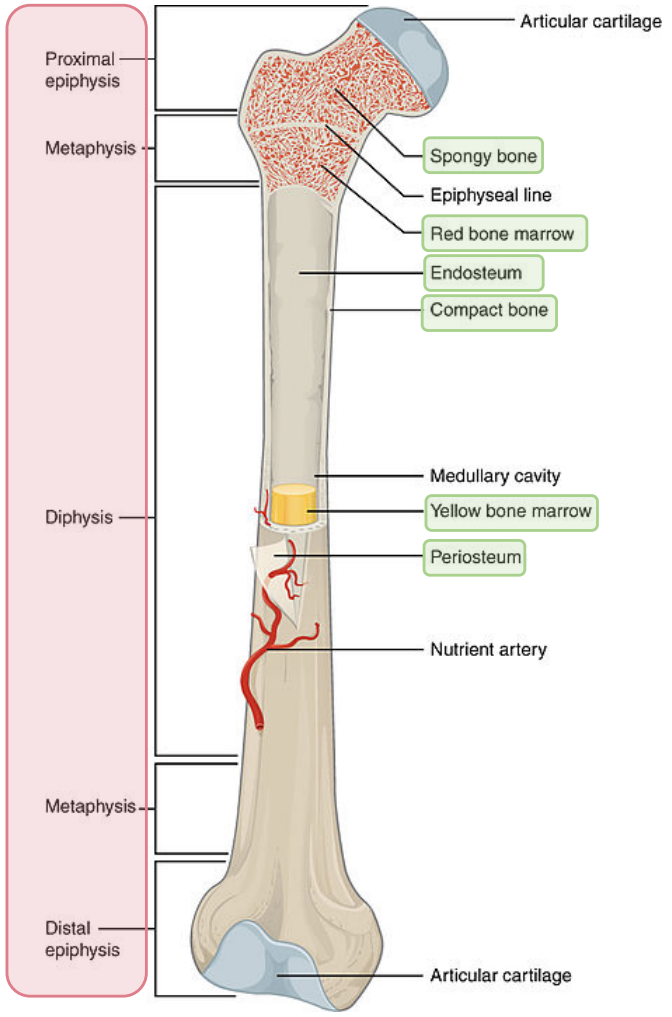
Long Bones

Longitudinally:

- **Epiphysis**
- **Metaphysis**
- **Diaphysis / Shaft**

Transversally:

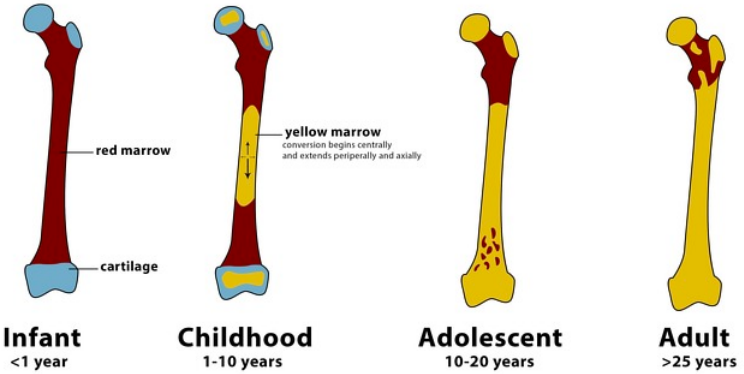
- **Periosteum**
- **Cortical / Trabecular Bone**
- **Endosteum**
- **Bone Marrow**

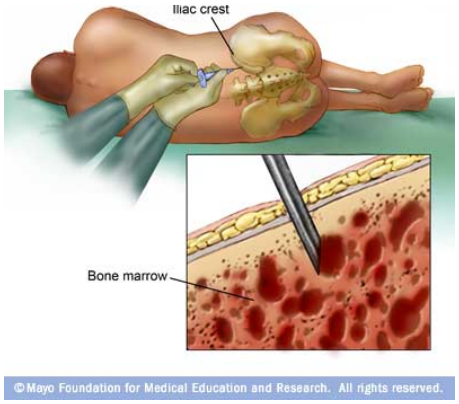


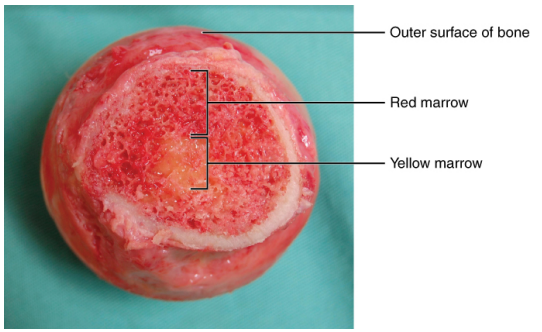
Bone Marrow

- **Red marrow**
  - Produces red blood cells, white blood cells and platelets
  - By age 25 it is essentially confined to the axial skeleton
  - Marrow transplant for leukemia and bone marrow cancer
- **Yellow marrow**
  - Produces fat cells (energy storage)
  - Located in the medullary cavity of the shaft

Normal Bone Marrow Conversion



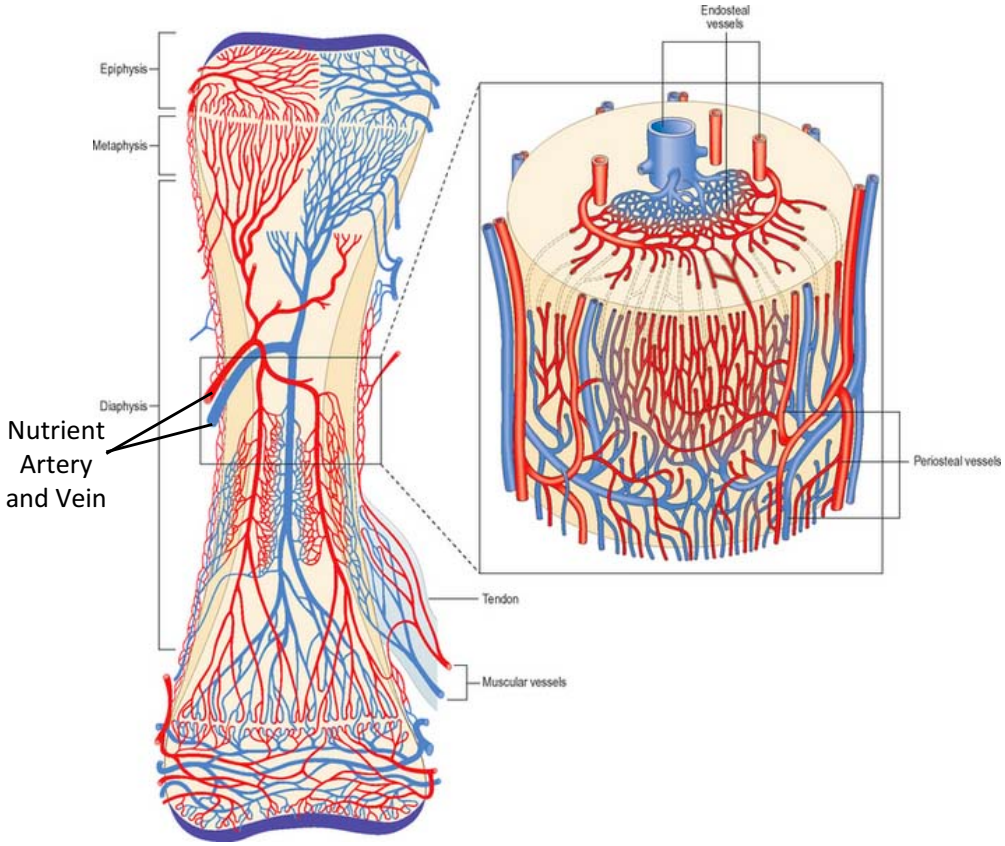




Bone vascular supply

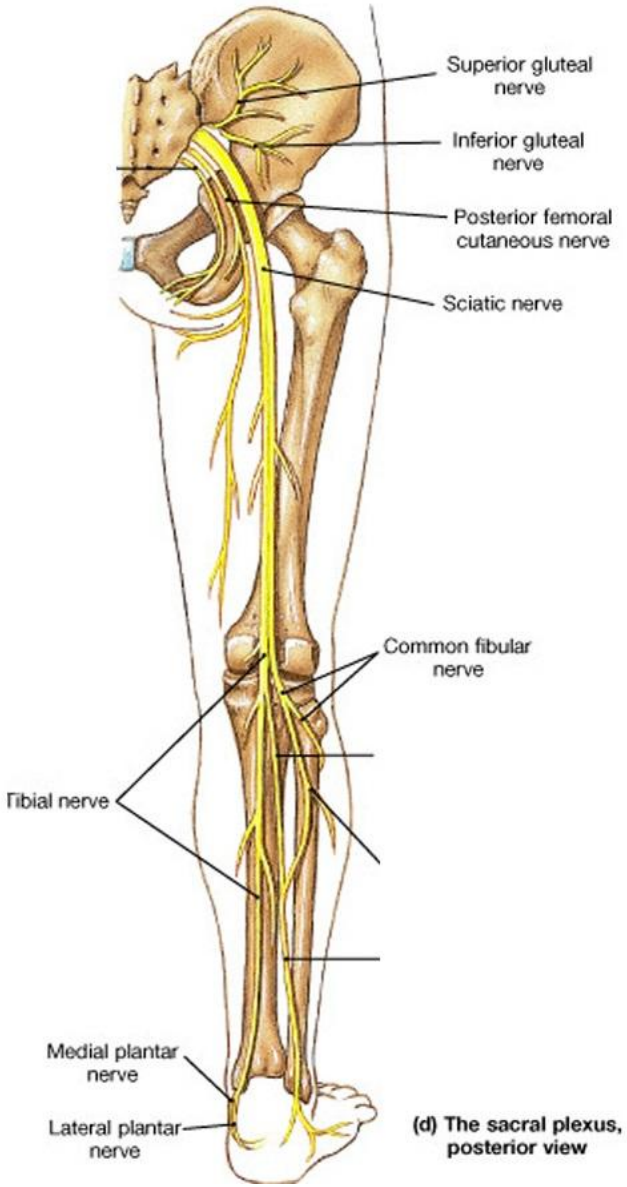
- The nutrient artery enters the long bone and divides into ascending and descending arteries
- Capillary arcades are formed in marrow spaces between trabeculae
- When growth is complete, the growth plate disappears and the trabecular bone circulation of the epiphysis and metaphysis join together

- Little of the hemodynamics of the circulation in bone is known



Bone nerves

- The nerve supply for bone is largely unknown
- Haversian canals, periosteum, and medullary vessels are innervated
- Recent electron microscopy studies showed bone is rich in nerve fiber processes running along vessels adjacent to bone trabeculae



The Tissue Level

Biology

BODY LEVEL

[m - cm]

ORGAN LEVEL

[cm - mm]

TISSUE LEVEL

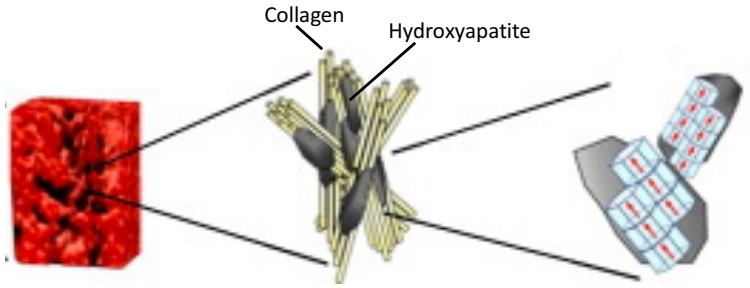
[mm - µm]

CELLULAR LEVEL

[µm]

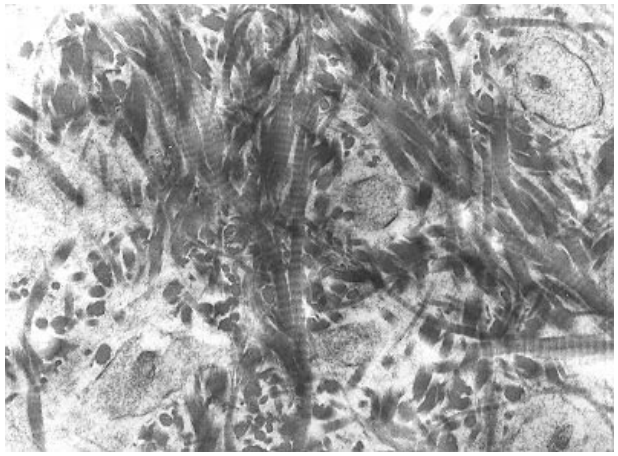
Classification of Bone Tissue: Woven and Lamellar

There are two types of bone tissue based on *collagen organization: woven* and *lamellar*



Woven Bone: collagen is poorly organized with short fibers oriented randomly.

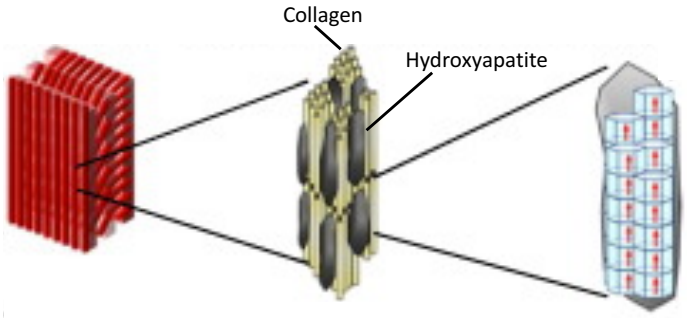
- It is formed during physiological *growing* and during *healing* from fracture
- It is replaced by lamellar bone



Classification of Bone Tissue : Woven and Lamellar

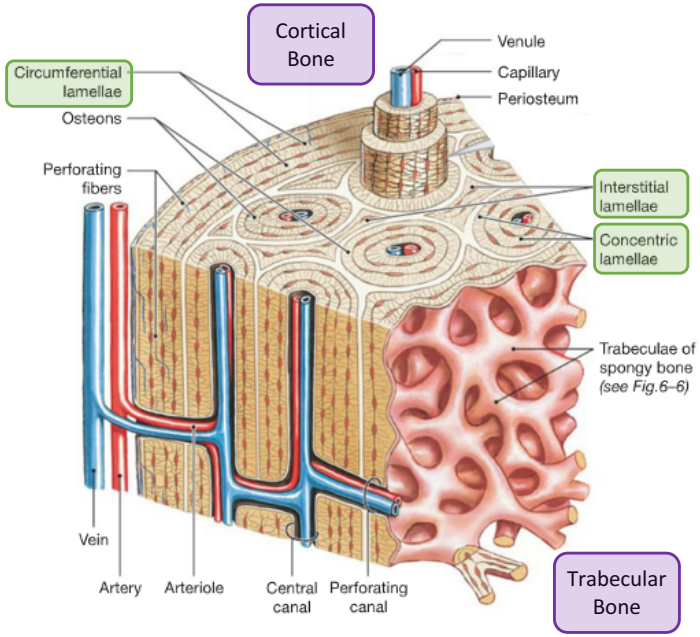
There are two types of bone tissue based on *collagen organization: woven* and *lamellar*

Lamellar Bone: collagen is organized in layers called **lamella** / **lamellae**



Lamellae are:

- Concentric
- Circumferential
- Interstitial

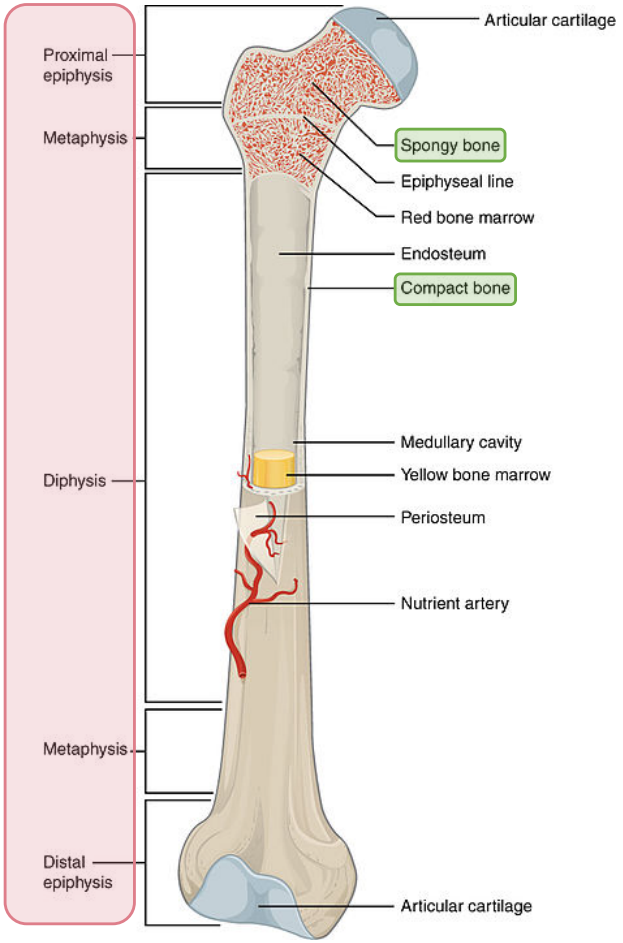


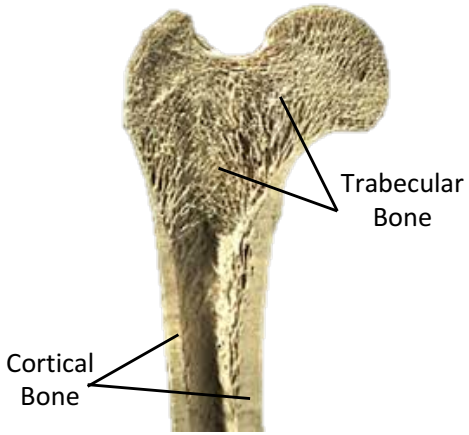
Lamellar bone forms:

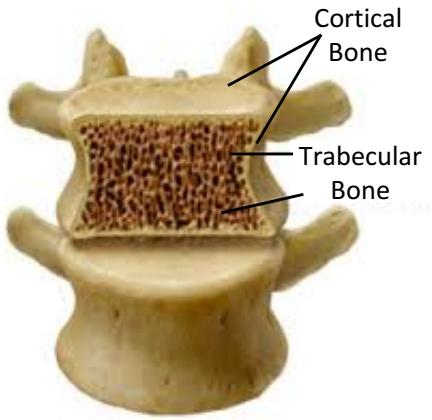
- **Cortical** bone
- **Trabecular** bone

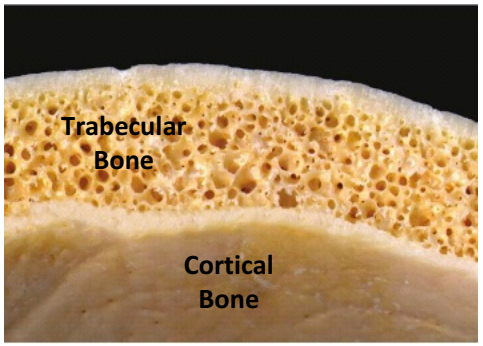
Lamellar Bone: Cortical and Trabecular

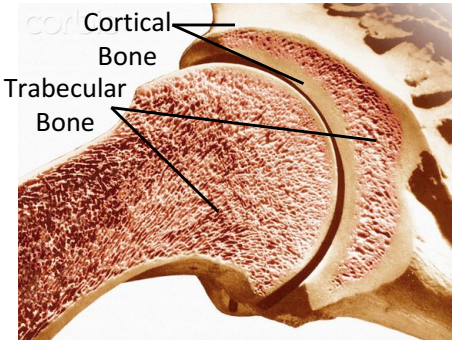
- **Cortical** (or **Compact**) bone is mainly in the *diaphysis*
- **Trabecular** (or **Cancellous** or **Spongy**) bone is mainly in *epiphysis* and *metaphysis*







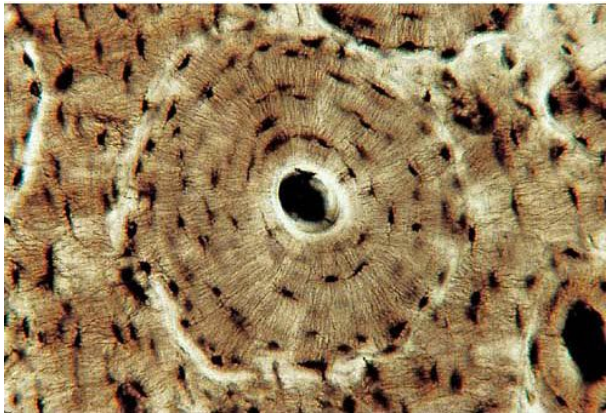


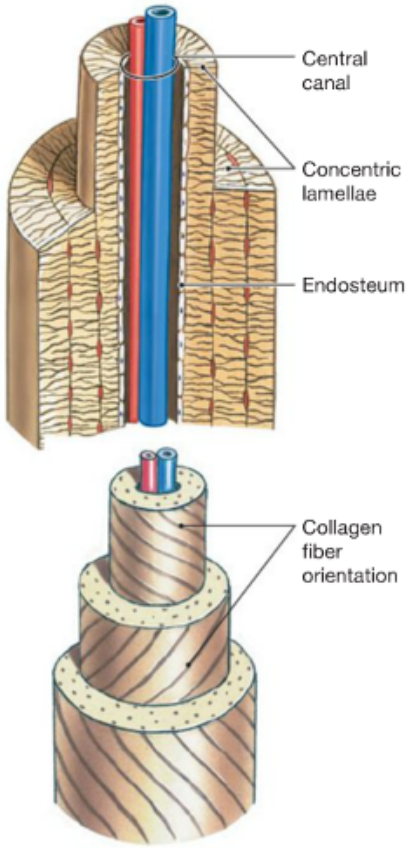


Cortical Bone

Cortical bone is composed by **osteons**

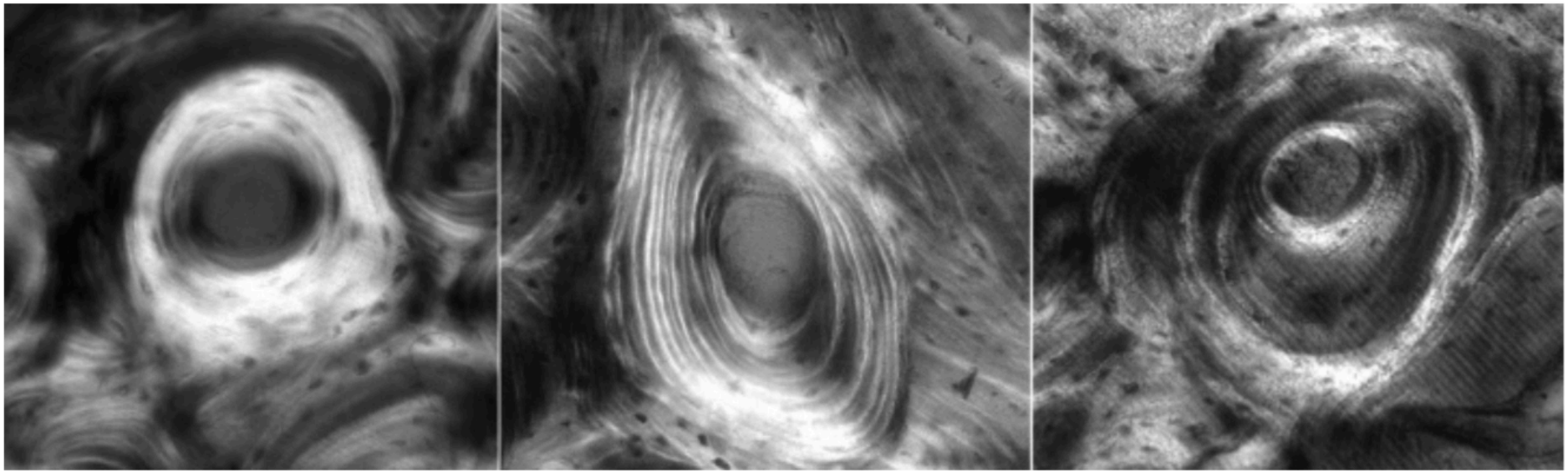
- Concentric **lamellae** with alternated fiber orientation
- At the center there is the **Haversian canal** with vasculature and innervations
- In between lamellae there are **lacunae** with osteocytes
- **Canaliculi** host osteocytes cytoplasmatic protrusions and fluid
- **Volkmann's canals** connect the Haversial canal with the periosteum providing energy and nutrients





Cortical Bone – How much do we know?

- There is still much to understand, e.g. lamellae orientation



Mainly transversal fibers

Alternation of longitudinal and transversal fibers

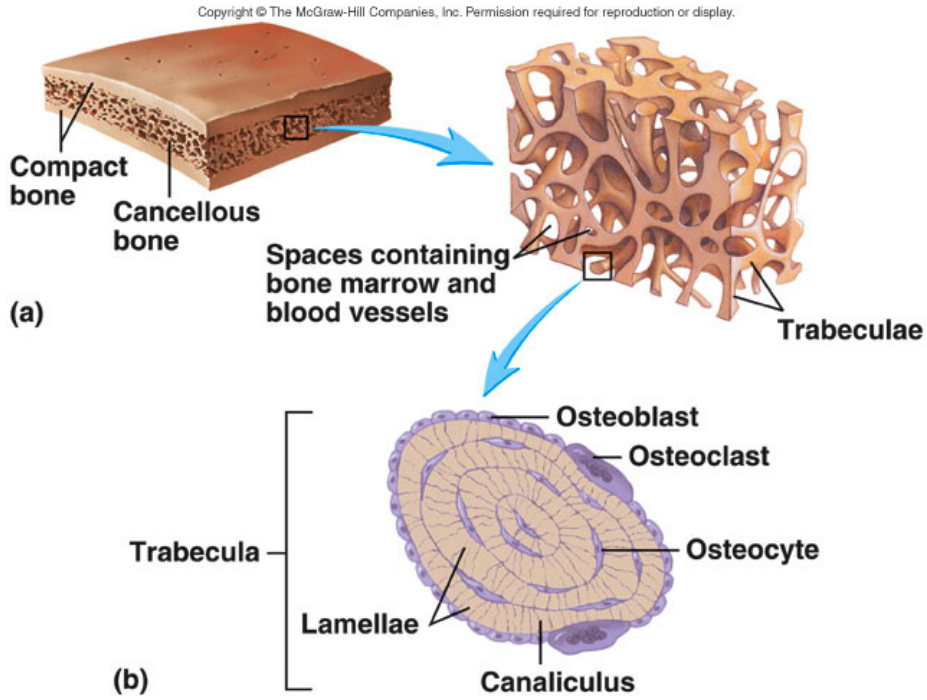
Mainly longitudinal fibers

Fibers oriented *transversally* with respect to the main axis

Fibers oriented *longitudinally* with respect to the main axis

Trabecular Bone

- Trabecular bone is formed by concentric lamellae without Haversian canal
- **Trabeculae** are divided in **plates** and **rods**
- Space in between trabeculae is filled with bone marrow and vessels



Cortical Bone and Trabecular Bone

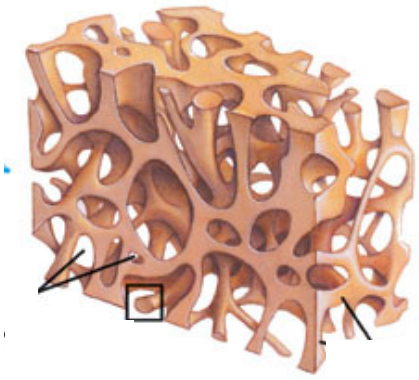
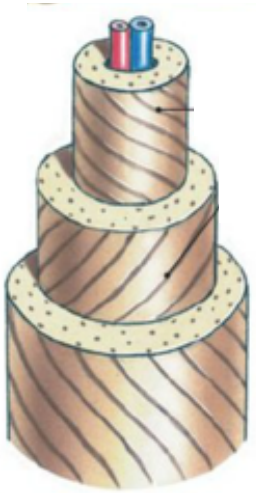


TABLE 1.2 Differences in Cortical and Cancellous Bone

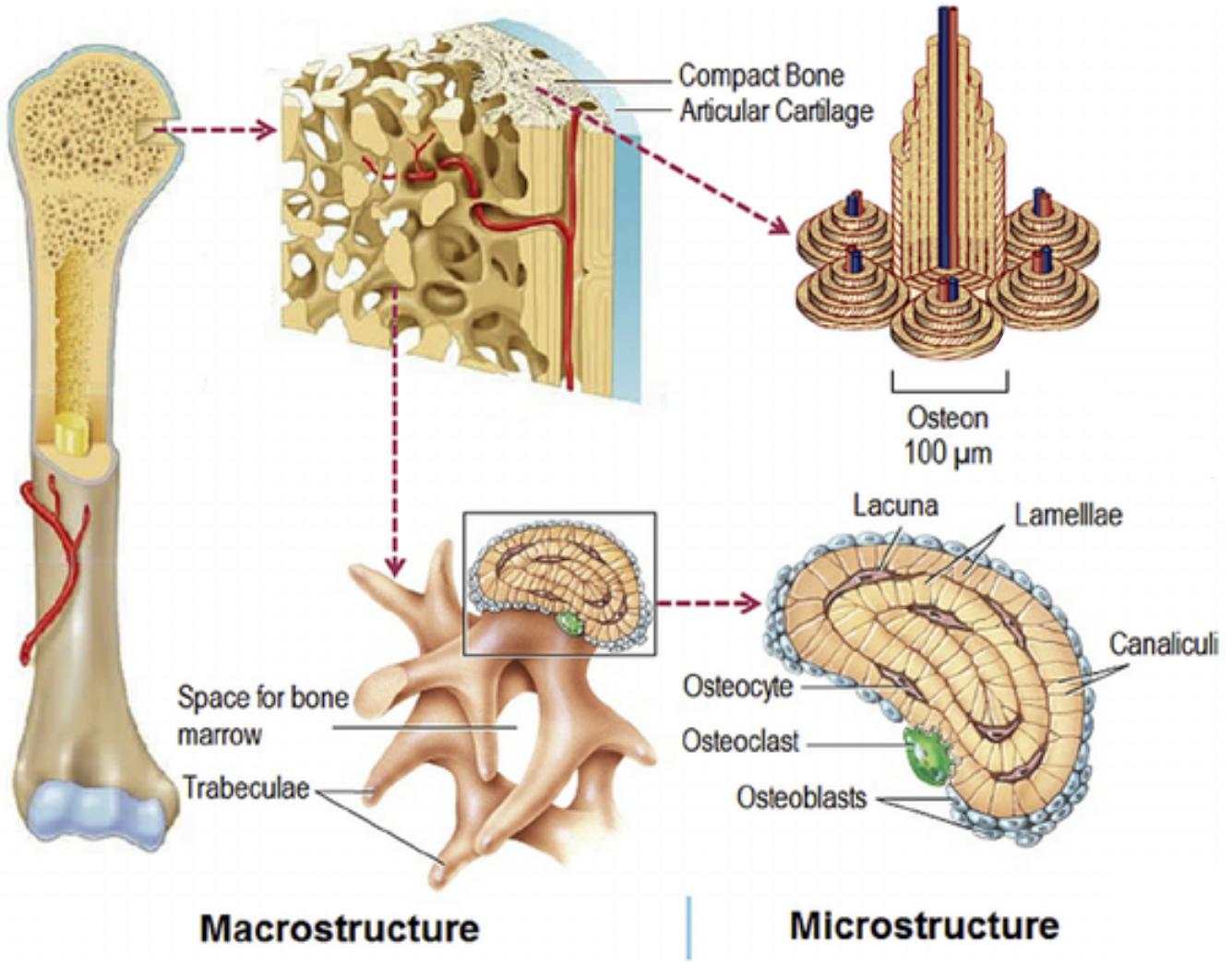
Cancellous		Cortical
20%	Skeletal mass	80%
67%	Bone surface	33%
2.5	Surface/volume ratio (mm^2/mm^3)	20
~75%	Soft tissue	~10%
Curved plates, rods (Hemiosteons)	Adult tissue	Secondary osteon (Haversian systems)
Interstitial lamellae		Interstitial lamellae
		Circumferential lamellae
High	Porosity	Low
Hematopoietic Marrow	Marrow	Fatty
	Main soft tissue	Viscera
Endochondral ossification	Developmental	Intramembranous ossification
Rapid	Turnover	Slow
Mainly mineral homeostasis, also supportive	Function	Mainly biomechanical also supportive and protective

Source: Bronner, F. and Worrell, R.V., Eds., *Orthopaedics, Principles of Basic and Clinical Science*, CRC Press, Boca Raton, FL, 1999. With permission.



Cowin, 2001

Cortical Bone and Trabecular Bone - Summary



The Cellular Level

Biology

BODY LEVEL

[m - cm]

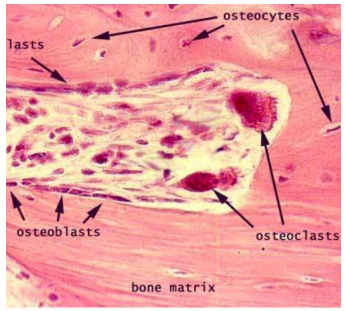
ORGAN LEVEL

[cm - mm]

TISSUE LEVEL

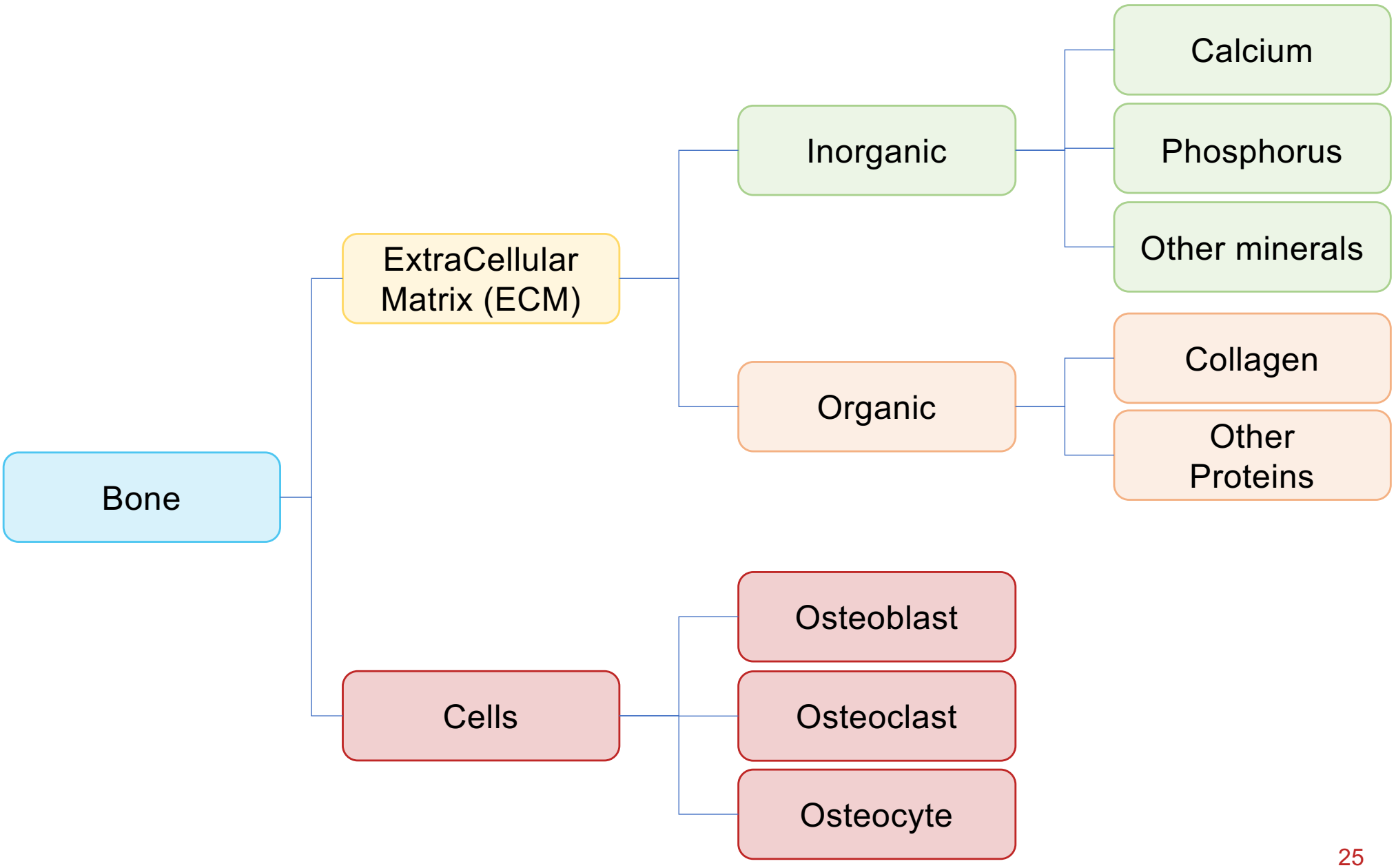
[mm - µm]

CELLULAR LEVEL

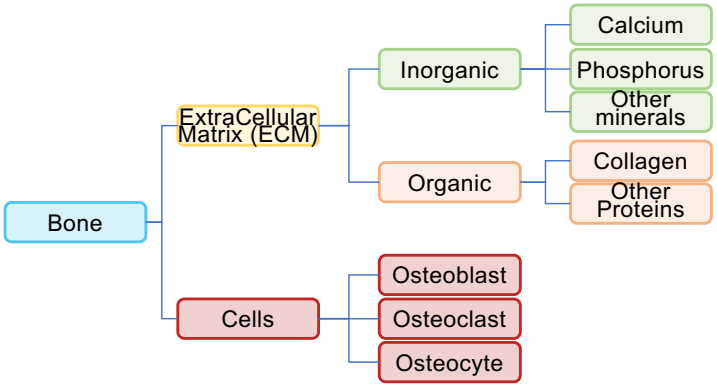


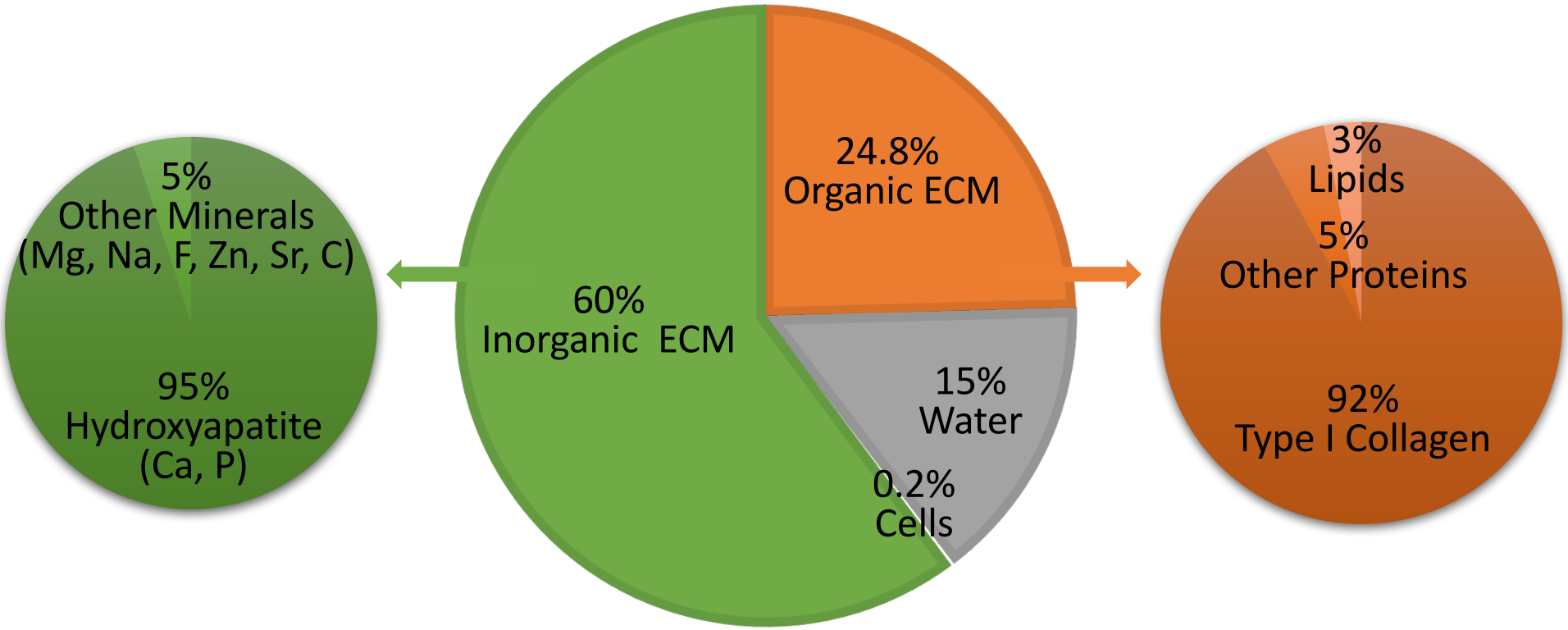
[µm]

Constituents of Bone



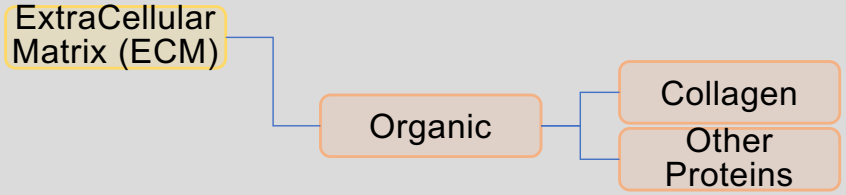
Constituents of Bone – Percentage Composition



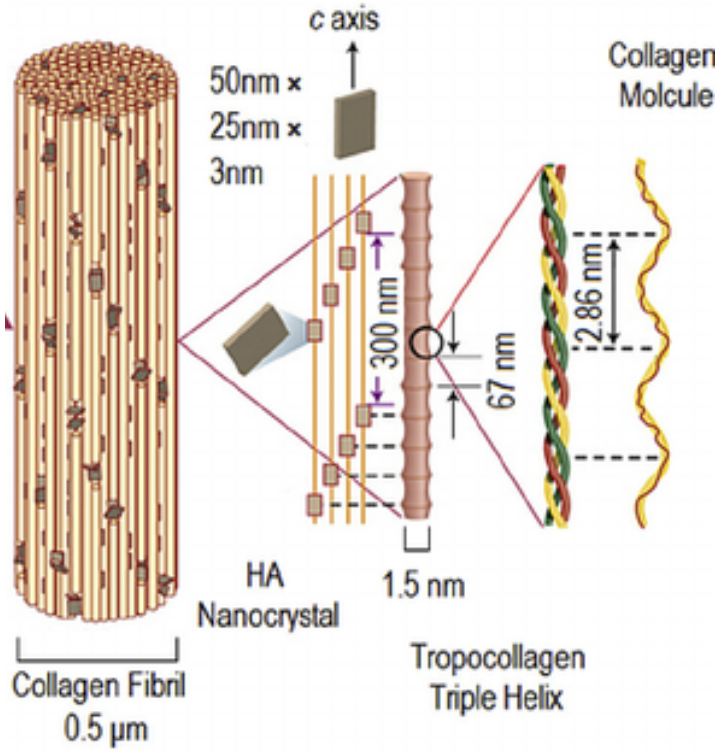


The percentage composition is an estimate

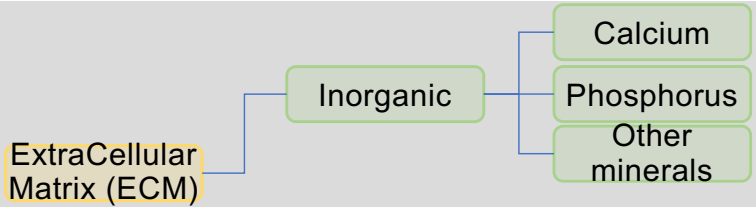
Type I Collagen



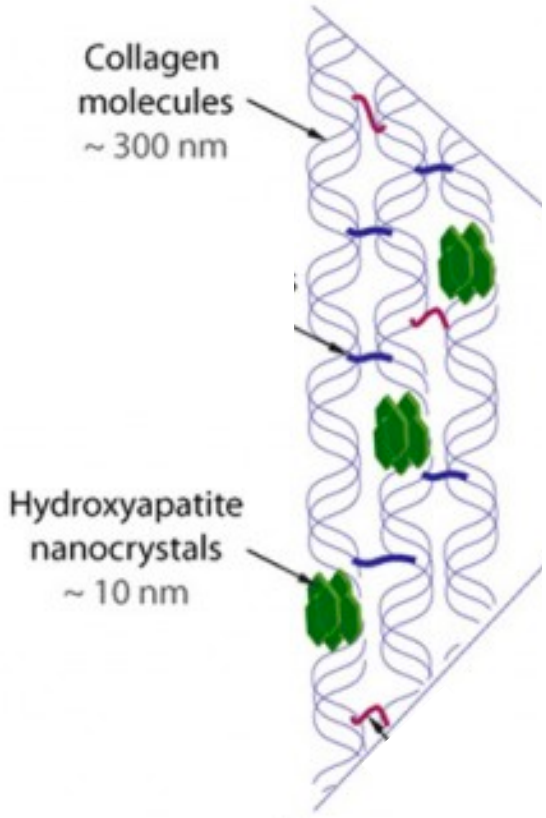
- It is the main component of the *organic* ECM (92%)
- It is the a *protein*
- There are at least 28 types of collagen, but the main type is Type I
- Cells secrete tropocollagen, which combines in triple helix forming collagen itself
- Collagen provides elasticity and flexibility to bone



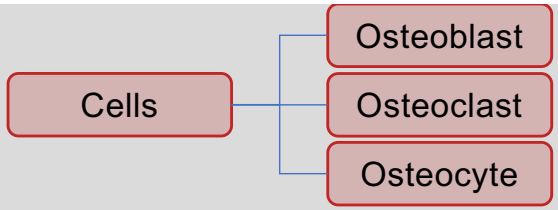
Hydroxyapatite (HA)



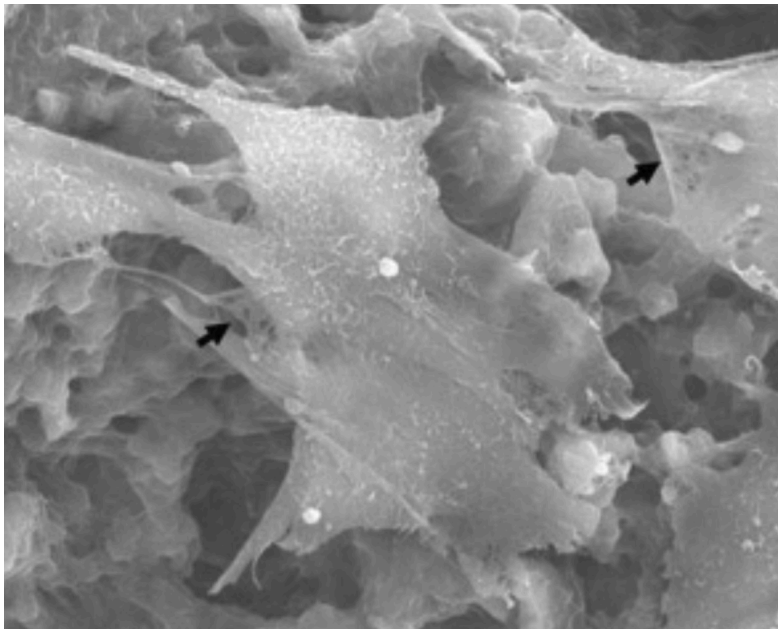
- It is the main *inorganic* component of the ECM (95%)
- It is an hexagonal crystal system where Ca^{2+} ions are surrounded by PO_4^{2-} and OH^- ions ($Ca_{10}(PO_4)_6(OH)_2$)
- It binds to collagen
- It provides rigidity and load-bearing strength to bone



Osteoblasts



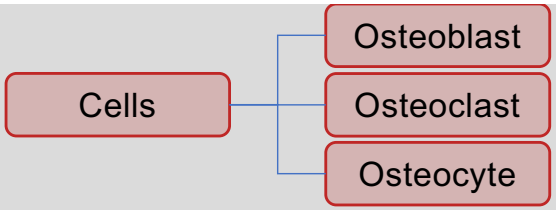
- Osteoblasts build the bone extracellular matrix by synthesizing collagen type I and other proteins



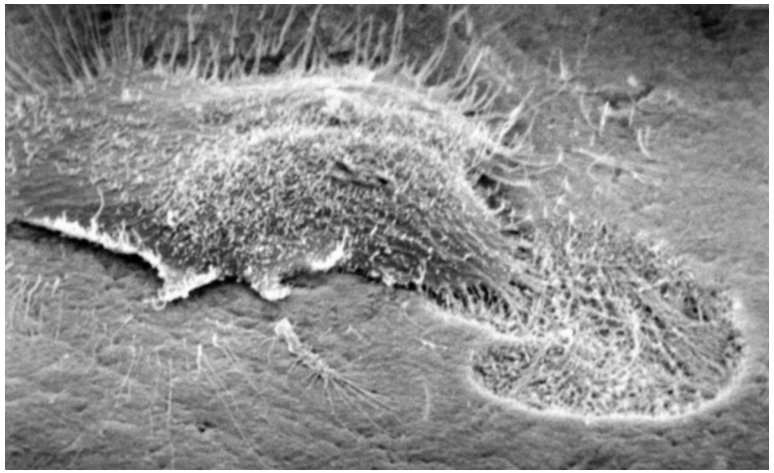
https://www.youtube.com/watch?v=78RBpWSOl08

- *Lining cell* are quiescent osteoblast covering the extracellular matrix surface

Osteoclasts

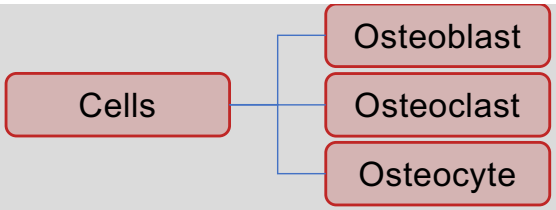


- Osteoclasts “clean/cancel” the bone extracellular matrix by resorbing the mineralized matrix

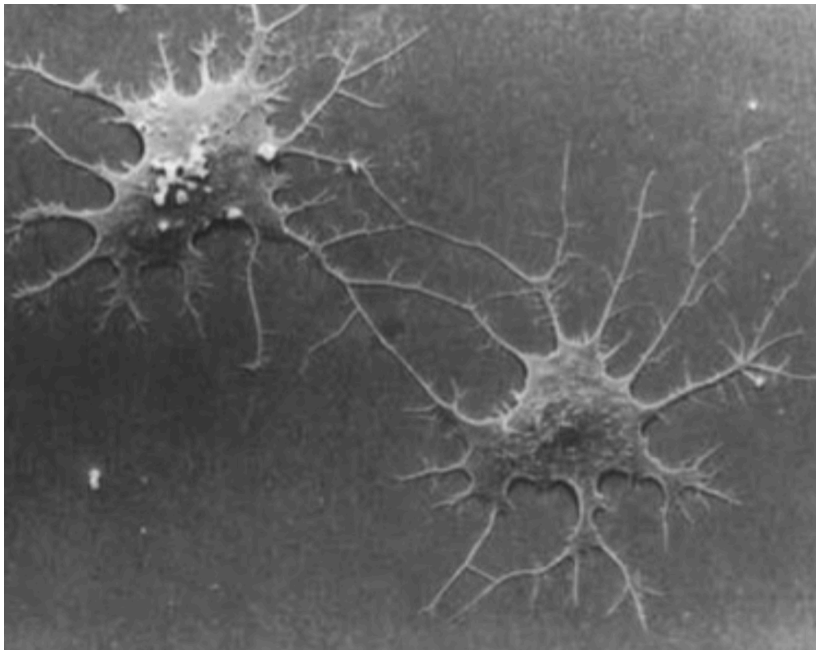


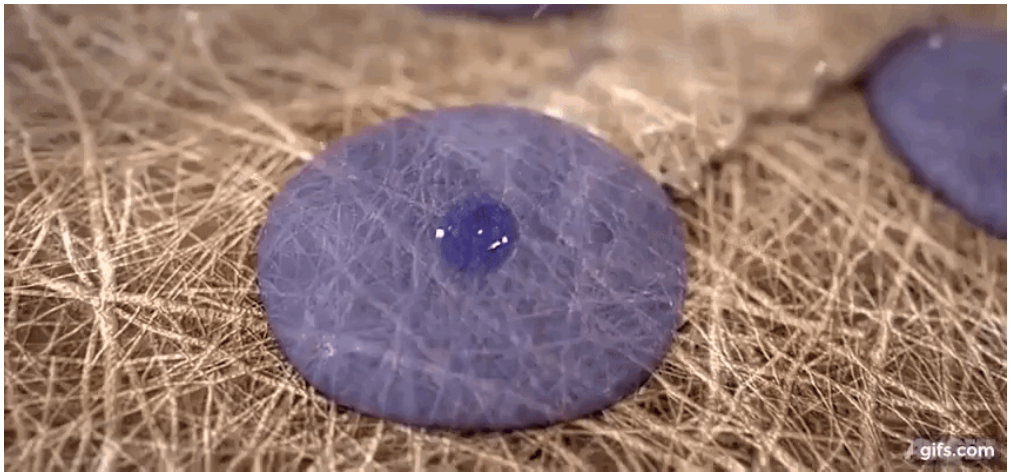
https://www.youtube.com/watch?v=78RBpWSOl08

Osteocytes



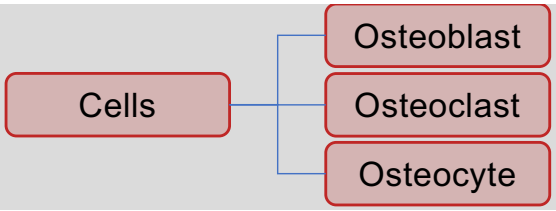
- Osteocytes live embedded in the bone forming a network that receives and transmits mechanobiological signals



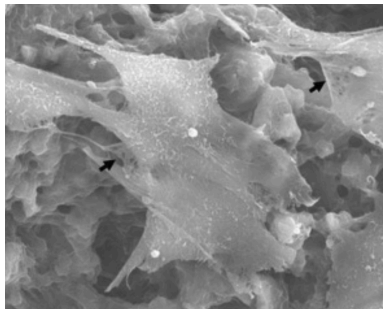


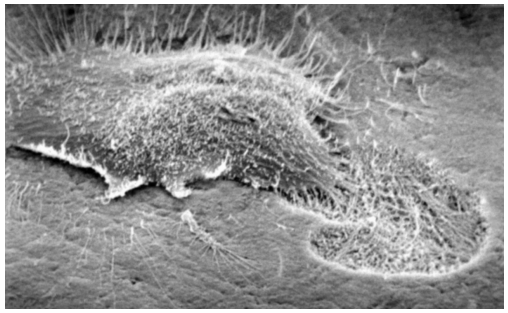
https://www.youtube.com/watch?v=78RBpWSOl08

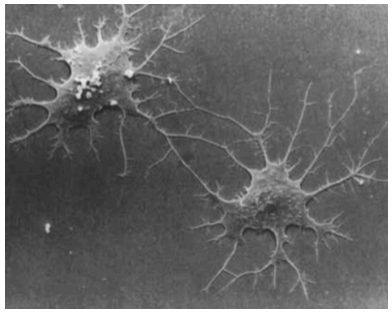
Bone Cells



	Osteoblast	Osteoclast	Osteocyte
Function	Produce Collagen Type I and other proteins	Resorb bone tissue	Mechanical biosignaling
Morphology	Small, round cell with large nucleus	Large, multinucleated cell (up to 50 nuclei)	Small, round cells with long cytoplasmatic processes
Dimension	20-30µm	150-200µm	5-20µm
Origin	Mesenchimal stem cells	Hematopoietic marrow	Differentiation of mature osteoblasts trapped in the secreted matrix

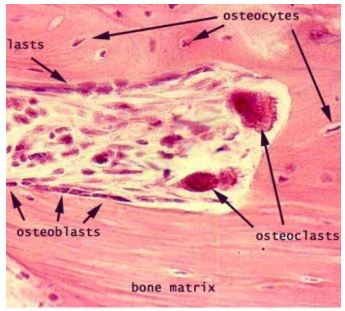




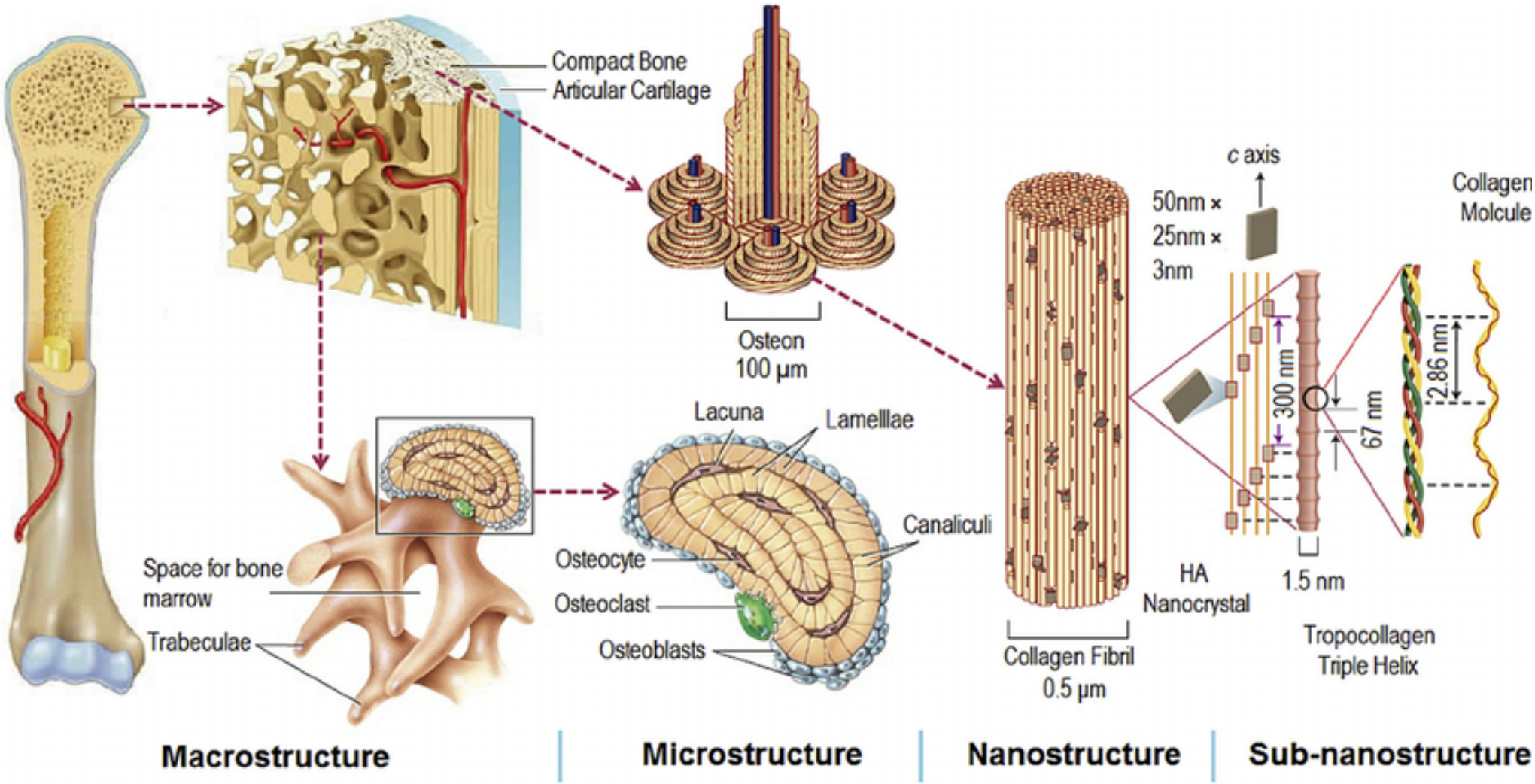


Multi-Scale Approach to Bone Study – Summary

Biology

BODY LEVEL	ORGAN LEVEL	TISSUE LEVEL	CELLULAR LEVEL
			
[m - cm]	[cm - mm]	[mm - µm]	[µm]

Multi-Scale Approach to Bone Study – Summary



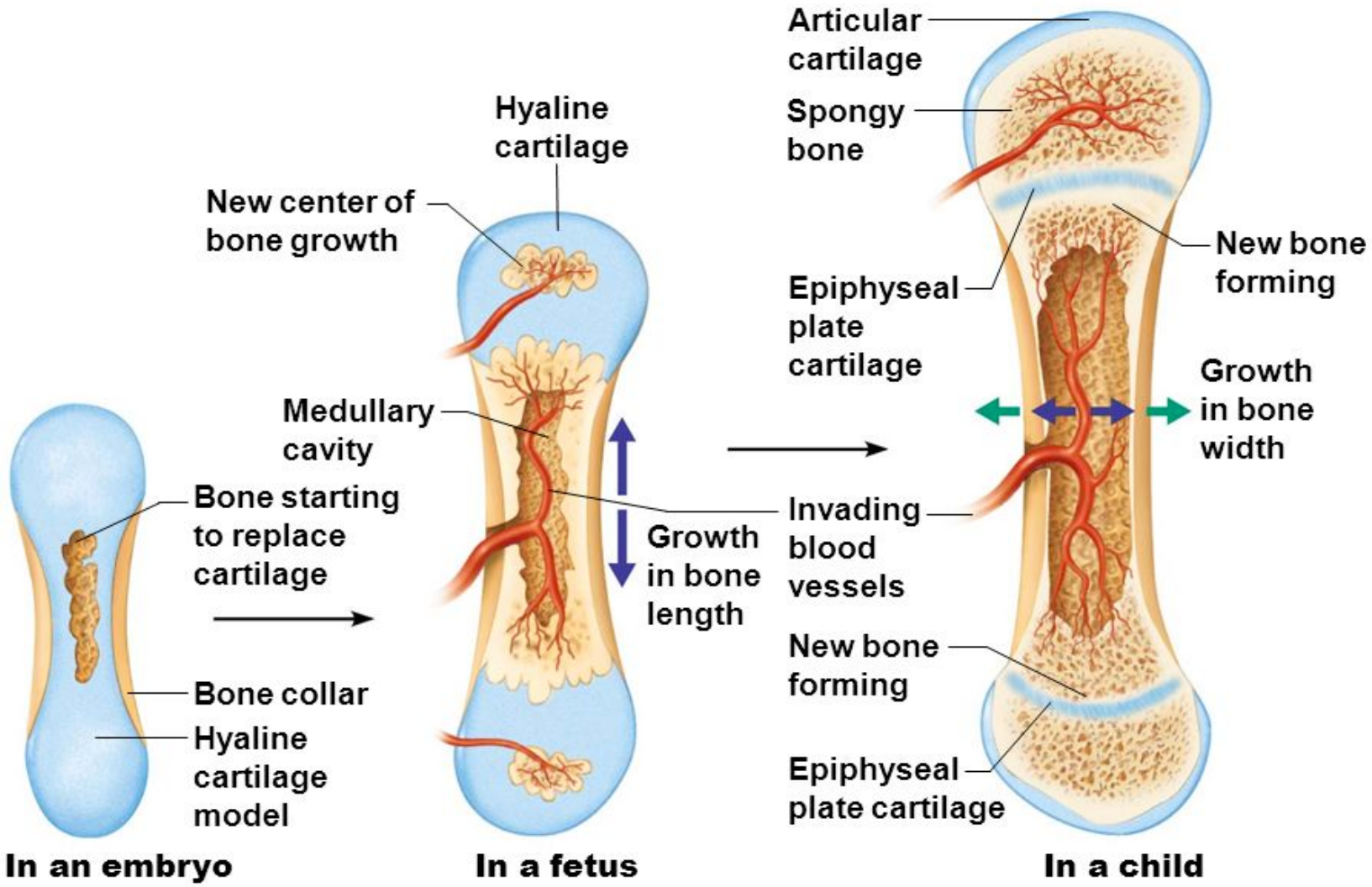
Bone Modeling and Remodeling

Definitions

- **Bone Modeling**: osteogenesis, i.e. bone embryonic formation and growth in immature individuals

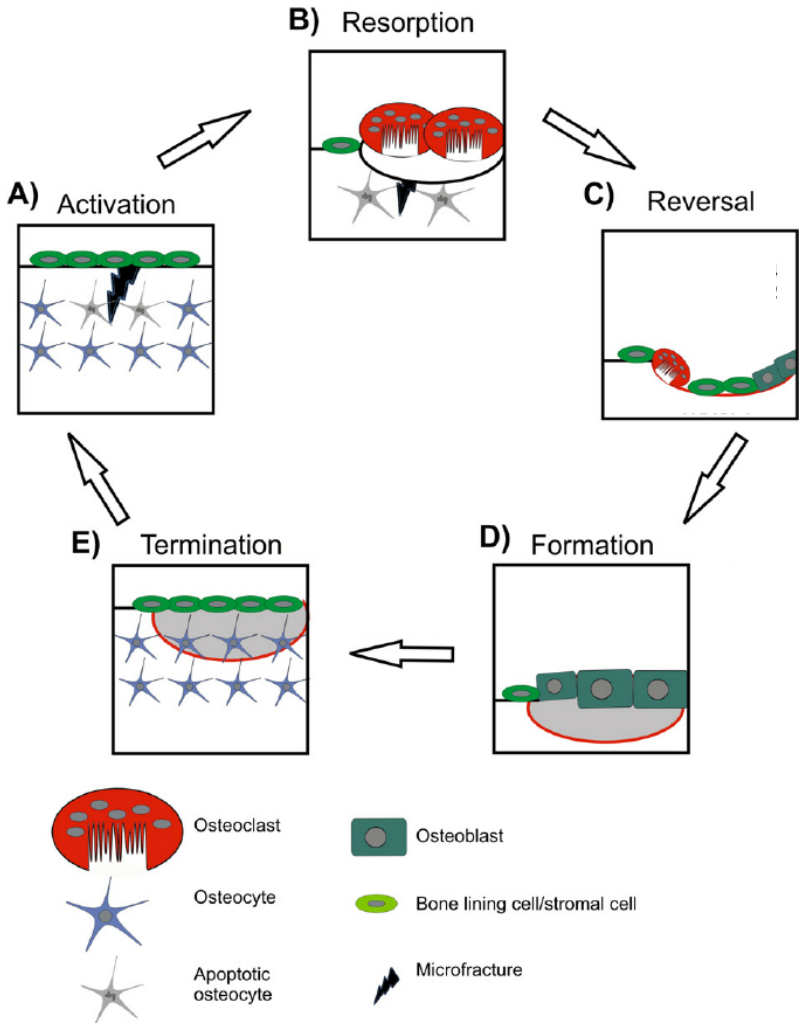
- **Bone Remodeling:** metabolic processes that constantly destroy and regenerate the bone extracellular matrix in mature individuals.
  - Produces no variation of the total skeletal mass (homeostasis) or variations of the total skeletal mass
  - **Bone Adaptation**: remodeling is due to the changes in the environmental conditions

Bone Modeling – Long bone

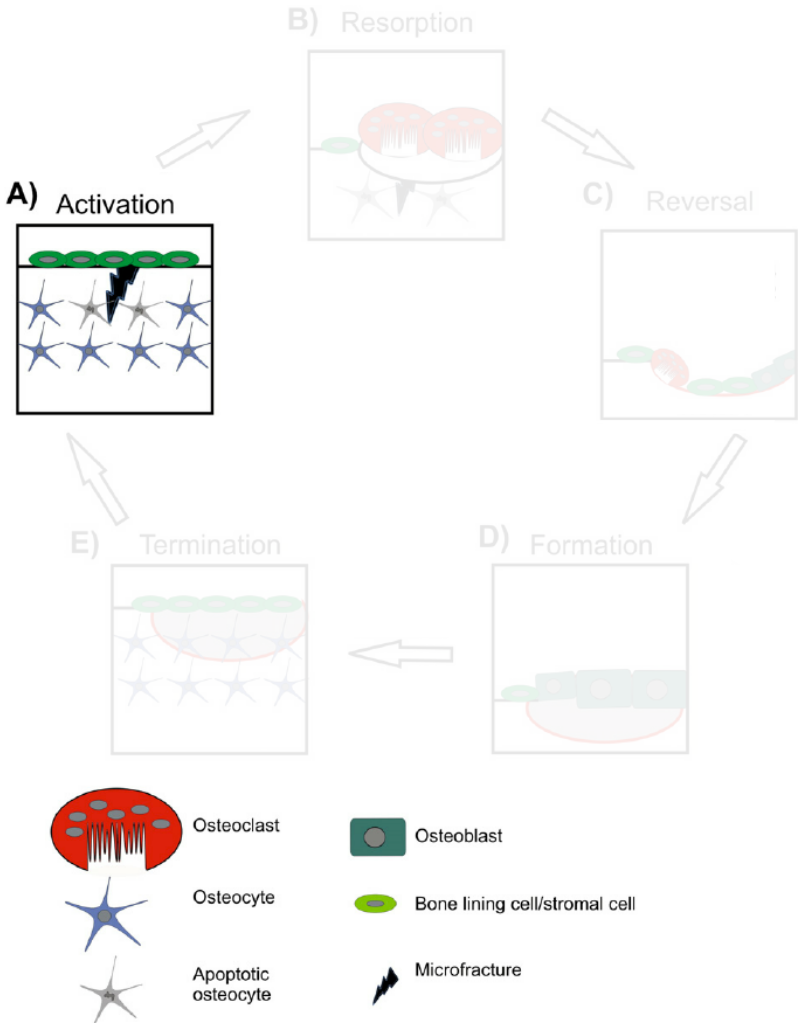


Bone Remodeling

- Bone remodeling helps to:
  - Repair structural damage and replace dead bone
  - Adapt microarchitecture to local stress (Bone Adaptation)
  - Regulate calcium homeostasis and hematopoiesis
- Bone *turnover* (= periodic replacement of bone) for normal adult:
  - Cortical bone: 20 years
  - Trabecular bone: 1-4 years



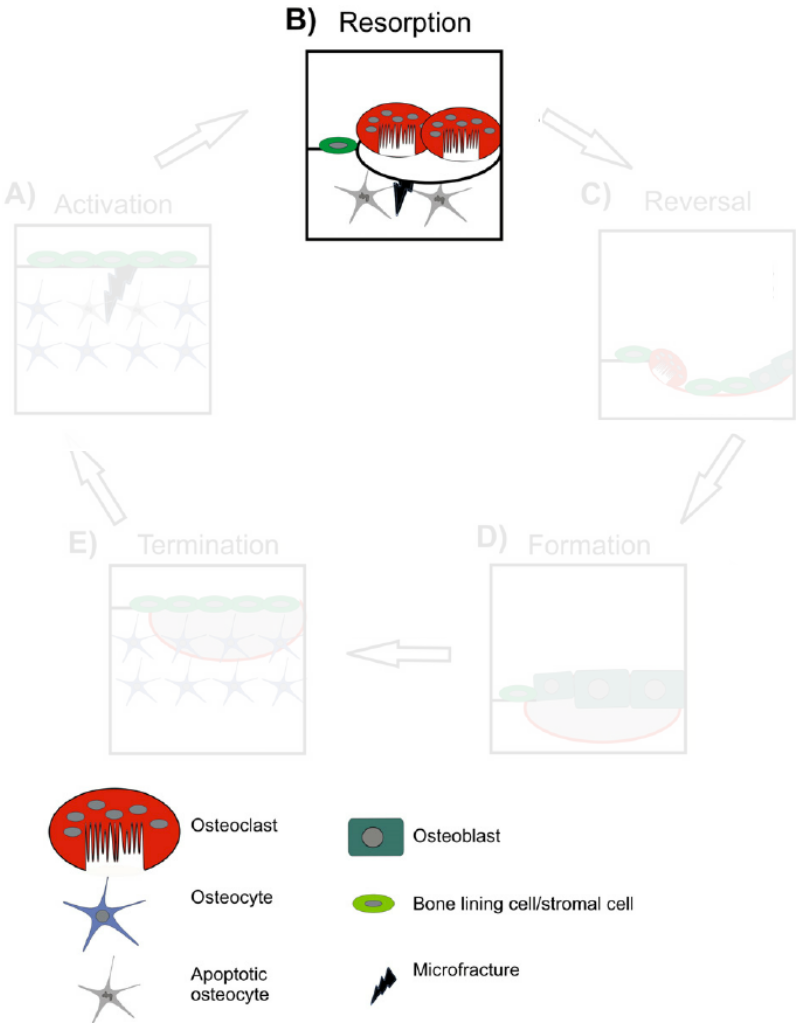
Bone Remodeling - Activation



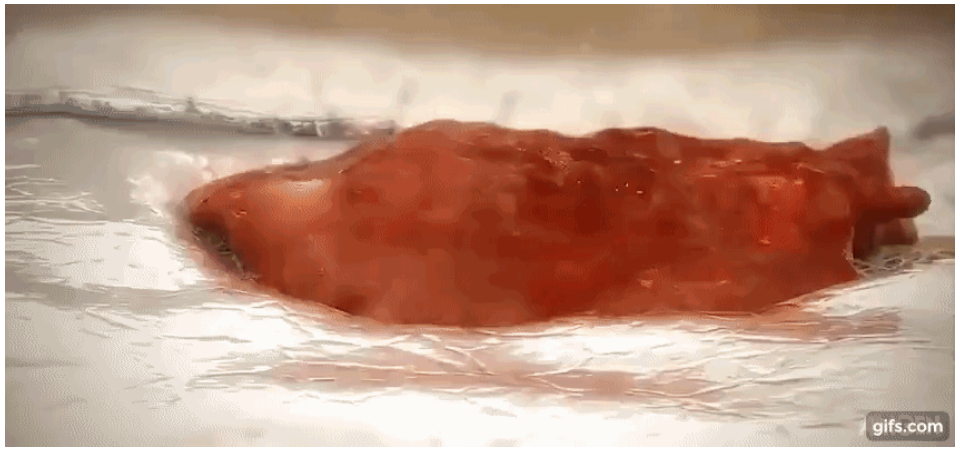
- Osteocytes probably sense bone deformation and send signals
- Lining cells lift from their attachment to form a closed sac around the remodeling site

https://www.youtube.com/watch?v=0dV1Bwe2v6c

Bone Remodeling - Resorption

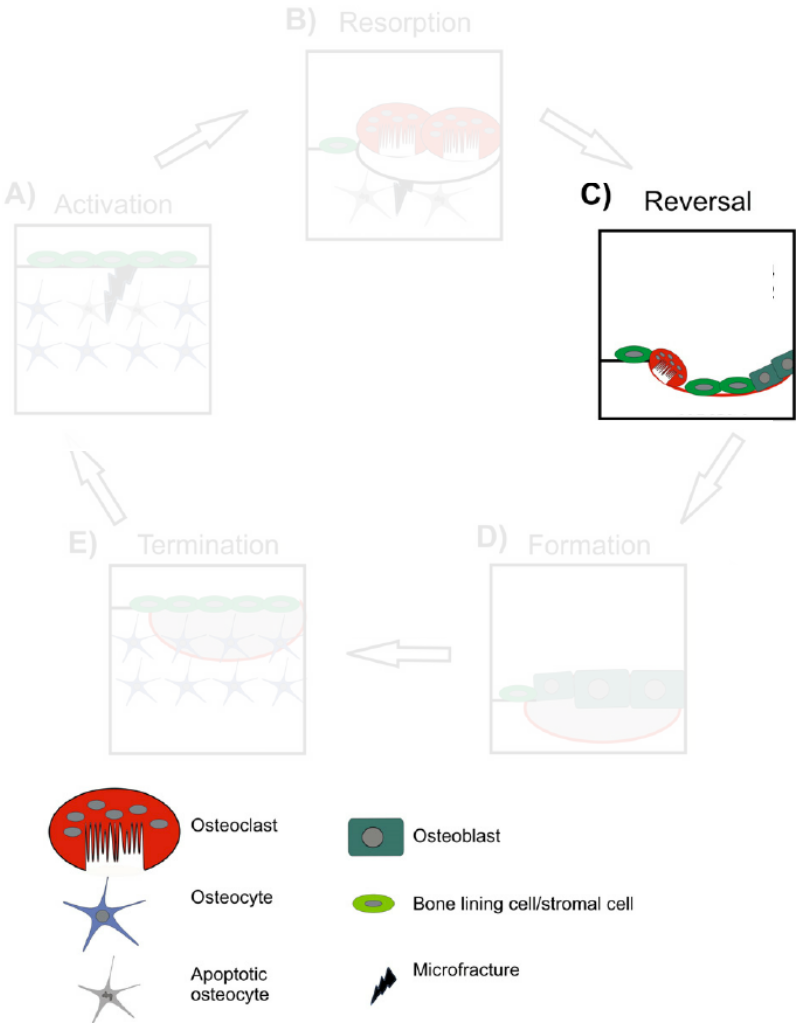


- Osteoclasts come in contact with bone surface and they start to erode it
- It takes 2 to 4 weeks



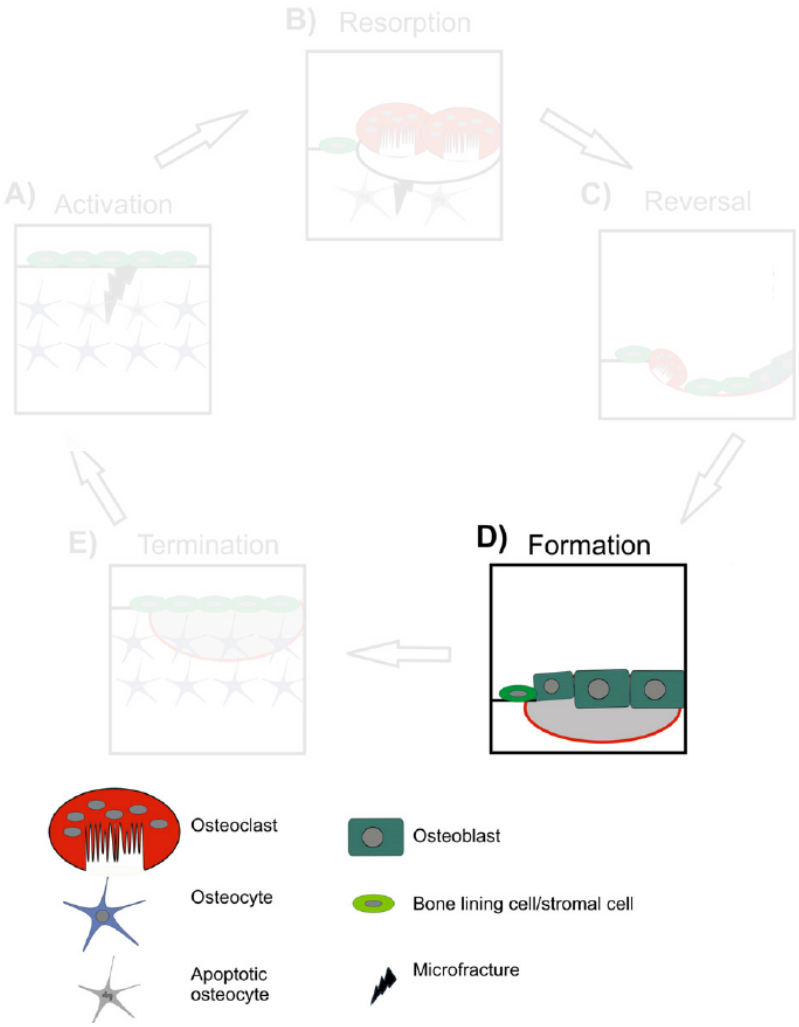
https://www.youtube.com/watch?v=0dV1Bwe2v6c

Bone Remodeling - Reversal



- It is a 1-2 week interval between bone resorption and formation
- Not well understood how cell signaling occurs

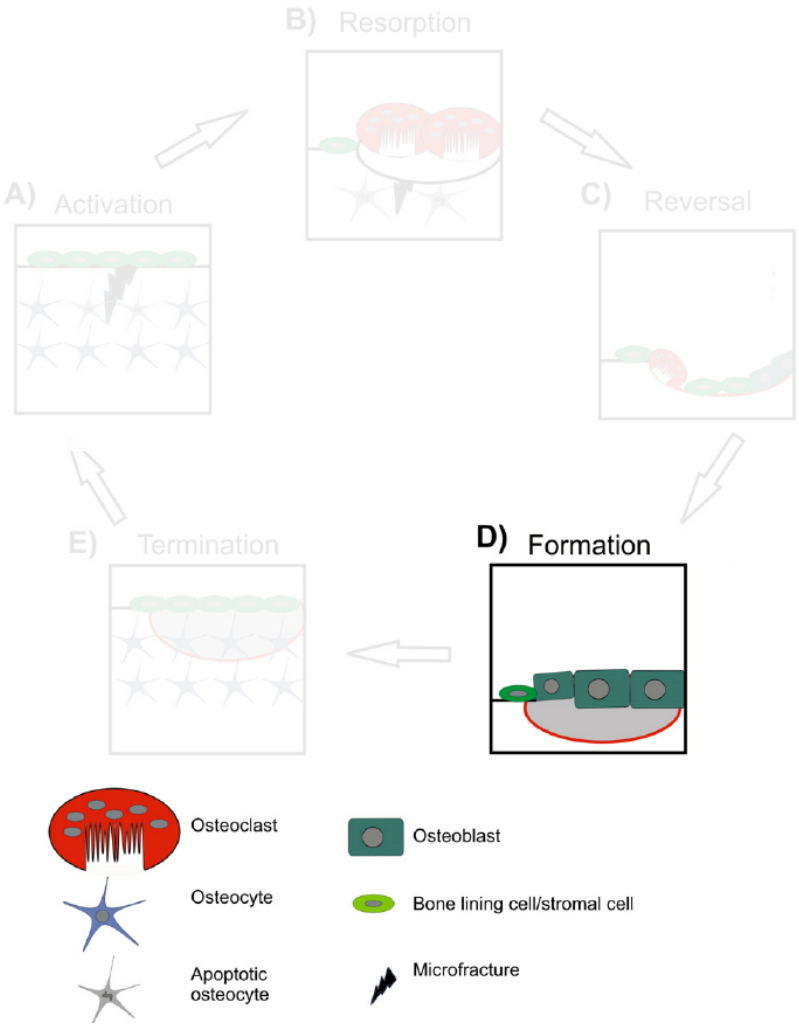
Bone Remodeling - Formation



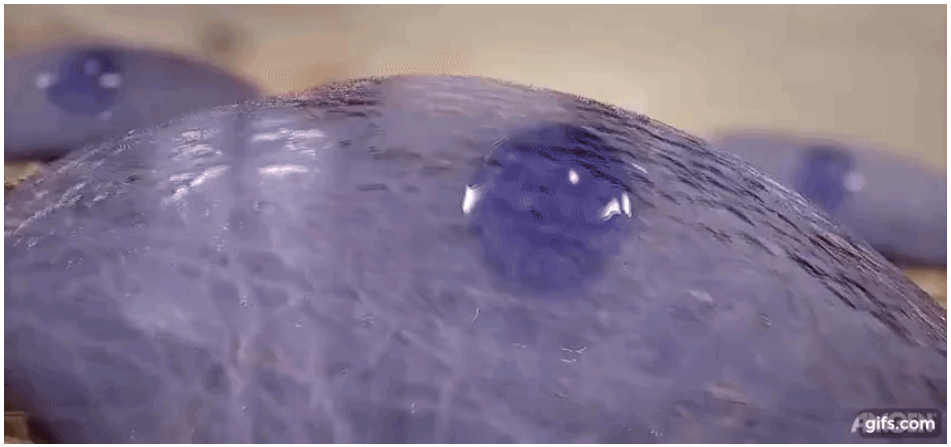
- Osteoblasts start to secrete collagen and other proteins to form new bone
- *Mineralization* occurs as HA precipitates next to collagen
- It takes 2-3 months

https://www.youtube.com/watch?v=0dV1Bwe2v6c

Bone Remodeling - Formation

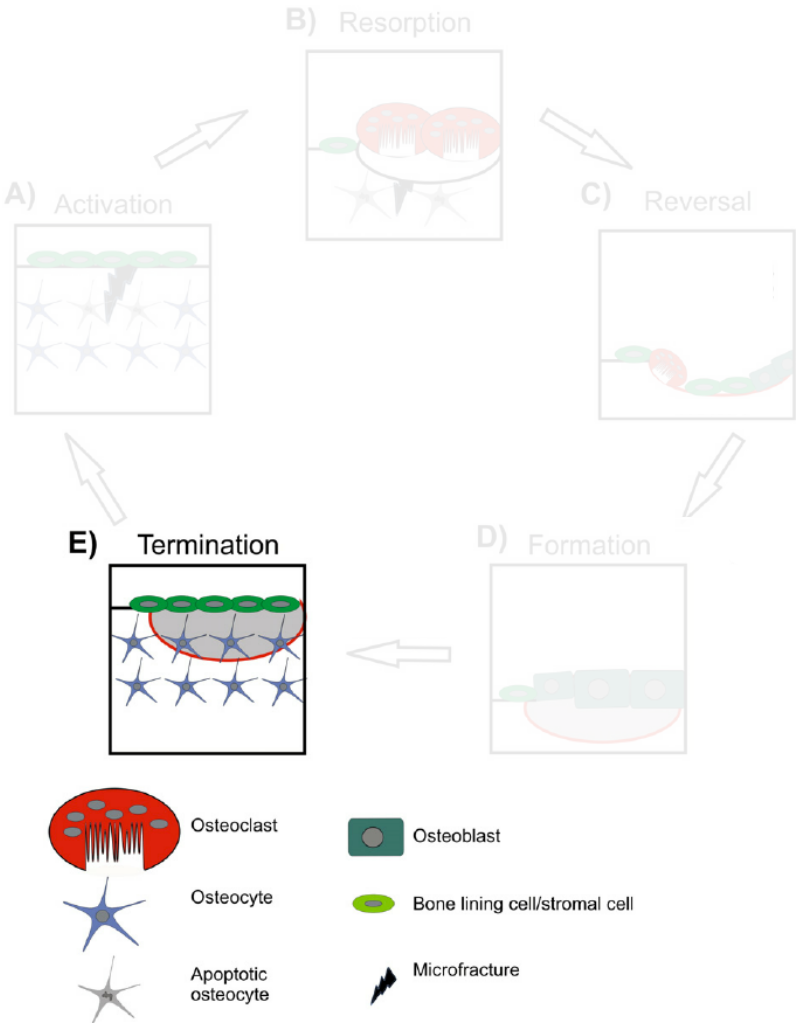


- Osteoblasts start to secrete collagen and other proteins to form new bone
- *Mineralization* occurs as HA precipitates next to collagen
- It takes 2-3 months
- Some osteoblasts remain trapped in the matrix they produce and become osteocytes

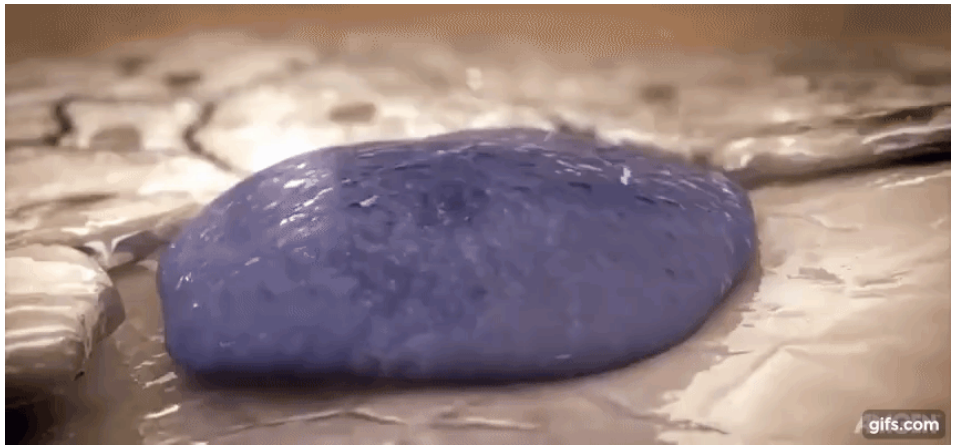


https://www.youtube.com/watch?v=0dV1Bwe2v6c

Bone Remodeling - Termination



- Osteoblasts on the surface become lining cells



https://www.youtube.com/watch?v=0dV1Bwe2v6c