

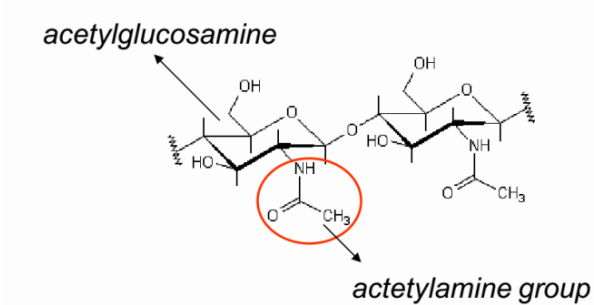
05.06.2019

1. Elements of biological materials

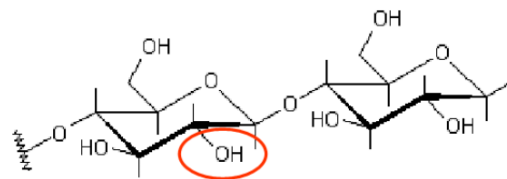
a) Name two fibrous polysaccharides and describe the difference.

Both cellulose and chitin are polysaccharides that naturally occur as fibers with similar dimension and stiffness.

Chitin molecule



Cellulose molecule



Cellulose is consisting of a linear chain of β linked D-glucose units. Adjacent chains and planes are linked together by hydrogen bonds. Cellulose is an important structural component of the primary cell wall of green plants, many forms of algae and the oomycetes.

thickness: 2-100 nm

$E \approx 140$ GPa

Chitin is very similar to cellulose but with a different side group. Chitin occurs in insect tissue.

thickness: 3-300 nm

$E > 140$ GPa

b) Name 3 types of polysaccharide fillers.

- **Pectins** (from fruit; lubricating gels or glues)
- **Carageenans** and **alginates** (gels extracted from dried seaweed)
- **Hyaluronic acids** (in synovial fluid, cartilage, ...)

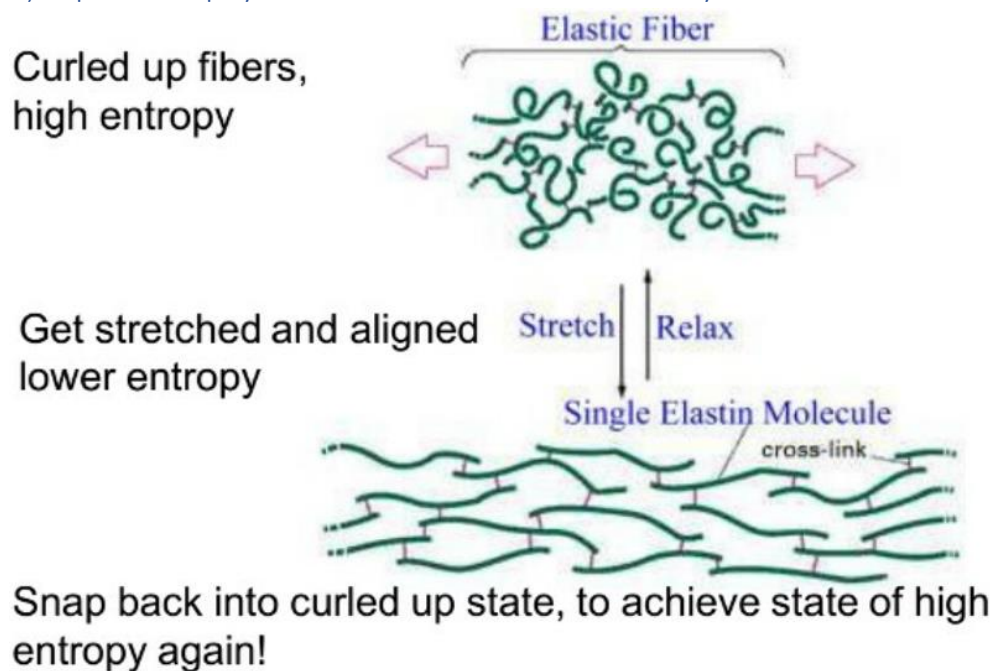
c) Are these materials proteins, polysaccharides, or a mixture? Name their most important components.

- cuticle
 - polysaccharide fibers (chitin) & protein matrix
 - chitin, proteins
- tendon
 - protein fibers & polysaccharide/proteoglycan matrix
 - collagen, proteoglycans
- muscle
 - protein fibers & polysaccharide/proteoglycan matrix

- collagen, myosin, actin
- cartilage
 - protein fibers & polysaccharide/proteoglycan matrix
 - collagen, proteoglycans, water, (non-collagenous proteins, glycoproteins)
- wood cell wall
 - polysaccharide fibers & polysaccharide matrix
 - cellulose, hemicellulose, lignin

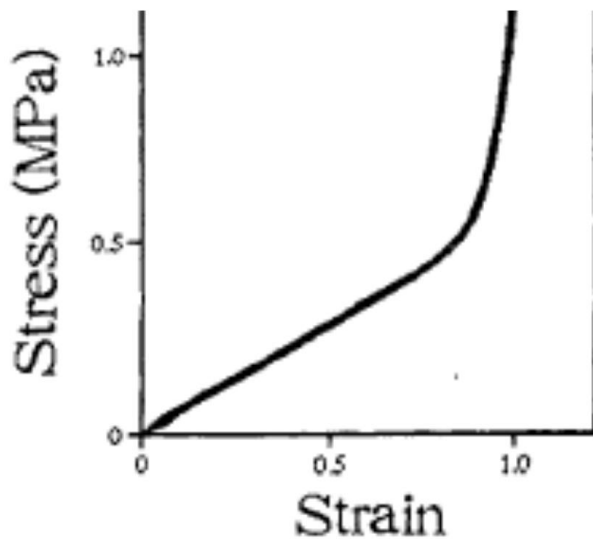
2. Mechanical concepts in biomaterials

a) Explain the physical behavior of rubber elasticity.



In more realistic terms: Temperature is the movement of atoms. As there is many of such atoms in each molecule and many molecules make up the rubber, the movement is statistically random. Therefore, the cross-linked molecules jitter randomly. If they are stretched out, this random wiggle pushes also into the directions perpendicular to the stretched direction and therefore pulls on the ends of the stretched fiber. Those many small pulls add up to the elastic pull back of the whole rubber. This causes the rubber elasticity. (For the most part. The other thing is a sudden very strong pull back at some point when you stretch the rubber too far and, in this process, pull on the backbone of the molecules. This strong pull back comes from the attractive forces in the intermolecular and intramolecular bonds. Going over this point leads to material failure.)

b) Draw a qualitative stress strain diagram of a material with rubber elasticity.



c) Name 2 elastic materials and 2 viscoelastic materials.

- Rubber elastic:
 - abductin
 - resilin
 - elastin
- Viscoelastic:
 - hair keratin
 - bone

3. Bioceramics

a) What's the material that magnetite is formed from in the magnetotactic bacteria?
Ferrihydrite (= rust) → Hematite (Fe_2O_3) → Goethite (FeOOH) → Magnetite (Fe_3O_4)

b) What function do the magnetite particles have in the bacteria?

Magnetotaxis: A widely accepted hypothesis about the function of magnetotaxis is that, because all known magnetotactic bacteria are either microaerophilic or anaerobic, they seek to avoid high oxygen levels and their navigation along the geomagnetic field lines facilitates migration to their favored position in the oxygen gradient. The preferred motility direction found in natural populations of magnetotactic bacteria is northward in the geomagnetic field in the northern hemisphere, whereas it is southward in the southern hemisphere. Because of the inclination of the geomagnetic field, migration in these preferred directions would cause cells in both hemispheres to swim downward.

c) Why could the occurrence of magnetite lead to extraterrestrial life?

Magnetic material consists of magnetic domains. Magnetic moments of different domains are not necessarily oriented in the same direction. Reduction of size can lead to single domain particles (maximum magnetic moment for given particle size). If size is further reduced, particle becomes paramagnetic (spins flip randomly).

Magnetite particles in magnetotactic bacteria are single domain particles. (Strict control over size and shape: particle size between 40-100 nm). Size is so special that magnetite particles have been looked for in the Martian meteorites as a possible sign of extraterrestrial life

d) Name two bioceramics that are used in optics.

- calcite
- ??

4. Self-Assembly

a) Why are weak interactions needed in self-assembly?

Because such bonds are easy to control in environmental surroundings (easy to form and reform after breaking). Therefore, those weak forces are also reversible.

b) What interaction is used to assemble the 3 alpha helixes in collagen?

Hydrophobic interaction due to glycine with the smallest side group.

c) Explain the hydrophilic hydrophobic interaction. What structures can it form? Name 2.

Hydrophobic interactions describe the relations between water and hydrophobes.

Hydrophobic ends in molecules are not attracted to water. Thus, when they come close to each other, they tend to stick together to minimize the interaction surface with water.

(When a hydrophobic particle touches water on the one side and hydrophobic particles on the other, the water and hydrophilic particles attract each other and passively push the hydrophobic particle into the others in the process. If a molecule has hydrophilic and hydrophobic parts, the hydrophilic parts are pulled towards the water molecules and the hydrophobic part is therefore passively forced to point to other hydrophobes.)

This interaction can form liquid crystals, e.g.:

- micelles
- bilayers
- cylindrical micelles

5. Bone

a) Explain the difference between cortical and trabecular bone. Where do the types occur?

Cortical bone is a compact structure found in long bone and generally as the outer layer of bone. It contains osteons.

Trabecular bone is a sponge like structure filling the inside of bones. The spaces are filled with bone marrow.

b) Shortly explain the structure of bone, at least mention the macrostructure, microstructure, and nanostructure.

Bone is a very hierarchically structured material. The macrostructure is the general shape of the bone and the alignment of bone material in trabecular and cortical bone according to the local needs. The microstructure is osteons with their diameter in the range of 10-500 μm . Those osteons are made of a sub-microstructure: the lamella with a thickness of 3-7 μm . Each of the lamella is made of collagen fibers which make up the nanostructure. The collagen fibers are made of collagen fibrils with a diameter of 0.5 μm , which each are made of collagen molecules with a diameter of 1 nm, and bone crystals. The last part is the sub-nanostructure.

c) What's the problem with bone remodeling and hip implants?

Bone is an adaptive material which is adding material where more stress is located while removing material where it is not needed. Artificial femoral heads change the load distribution in the femur. Most of the load is located at the lower end of the inserted implant and much less is around the upper end of the implant. Therefore, material is added at the bottom end and removed around the implant. This causes the implant to loosen over time.

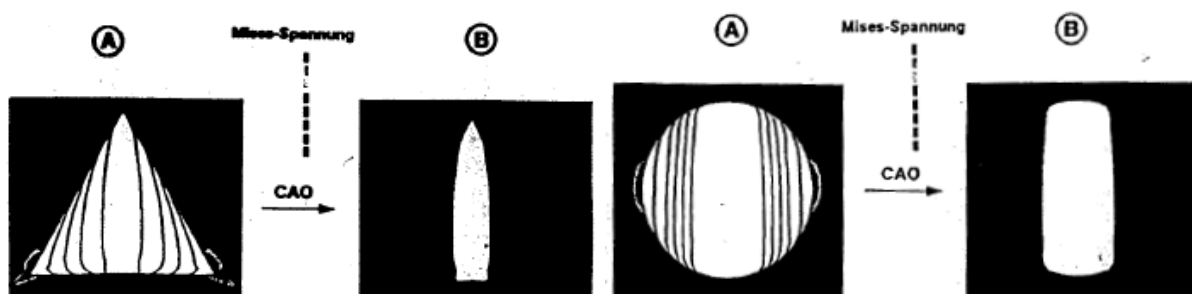
6. Wood

a) How does wood heal wounds?

As wood is essentially dead tissue, it grows by addition of material only. Underneath the bark, the cambium is the living layer making new material. When the tree is wounded, the cambium adds material.

b) Which shape will the healed wound have? (Draw outline in a sketch; Triangle horizontal, triangle vertical, circle) Explain why it will form this shape.

The gravitational and other forces acting on the tree cause the distribution of the new material accommodate to minimize the Mises stresses. Due to the minimization of the Mises stresses, the wound will over time adapt to a longitudinal, oval shape.



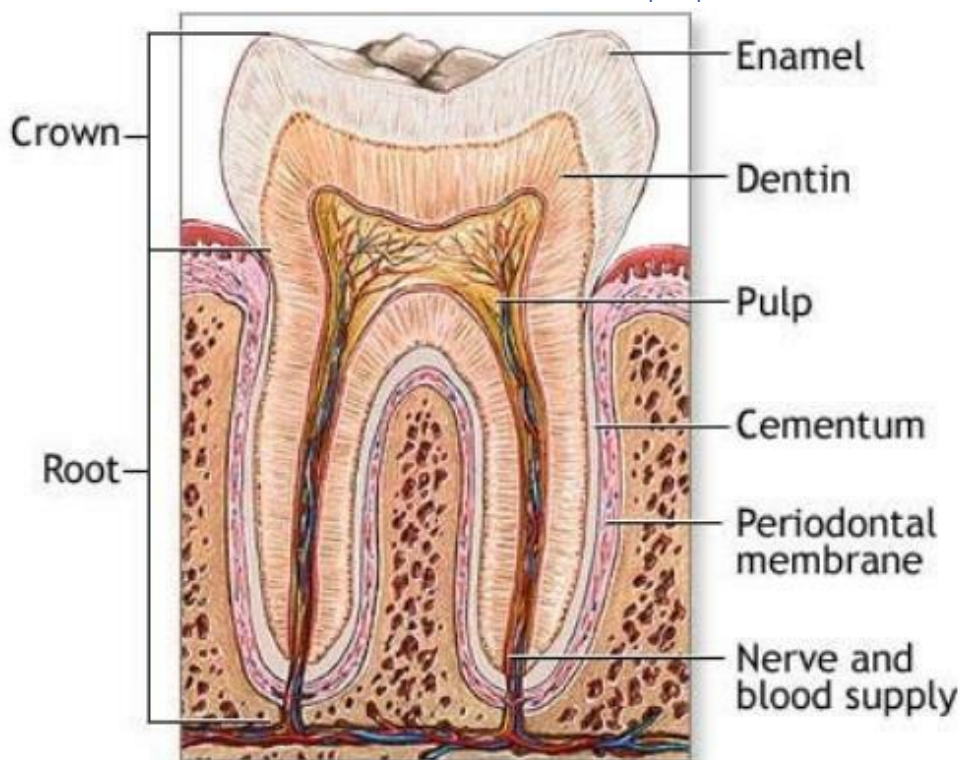
c) What are typical safety factors in biomaterials? Compare them to safety factors in engineering.

Material	Safety factor	Equipment	Factor of Safety - FOS -
Bones	2-6	Aircraft components	1.5 - 2.5
Tree trunks	4	Boilers	3.5 - 6
Stems of annual plants	2	Bolts	8.5
Buoyancy chambers of mollusks	1.4	Cast-iron wheels	20
		Engine components	6 - 8
		Heavy duty shafting	10 - 12
		Lifting equipment - hooks ..	8 - 9
		Pressure vessels	3.5 - 6
		Turbine components - static	6 - 8
		Turbine components - rotating	2 - 3
		Spring, large heavy-duty	4.5
		Structural steel work in buildings	4 - 6
		Structural steel work in bridges	5 - 7
		Wire ropes	8 - 9

14.05.2019

Dentin and Enamel

Where can you find Dentin & Enamel in teeth, sketch it. What is the composition of them and what is the difference in mechanical properties?



Enamel is the white topcoat; it is hard and highly mineralized. Tooth enamel consists of relatively large crystals of hydroxyapatite in high quantity. Only about 2%vol are protein and very little water is contained in enamel. The structure is a plywood arrangement of micrometer sized mineral rods.

Dentin is the mineral underneath; it is softer and bone-like. The structure of dentin is tubular.

	bone	dentin	enamel
HAP vol% (wt%)	41 (64)	48 (69)	92 (97)
Organic vol% (wt%)	48 (31)	29 (20)	2 (1)
Water vol% (wt%)	11 (5)	23 (11)	6 (2)
Youngs modulus GPa	17-20	10-20	75-90
Tensile strength MPa	150	30-100	8-35
Compressive strength MPa	220	250-350	200-400

Strategies against delamination of the Dentin/Enamel Interface.

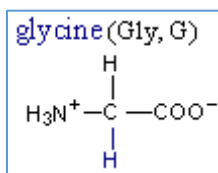
A modulus mismatch on the junction would cause high stress concentration and lead to delamination. A toothed structure on the micrometer scale, roughness on the nanometer scale, and a mineralization gradient create a mechanical gradient to prevent the buildup of stress concentrations.

Fluorization of Teeth: What is the effect of Fluor Treatment and what changes on mineralization level?

Hydroxyapatite is affected by acids; its solubility is pH dependent. When an OH group in HAP is replaced by fluoride, it becomes fluorapatite. Fluorapatite is much less affected by acids.

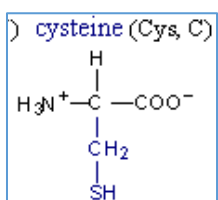
Proteins

What is the smallest Amino Acid and what is its R-Group?



The smallest amino acid is glycine with an H as the side group.

There is an amino acid that can form disulfide bonds with neighbors. How is this Amino Acid called and where does it predominantly occur?



The amino acid cysteine has a sulfur atom in its R-group. This is capable of forming a covalent bond with another sulfur atom on a different cysteine molecule, creating the so-called disulfide bond. This bond acts as a stabilization for the tertiary structure of proteins that have such bonds, like keratin or procollagen.

How many Amino Acids occur naturally?

20

Wood

How does wood adapt to external loading?

As wood can only add material, it adapts by adding material on the right place to minimize stress. For example, in softwood material is added where the wood suffers compressive loads while in hardwood material is added where the wood is in tension.

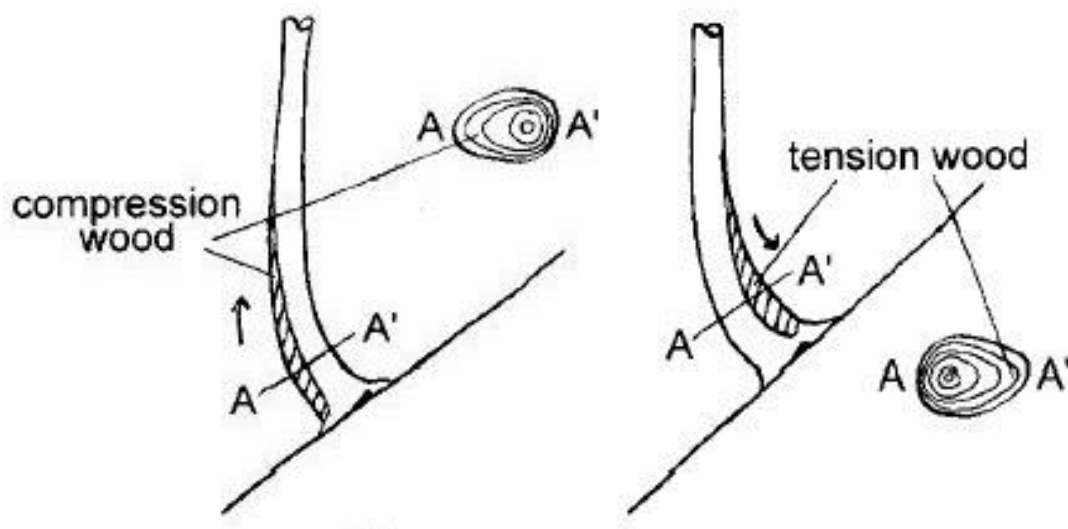
Name and explain the main components of the wood cell wall.

Cellulose is a fiber consisting of cellobiose units. Adjacent chains and planes are linked by hydrogen bonds. This creates the crystalline structure of cellulose fibers. Cellulose is an important structural component of the wood cell wall.

Unlike cellulose, **hemicelluloses** consist of shorter chains. In addition, hemicelluloses may be branched polymers, while cellulose is unbranched. Hemicelluloses are embedded in the cell walls of plants, sometimes in chains that form a 'ground' – they bind with pectin to cellulose to form a network of cross-linked fibers.

Lignin is an organic polymer. It is hydrophobic and acts as an adhesive in the cell walls. It stiffens wood.

Reaction Wood: Name & explain the difference in the behavior of conifers (softwood) and deciduous trees (hardwood). Explain their nanostructure.



In **softwood**, more material is added at the site of compression. At the lower end of steep growing sites, the wind shadow in windy places or generally at the lower side of branches,

compression wood forms due to the occurring forces. The nanostructure of softwood has large cellulose microfibril angles, which cause wood to be more flexible. After the deposition of cellulose wood is lignified. Compression wood contains more lignin, which spatially separates cellulose fibers and by doing so elongates the wood, creating a push-up effect.

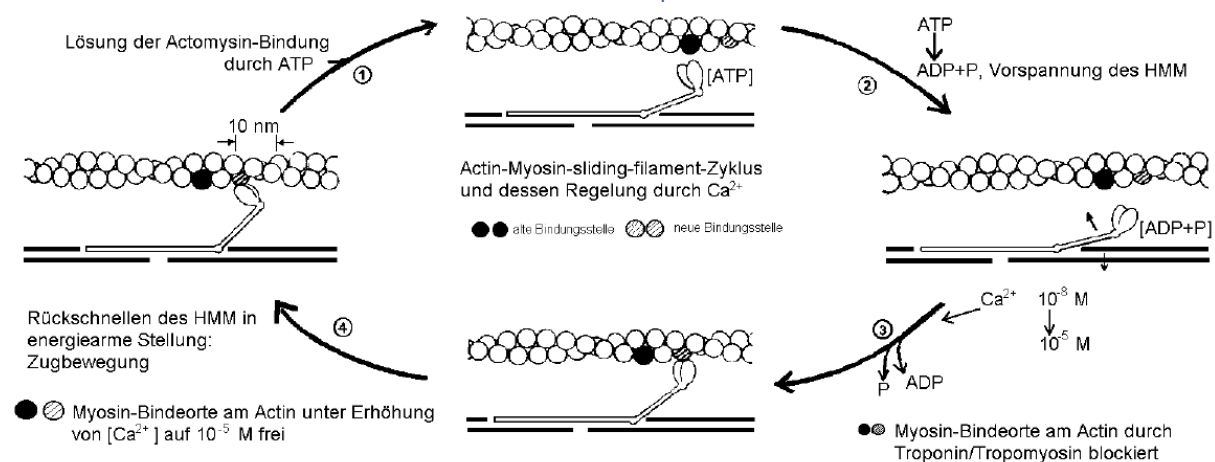
In **hardwood**, the exact opposite is true. More material is added at the site of tension. At the higher end of steep growing sites, the windy side in windy places or generally at the higher side of branches, tension wood forms due to the occurring forces. The nanostructure of hardwood has small cellulose microfibril angles, which cause wood to be more rigid. The cellulose fibrils are embedded in a gelatinous layer that can swell upon hydration. The swelling separates the cellulose fibers laterally and, in the process, contract them in the longitudinal direction, creating a pull-up effect.

Muscles

Name the proteins in skeletal muscles.

- myosin
- myosin binding protein
- actin
- α -actinin
- troponin
- tropomyosin

How does the contraction of muscles work? Explain!



- 1) Myosin heads are detached from actin.
- 2) Myosin ATPase splits ATP into ADP+P and energy is released. The myosin head absorbs energy, gets pre-stressed and oscillates. The actin binding sites are still blocked by tropomyosin/troponin.
- 3) A nerve impulse sets free Ca^{2+} . The tropomyosin yields HMM binding sites on actin, and the pre-stressed myosin gets bound to actin (actomyosin-ATPase; ADP + P are released).
- 4) The myosin head snaps back into its energetically favorable, kinked configuration; in this way, the actin slides by about 10 nm with respect to the myosin.

Where do the limitations in terms of mechanical behavior of muscle force come from?

Muscle contraction comes from the sliding of myosin and actin. The force is proportional to the number of fibers sliding past each other, and thus proportional to the physiological cross-sectional area. The filaments can only slide a certain distance before reaching an end. Therefore, the muscle can only contract a certain length. Also, muscles can only create power in one direction: contraction. They cannot extend, only contract or relax; therefore, a second, antagonistic muscle is needed.

Bone

Explain the Remodeling of Bone, which cells are used for it and explain their function!

Bone is constantly remodeled. When bone material is not needed at some place because there is no stress present, it gets removed. When more bone material is needed at some place because there is a lot of stress present, it gets added. If damages occur at some point, the bone around the damage is removed and new bone is made at its place. Three types of cells are used for bone remodeling:

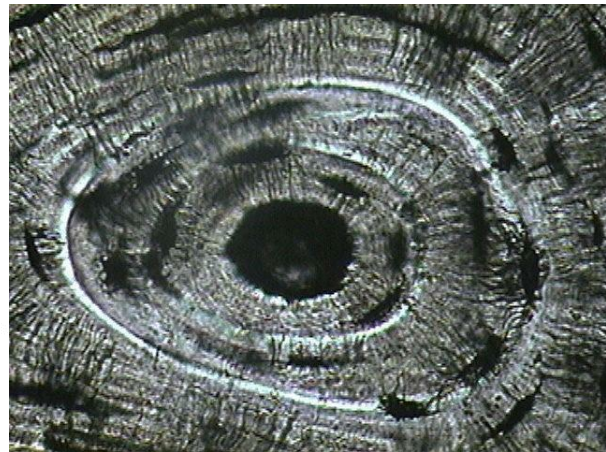
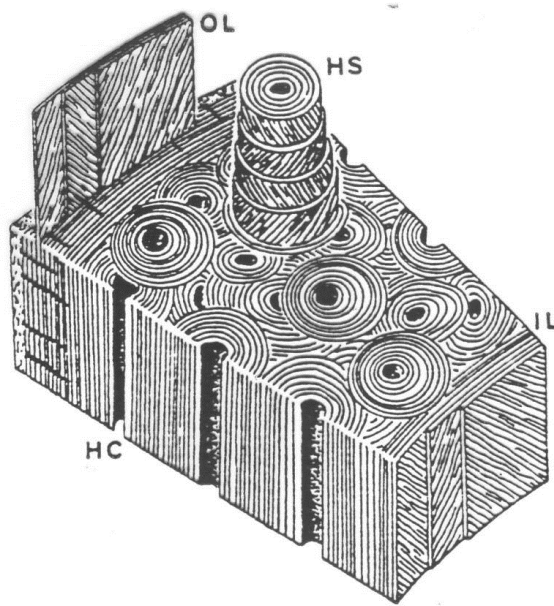
- **Osteoclasts** are large cells, attached to the bone surface, which are responsible for resorbing bone. They seal off the interface and start by dissolving mineral in acid and then resorb the collagen molecules. The holes are filled again by *osteoblasts*, they add a layer of so-called cement between old and new bone.
- **Osteoblasts** make bone. They are found on the surface and produce non-mineralized collagen fibers. If they later become trapped inside the bone, they turn into *osteocytes*.
- **Osteocytes** are osteoblasts trapped in so-called lacunae inside bone. Their task is not exactly known, they maybe act as sensors for external stresses and may direct adaptive growth.

What disease results in the reduction of bone density and microfractures.

Osteoporosis describes the decrease of general bone density and trabecular thickness in spongy bone due to higher bone resorption than deposition.

Osteogenesis imperfecta is characterized by bones that break easily. It is caused by a genetic defect that affects the production of collagen, either less collagen or poorer quality of collagen, leading to weak bones.

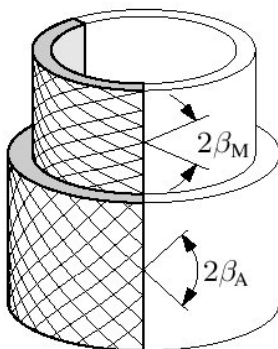
Explain the function of an osteon and sketch its structure.



Osteons are structural elements found in cortical bone. They are of cylindrical shape, having many layers wrapped around a hole. The hole in the middle is called haversian canal and contains blood vessels. The concentric layers around the canal are mineralized collagen fibers wound in a spiral-like way. Each layer has a different angular orientation of the fibers. Bone growth starts from inside the osteon in layers. At the end of the bone remodeling, the osteon is surrounded by a cement layer with very little collagen.

Reading Exercise

Which way do collagen fibers in artery walls align? Mark the correct one.



Explain your decision on mechanical behaviors.

- missing info - assuming explanation for the previous question instead.

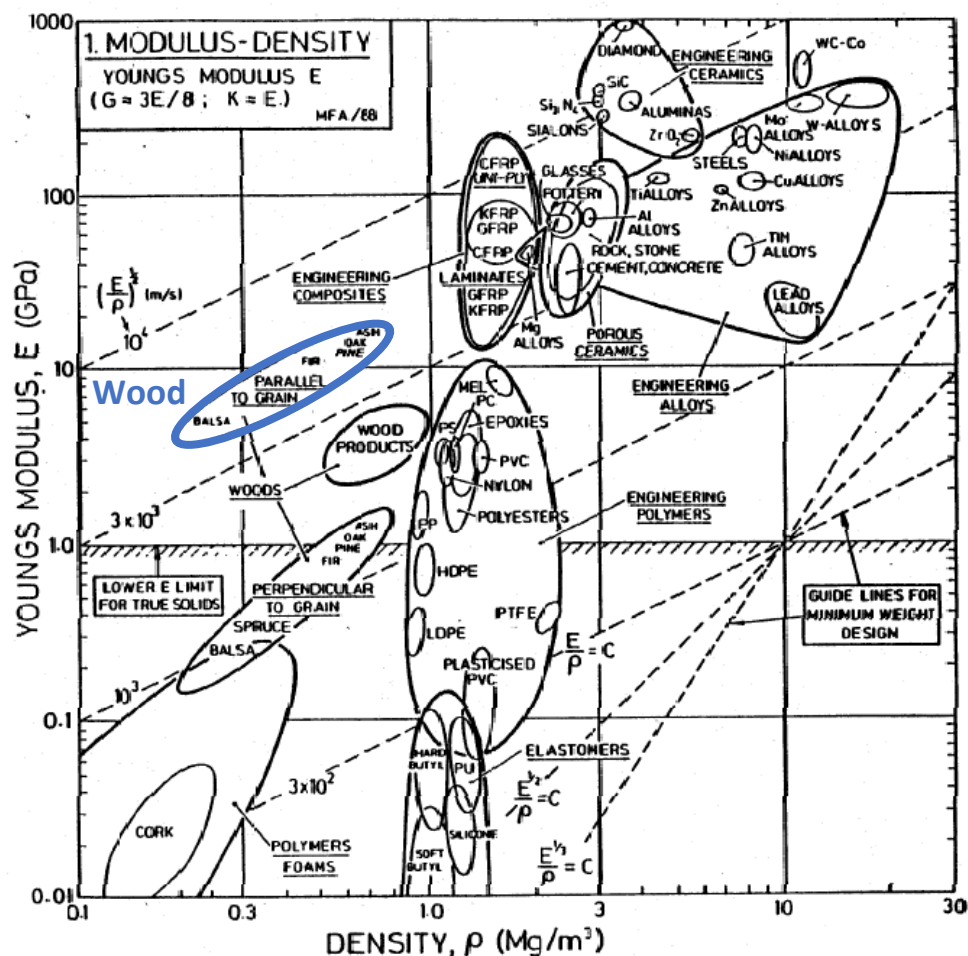
The collagen fibers in artery walls align this way, because if a small slit is introduced and the wall is stretched, the collagen fibers orient across the crack path, effectively stopping it and preventing catastrophic failure. The reorientation is very local, it disappears at a distance of only 0.5 mm from the crack tip.

You want to build a high tower that shouldn't buckle under its own weight, which material would you choose

Material	Safety factor
Bones	2-6
Tree trunks	4
Stems of annual plants	2
Buoyancy chambers of mollusks	1.4

This is an assumed example for biomaterial choice. The true selection is not known. In this case I would choose tree trunks/wood, because they have a reliably high safety factor and trees can grow extremely large without buckling under their own weight. Their only height limiting factor is that water cannot be transported high enough. Furthermore, most of the wood is dead material and thus does not need a lot of additional maintenance.

Mark the area where the chosen material can be found in the Ashby plot



06.06.2018

1. Proteins

Synthesis of proteins

The synthesis takes two steps. The first step is the transcription in the nucleus and the second is the translation outside the nucleus.

First, a section of DNA unwinds, and complementary bases attach to one DNA strand to form the mRNA. This transcribed mRNA then leaves the nucleus through nuclear pores.

The mRNA is then docked between the small and large compartment of the ribosome. tRNA with an anticodon attaches to the codon (base triplet) of the mRNA inside the ribosome. On the other end of the tRNA is an amino acid coded by the codon. The next tRNA attaches to the next codon and the amino acid of the previous tRNA links to the one of the new tRNA. The ribosome moves along the mRNA and this process continues until the mRNA ends and the whole polypeptide chain is complete. This chain then detaches and folds to a specific, complex shape to form the protein.

Building blocks of proteins

The building blocks of proteins are amino acids.

Where does the synthesis happen?

Protein synthesis takes place in the ribosomes, in the cytoplasm outside the nucleus.

2. Silk

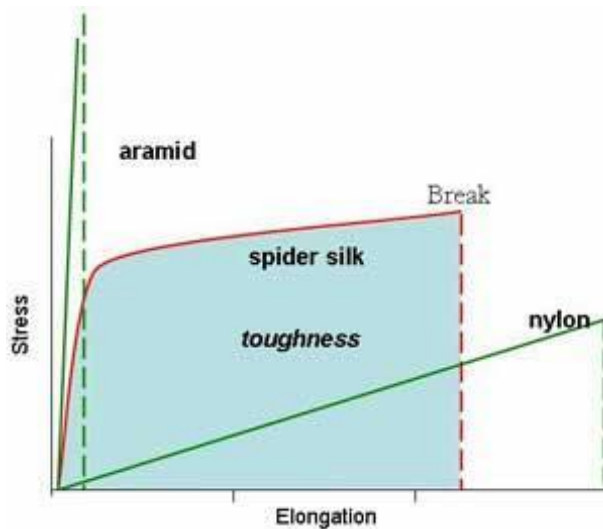
What is silk?

Silk is a fibrous structural protein, which is not naturally occurring in the human body. On a molecular level, silk is based on beta sheets composed mainly of fibroin. There are different types of silk like the soft silkworm silk or the stiff and tough spider silk.

Silkworm silk is mainly held together via covalent binding forces in the fibers, hydrogen bonding forces in between the fibers holding the beta sheets together, and weak van der Waals forces in between the sheets, which are the reason for the pliability of this type of silk.

Spiders produce different types of silk. Dragline silk is strong and thick, and it is used for framing, supporting radii or abseiling. Cribellate capture silk is extremely fine, more elastic and does not need glue to stick to prey. Ecribellate capture silk is silk covered with sticky glue.

Give the mechanical properties of silk.



Material	Tensile Strength	Extensibility	Fracture Energy
Bone	150 MPa	2 %	1,500 J/kg
Mild Steel	350 MPa	40 %	13,000 J/kg
High-Strength Steel	1500 MPa	0.8 %	800 J/kg
Kevlar	3600 MPa	2.7 %	35,000 J/kg
Spider Silk I (MAS)	1100 MPa	30 %	150,000 J/kg
Spider Silk II (viscid silk)	500 MPa	800 %	140,000 J/kg

Spider silk is very tough, and it is 5 times as strong as steel relative to its density. (high strength steel: 1,5 GPa, spider silk 1.1 GPa, density of steel about 8 kg/dm³, density of silk: 1-1.5 kg/dm³)

3. Keratin

Describe the stress strain curve of keratin.

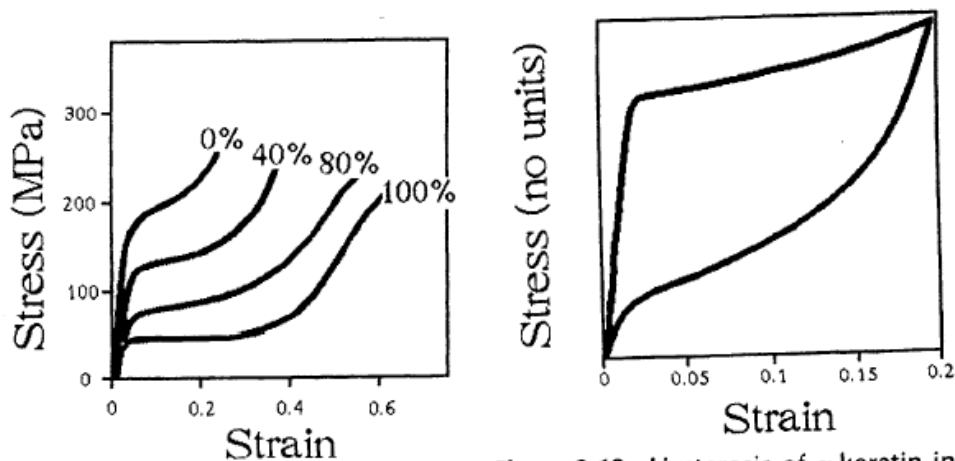


Figure 2.12 Hysteresis of α -keratin in h

Hair keratin is hierarchically structured. Each hair is consisting of hair cells made of macrofibrils. Each macrofibril is made of microfibrils, each microfibril of protofibrils. The protofibrils are superhelices made of 2 α -helices. When the hair keratin is pulled, first the helices are pulled like a spring, creating this steep increase at the beginning. Then the helices are plastically deformed due to the breakage of the intermolecular disulfide bonds (from cysteines), causing a plateau. At the end, the covalent bonds of the helix backbones are pulled on, which causes again a steep increase in the stress strain diagram.

4. Wood

Name the three building blocks of wood.

- Cellulose
- Hemicellulose
- Lignin

What is the microfibril angle?



The microfibril angle μ is the angle of the microfibrils in the wood's cell walls relative to the axis of symmetry. It is larger in softwood and smaller in hardwood.

5. Nacre

Why is nacre made of aragonite and not calcite?

Calcite is a stable form of calcium carbonate; aragonite is a metastable form. During the crystal growth of aragonite on an organic layer, it is after some time inhibited by another organic layer. This creates a sheeted platelet structure. Due to the structure of the organic layer between the platelets, the spacing in aragonite a-b-planes is a better match, which is why this is stabilized and does not turn into calcite.

Why is nacre so hard?

Due to the special structuring of aragonite platelets and organic material in between, several effects increase the toughness of nacre:

- **Crack path deviation** greatly increases the crack path length.

- **Organic phase deformation** is taking up a lot of deformation energy to pull apart the proteins.
- **Platelet pullout**
- **Platelet interlocking** leads to spreading of the gliding process throughout the material.
- **Microbuckling** deflects the failure and by doing so takes up energy without letting the main crack propagate further.

22.06.2017

One topic was about cartilage, constituents etc.

One topic was about collagen.

One topic was about wood.

One topic was about biomaterials in general e. g. synthesis, how they grow, what is storage ... something, examples.

Hmm the other two... one was a picture of collagen and keratin and one had to note down which one was which.

2016

1) Structural Levels of Proteins (4 CP)

a) What is the primary, secondary, tertiary, and quaternary structure of a protein?

The *sequence of amino acids* is called the **primary structure** of a protein.

The **secondary structure** of a protein describes certain repetitive, local conformations that are found in most peptide chains; it illustrates the structure of small regions of the peptide (e.g., α -helix, β -sheet).

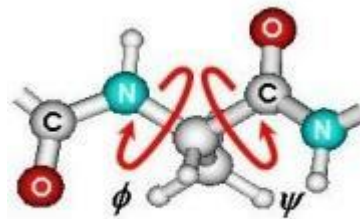
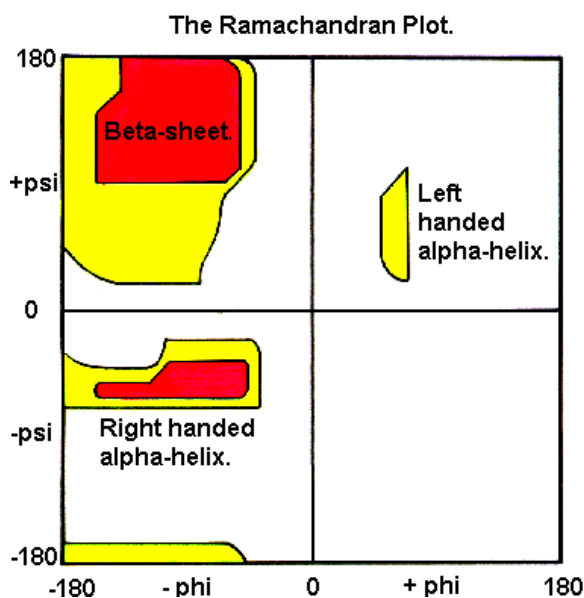
The **tertiary structure** describes the folding of the whole peptide chain due to the interactions between R-groups.

The **quaternary structure** describes the interactions between different peptide chains that make up a multimeric protein.

b) What does it depend on which secondary structure is realized? What is a Ramachandran plot?

The secondary structure is determined by the primary structure. Certain amino acids for example tend to form helices and sequences that contain a lot of those amino acids will most likely form such helices.

The formation of α -helix or β -sheet due to a certain primary structure ultimately depends on the possible rotation angles ϕ and ψ of the protein chain around the alpha carbon C^* , which is the central carbon of the amino acid. The Ramachandran plot describes possible secondary structures as a function of those two angles.



2) Keratin (4 CP):

a) Briefly describe the structure of keratin at the molecular level.

Keratin is a fibrous structural protein. Keratin monomers assemble into bundles to form intermediate filaments, which are tough and form strong unmineralized tissues.

b) How does the presence of the amino acid cysteine influence the mechanical stability of keratin?

Cysteine has a SH in its side group and can thus form strong disulfide bonds with cysteine of other protein chains. The more cysteine there is, the more disulfide bonds, the stronger the keratin.

c) What is the difference between hair keratin and feather keratin?

Hair keratin is hierarchically structured. Each hair is consisting of hair cells made of macrofibrils. Each macrofibril is made of microfibrils, each microfibril of protofibrils. The protofibrils are superhelices made of two α -helices: α -keratin rich in alanine, leucine, arginine, and cysteine. The first two are helix formers. The keratin fibers are embedded in a nonfibrous matrix. Hair keratin is highly viscoelastic, and the mechanical properties are hydration dependent.

Feather keratin has more glycine, serine, and proline than α -keratin, which are helix breakers. It is thus not an α -helix, but more like a twisted beta structure. Therefore, it behaves more linear elastic like a spring with only a small hysteresis and is twice as stiff as hair. The ends have non-crystalline sections rich in cysteine while the center has large crystalline regions with many hydrophobic residues, due to which the stability of the interactions is increased in an aqueous environment.

3) Remodeling of bone (4 CP):

a) Describe the remodeling process in bone! Which cells are involved and what are their functions?

Bone is constantly remodeled. When bone material is not needed at some place because there is no stress present, it gets removed. When more bone material is needed at some place because there is a lot of stress present, it gets added. If damages occur at some point, the bone around the damage is removed and new bone is made at its place. Three types of cells are used for bone remodeling:

- **Osteoclasts** are large cells, attached to the bone surface, which are responsible for resorbing bone. They seal off the interface and start by dissolving mineral in acid and then resorb the collagen molecules. The holes are filled again by *osteoblasts*, they add a layer of so-called cement between old and new bone.
- **Osteoblasts** make bone. They are found on the surface and produce non-mineralized collagen fibers. If they later become trapped inside the bone, they turn into *osteocytes*.
- **Osteocytes** are osteoblasts trapped in so-called lacunae inside bone. Their task is not exactly known, they maybe act as sensors for external stresses and may direct adaptive growth.

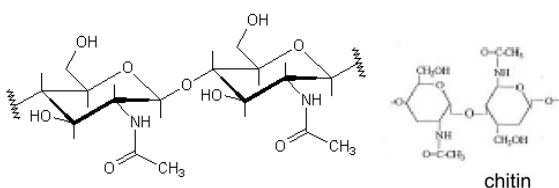
b) What is osteoporosis?

Osteoporosis describes the decrease of general bone density and trabecular thickness in spongy bone due to higher bone resorption than deposition.

4) Insect Cuticle (4 CP):

c) Chemical composition (main component) of insect cuticle and their arrangement in the composite.

Insect cuticle is mostly made of chitin and proteins.



Chitin is a polysaccharide very similar to cellulose except for a side group. The chitin molecules make a chain of N-acetylglucosamine, the chains are bound by proteins to form

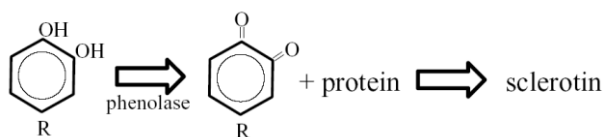
sheets or lamellae. The lamellae are laid down at different angles every half hour, strongly reducing the stretchability of insect cuticle.

d) Insect Cuticle can be soft or stiff at very similar density. Name and briefly describe at least 2 strategies in insect cuticle to tune the mechanical properties! What is "tanning"?

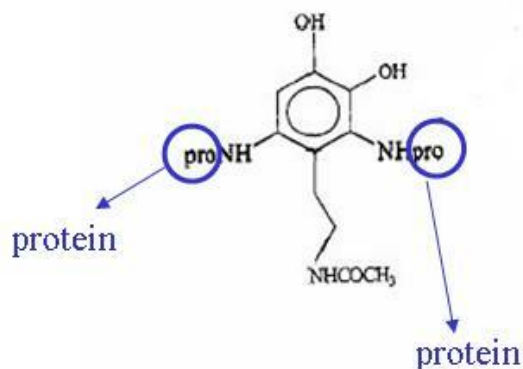
The mechanical properties vary with:

- Type of protein
- Chitin/protein ratio
- Orientation of chitin
- Amount of water / degree of tanning
- Presence of lipids, salts, ...
- Added metals
- Added CaCO_3

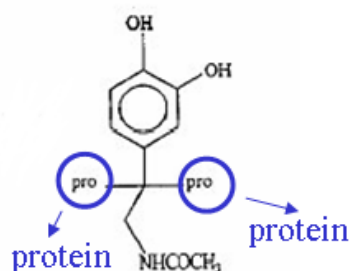
Tanning is the slow process of chemically hardening the exocuticle through cross-linking of cuticular matrix proteins with oxidized phenols (sclerotization). An only hardly cross-linked matrix protein is the hydrophilic, highly elastic resilin. After cross-linking it becomes hydrophobic, stiff sclerotin. The cuticle is stiffened with two strategies:



1. Quinone tanning (results in darker color)



2. β -sclerotization (results in lighter color)

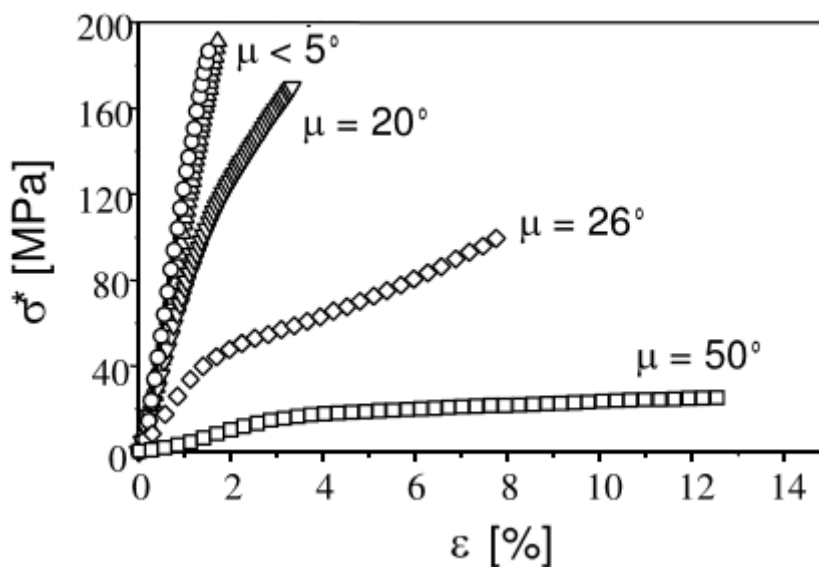


The same effect can be obtained by **drying** untanned or less heavily tanned insect cuticle. The effect of tanning is therefore mainly dehydration by controlling the degree of hydrophobicity via degree of cross-linking.

- Soft, compliant cuticle: more hydrophilic. It has a water content of 40-75%, with a dry weight of 50% chitin, 50% protein.
- Hard, stiff cuticle: more hydrophobic. It has a water content of ~12%, with a dry weight of 15-30% chitin and the rest protein.

5) Reaction Wood / diagram reading exercise (4 CP)

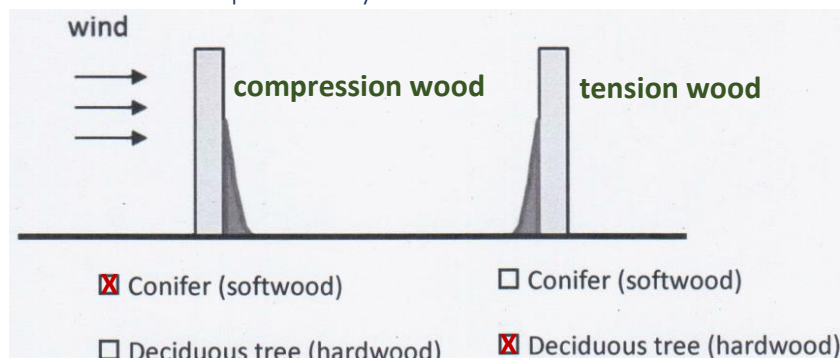
a) The mechanical properties of wood strongly depend on the orientation of cellulose fibrils in the wood cell wall (microfibril angle; MFA). Below you find stress-strain curves of wood with different MFA (20° and 50°). Mark the correct ones!



b) Wood adapts to repeated, excessive loading by forming reaction wood. The below stems of trees are subject to constant wind forces (direction of wind marked by arrows) and contain tension and compression wood respectively (thickening of stem).

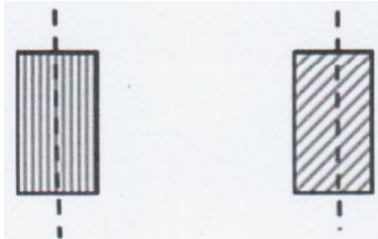
-> Which one is tension and compression wood? Mark them correctly in the diagram.

-> In which tree species do you find one or the other? Mark the check box.



c) Below the cellulose microfibril arrangement in tension and compression wood is shown (longitudinal cell axis denoted by dashed line)

-> Which one is tension and which one is compression wood? Mark them correctly in the diagram.



tension wood compression wood

-> Why is the arrangement different? Describe the functionality of tension wood and compression wood.

In **softwood**, the MFA in the nanostructure is larger, which cause wood to be more flexible. After the deposition of cellulose, the wood is lignified. Compression wood contains more lignin, which spatially separates cellulose fibers and by doing so elongates the wood, creating a push-up effect.

In **hardwood**, the opposite is true. The nanostructure of hardwood has small cellulose MFA, which cause wood to be more rigid. The cellulose fibrils are embedded in a gelatinous layer that can swell upon hydration. The swelling separates the cellulose fibers laterally and, in the process, contract them in the longitudinal direction, creating a pull-up effect.

6) Self-assembly (4 CP)

Self-assembly is driven by physical forces, typically weak ones.

a) Name at least two relevant forces!

- Attractive:
 - **Covalent bonds**
 - **Van der Waals forces**
 - **Attractive electrostatic forces in solution**
 - Hydrophobic interaction
 - **Hydrogen bonds**
- Repulsive:
 - Steric repulsion
 - **Repulsive electrostatic forces in solution**
 - Hydration forces in water

b) The thermal energy at room temperature is about 25 meV (milli electron Volt). Which is the (approximate) binding energy of the above weak forces?

Bond	Binding energy [meV/bond]	Boltzmann factor at 20°C
Covalent	approx. 4000	10^{-69}
Electrostatic, in vacuum	approx. 5000	10^{-87}
Hydrogen bond	100-500	$0,01 - 10^{-9}$
Electrostatic, in solution	100-300	$0,01 - 10^{-6}$
Van der Waals	5-50	$0,8 - 0,14$
Thermal energy at RT	25	

c) Describe an example of self-assembly in a biological tissue involving one of the above forces (2-3 sentences)

Soap molecules have a hydrophilic and a hydrophobic end. When in water, the hydrophilic ends and water attract each other, forcing the hydrophobic ends to cluster up, and forming micelles, cylindrical micelles or bilayers.

16.05.2015

1) Structural Levels of Proteins (4 Credit Points, CP):

a) Where (in which part of the cell) does protein synthesis take place?

Transcription takes place in the nucleus, translation takes place outside the nucleus, at ribosomes in the cytoplasm.

b) What does the code for different amino acids consist of?

Each amino acid is coded by a codon, which is a sequence of three nucleotides on an mRNA.

c) How does (bio)synthesis (of proteins) work?

The synthesis takes two steps. The first step is the transcription in the nucleus and the second is the translation outside the nucleus.

First, a section of DNA unwinds, and complementary bases attach to one DNA strand to form the mRNA. This transcribed mRNA then leaves the nucleus through nuclear pores.

The mRNA is then docked between the small and large compartment of the ribosome. tRNA with an anticodon attaches to the codon (base triplet) of the mRNA inside the ribosome. On the other end of the tRNA is an amino acid coded by the codon. The next tRNA attaches to the next codon and the amino acid of the previous tRNA links to the one of the new tRNA. The ribosome moves along the mRNA and this process continues until the mRNA ends and the whole polypeptide chain is complete. This chain then detaches and folds to a specific, complex shape to form the protein.

2) Silk (4 CP):

a) What kind of material is silk? (organic/inorganic; polysaccharide/Protein)

Silk is an organic, fibrous structural protein based on beta sheets.

b) By which organism is it produced?

Silk is produced by silkworms and spiders.

c) What is special about its mechanical properties? (2-3 sentences)

Silkworm silk is very pliable and soft, spider silk is stiff and tough. Spider silk is even 5 times as strong as steel relative to its density and has a very high toughness. Its absolute tensile strength is not as good as high-strength steel or Kevlar, but it is much more extensible and has a way higher fracture energy.

3) Mechanical Properties of bone (4 CP):

a) Bone is a mechanically anisotropic material. Its stiffness and strength depend on the direction of loading and deformation mode, respectively. Complete the following sentences:

i) Bone is stiffer in ... direction (transverse, longitudinal)

Bone is stiffer in **longitudinal** direction.

ii) Bone is stronger in ... than in ... than in ... (modes of deformation: compression, tension, shear)

Bone is stronger in **compression** than in **tension** than in **shear**.

b) How do the mechanical properties of bone (stiffness, hardness, maximum strain, toughness) relate to the mineral content?

Stiffness and hardness *increase* with increasing degree of mineralization.

Maximum strain and toughness *decrease* with increasing degree of mineralization.

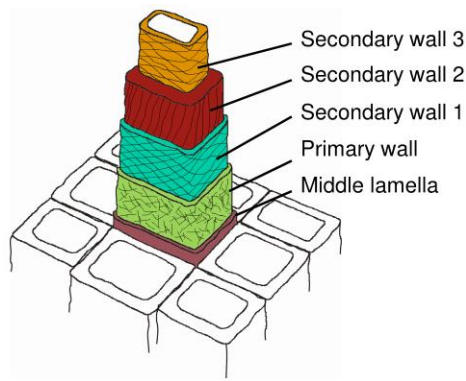
4) Wood cell wall (4 CP):

a) Which are the 3 main components of the wood cell wall? How are they arranged into a composite material?

Cellulose is a fiber consisting of cellobiose units. Adjacent chains and planes are linked by hydrogen bonds. This creates the crystalline structure of cellulose fibers. The fibers are arranged in the cell walls in layers with certain microfibril angles in each layer.

Unlike cellulose, **hemicelluloses** consist of shorter chains. In addition, hemicelluloses may be branched polymers, while cellulose is unbranched. Hemicelluloses are embedded in the cell walls, sometimes in chains that form a 'ground' – they bind with pectin to cellulose to form a network of cross-linked fibers.

Lignin is an organic polymer. It is hydrophobic and acts as an adhesive in the cell walls. It stiffens wood.

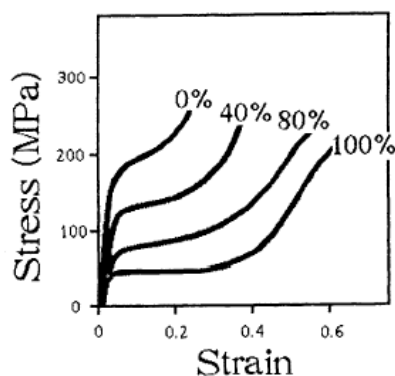


b) What is the "microfibril angle", and what is its mechanical function?

The microfibril angle μ is the angle of the microfibrils in the wood's cell walls relative to the axis of symmetry. It determines the flexibility of the wood: The tensile strength and stiffness decrease with increasing MFA while the maximum strain increases. A higher MFA thus leads to softer but more extensible wood.

5) Diagram reading exercise (4 CP):

a) The below diagram shows typical stress-strain curves of alpha-keratin (e. g. wool, hair)



-> Explain the shape of the curve qualitatively. What happens to the structure of keratin on the molecular level?

When the hair keratin is pulled, first the helices are pulled like a spring, creating this steep increase at the beginning. Then the helices are plastically deformed due to the breakage of the intermolecular disulfide bonds (from cysteines), causing a plateau. At the end, the covalent bonds of the helix backbones are pulled on, which causes again a steep increase in the stress strain diagram.

-> One curve was recorded at lower, one at higher degree of hydration. Which one is which? Mark the curves accordingly in the diagram.

(Hydration in the diagram is given in percent.)

b) Find the correct name for the amino acids below and mark the corresponding check box! In which proteins do these amino acids occur!

$\begin{array}{c} \text{H} \\ \\ \text{H}_3\text{N}^+ - \text{C} - \text{COO}^- \\ \\ \text{H} \end{array}$	$\begin{array}{c} \text{H} \\ \\ \text{H}_3\text{N}^+ - \text{C} - \text{COO}^- \\ \\ \text{CH}_2 \\ \\ \text{SH} \end{array}$
☐ Aspartate	☐ Aspartate
☐ Cysteine	☒ Cysteine
☒ Glycine	☐ Glycine

Glycine typically appears in **silk** and **collagen**

Cysteine typically appears in **α -keratin**.

6) Nacre or "Mother of Pearl" (4 CP)

Nacre (Mother of Pearl) is a biomineralized material grown by seashells.

a) Why is the mineral in nacre aragonite and not calcite (which would be the most stable crystalline polymorph of calcium carbonate)? Explain!

Calcite is a stable form of calcium carbonate; aragonite is a metastable form. During the crystal growth of aragonite on an organic layer, it is – after some time – inhibited by another organic layer. This creates a sheeted platelet structure. Due to the structure of the organic layer between the platelets, the spacing in aragonite a-b-planes is a better match, which is why this is stabilized and does not turn into calcite.

b) Nacre is harder and in particular much tougher than pure calcium carbonate (CaCO_3). Name and shortly describe 3 toughening strategies found in nacre!

Due to the special structuring of aragonite platelets and organic material in between, several effects increase the toughness of nacre:

- **Crack path deviation** greatly increases the crack path length.
- **Organic phase deformation** is taking up a lot of deformation energy to pull apart the proteins.
- **Platelet pullout**
- **Platelet interlocking** leads to spreading of the gliding process throughout the material.
- **Microbuckling** deflects the failure and by doing so takes up energy without letting the main crack propagate further.

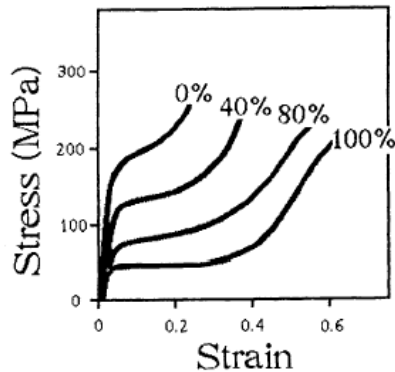
17.06.2014

Given is the structure of cysteine and glycine. Name where it occurs.

Glycine typically appears in **silk** and **collagen**

Cysteine typically appears in **α -keratin**.

Stress- strain diagram for keratin at different humidity. Tell which one is high hydration, which one is low. Also explain why it has those three significant intersections.



When the hair keratin is pulled, first the helices are pulled like a spring, creating this steep increase at the beginning. Then the helices are plastically deformed due to the breakage of the intermolecular disulfide bonds (from cysteines), causing a plateau. At the end, the covalent bonds of the helix backbones are pulled on, which causes again a steep increase in the stress strain diagram.

What is silk? Where does it occur? Does different types of spider silk?

Silk is an organic, fibrous structural protein based on beta sheets. It is produced by silkworms and spiders.

Spiders produce two different types of silk: Dragline silk and capture silk.

Dragline silk is strong and thick, and it is used for framing, supporting radii or abseiling.

Cribellate capture silk is extremely fine, more elastic and does not need glue to stick to prey.

Ecribellate capture silk is silk covered with sticky glue.

Name the four bases for DNA. What does DNA contain too? Explain the process of protein syntheses. At which organelle does it happen?

- Adenine
- Thymine
- Guanine
- Cytosine

Besides the bases, DNA also contains deoxyribose sugar and phosphate.

Explain the role of glycine in the binding of collagen.

The amino acid sequence of collagen is usually of type $(\text{Gly-X-Y})_n$. The glycine has the smallest possible side group of just a single H and is hydrophobic. From three collagen helices, the glycine attach to each other via hydrophobic interaction, creating a triple helix.

Why is aragonite stable in nacre and doesn't transform in calcite? Name at least 4 mechanisms in nacre that help to increase its toughness.

Calcite is a stable form of calcium carbonate; aragonite is a metastable form. During the crystal growth of aragonite on an organic layer, it is after some time inhibited by another organic layer. This creates a sheeted platelet structure. Due to the structure of the organic layer between the platelets, the spacing in aragonite a-b-planes is a better match, which is why this is stabilized and does not turn into calcite.

Due to the special structuring of aragonite platelets and organic material in between, several effects increase the toughness of nacre:

- **Crack path deviation**
- **Organic phase deformation**
- **Platelet pullout**
- **Platelet interlocking**
- **Microbuckling**

Bone is stronger in _____ then _____ then _____ (compression, tension, shear).

Bone is stronger in **compression** than in **tension** than in **shear**.

Effect of mineralization on the toughness, strength, and maximal strain?

The strength *increases* with increasing degree of mineralization.

Maximum strain and toughness *decrease* with increasing degree of mineralization.

Structural elements in wood? How does the MFA influence the mechanical properties of wood? What is the MFA?

Cellulose is a fiber consisting of cellobiose units. Adjacent chains and planes are linked by hydrogen bonds. This creates the crystalline structure of cellulose fibers. The fibers are arranged in the cell walls in layers with certain microfibril angles in each layer.

Unlike cellulose, **hemicelluloses** consist of shorter chains. In addition, hemicelluloses may be branched polymers, while cellulose is unbranched. Hemicelluloses are embedded in the cell walls, sometimes in chains that form a 'ground' – they bind with pectin to cellulose to form a network of cross-linked fibers.

Lignin is an organic polymer. It is hydrophobic and acts as an adhesive in the cell walls. It stiffens wood.

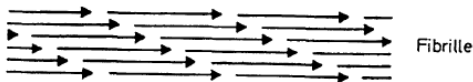
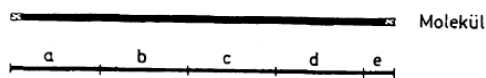
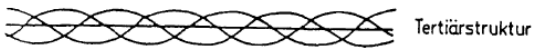
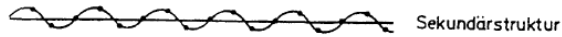
The **microfibril angle** (MFA) is the angle of the microfibrils in the wood's cell walls relative to the axis of symmetry. It determines the flexibility of the wood: The tensile strength and stiffness decrease with increasing MFA while the maximum strain increases. A higher MFA thus leads to softer but more extensible wood.

04.06.2014

Collagen

1. Primary, secondary and tertiary structure.

Gly-X-Y-Gly-X-Hyp-Gly-Pro-Y-Gly-Pro-Hyp Primärstruktur



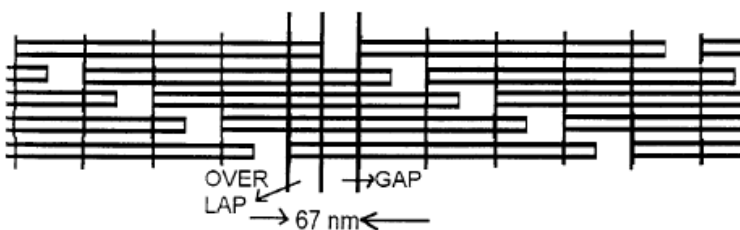
The *sequence of amino acids* is called the **primary structure** of a protein.

The **secondary structure** of a protein describes certain repetitive, local conformations that are found in most peptide chains; it illustrates the structure of small regions of the peptide (e.g., α -helix, β -sheet).

The **tertiary structure** describes the folding of the whole peptide chain due to the interactions between R-groups.

The **quaternary structure** describes the interactions between different peptide chains that make up a multimeric protein.

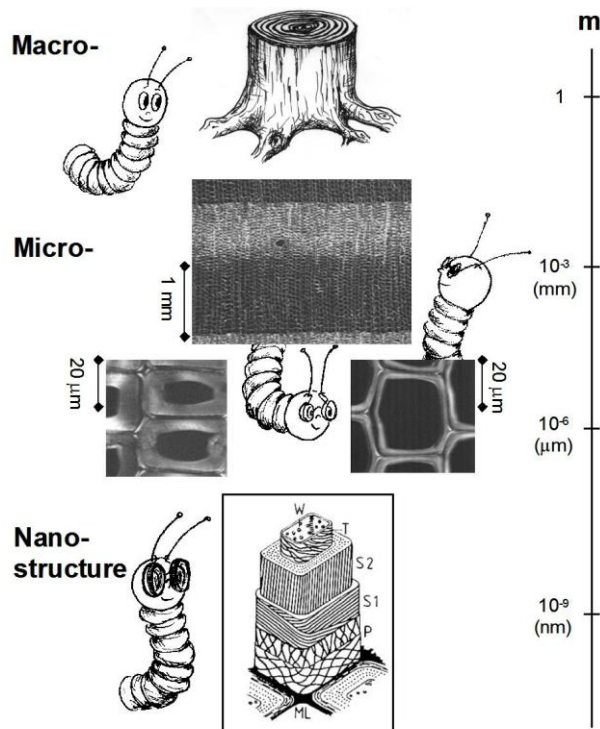
2. Sketch the staggered structure. Where does mineralization occur?



Mineralization occurs in the gaps between the collagen molecules.

Wood

1. Macro-, micro-, nanostructures



The **macrostructure** describes the overall visible structure of a tree.

The **microstructure** describes the rings and further down also the wood cells.

The **nanostructure** describes the composition and structure of each wood cell.

2. Principal components

- outdated? -

3. Is wood stiffer in compression or tension?

Wood is generally stiffer in compression than in tension.

Insect cuticle

1. Different composites and their arrangement

Chitin and proteins

Cartilage

1. What does it contain?

Cartilage contains collagen, proteoglycans, water, non-collagenous proteins and glycoproteins.

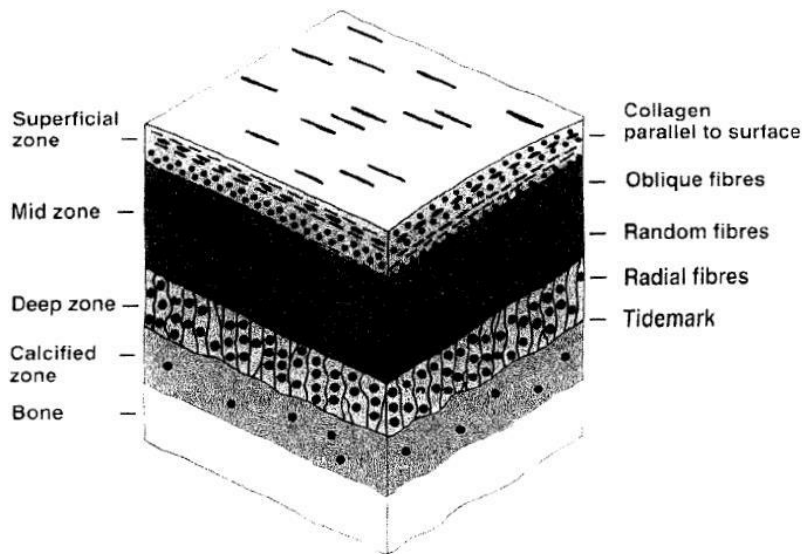
Hyaline cartilage contains small, evenly distributed collagen fibers (50-80% dry weight) and only a negligible amount of elastin.

Fibrous cartilage contains more densely packed collagen fibers (90% dry weight).

Elastic cartilage is like hyaline cartilage but with more elastin fibers.

2. Briefly describe the structure.

Natural cartilage shows complex layered structures with collagen fibers in specific orientations in each of the layers. There is a structural variation through the thickness of articular cartilage showing a zonal arrangement of chondrocytes and collagen fibers.



3. Bone/cartilage interface: strategies to prevent delamination.

- outdated? –

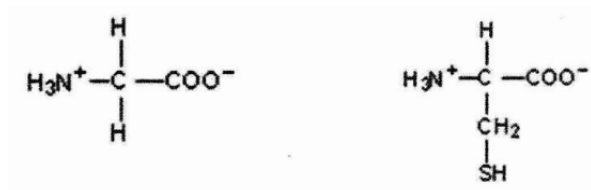
→ delamination of dentin/enamel interface

4. Damping mechanism.

The collagen fibers and proteoglycan form a network. Proteoglycans are hydrophilic, the gel imbibes a lot of water by osmosis. Cartilage swells until it is stopped by the maximal extensibility of collagen fibers. The collagen fibers are then prestressed in tension. Water flows in and out of cartilage during loading and unloading. The shock absorption and dampening therefore happens through viscous flow.

Collagen/keratin

1. Ability to recognize molecules



Glycine → Collagen

Cysteine → Keratin

2. Interaction that assemble the superhelices

The amino acid sequence leads to a hydrophobic stripe along one side of a helix. Via **hydrophobic interaction**, this leads to the assembly of two right-handed keratin helices to form a left-handed superhelix, and the assembly of three left-handed collagen helices to form one right-handed superhelix.

Resilin/hair keratin

1. Ability to recognize the stress-strain diagram

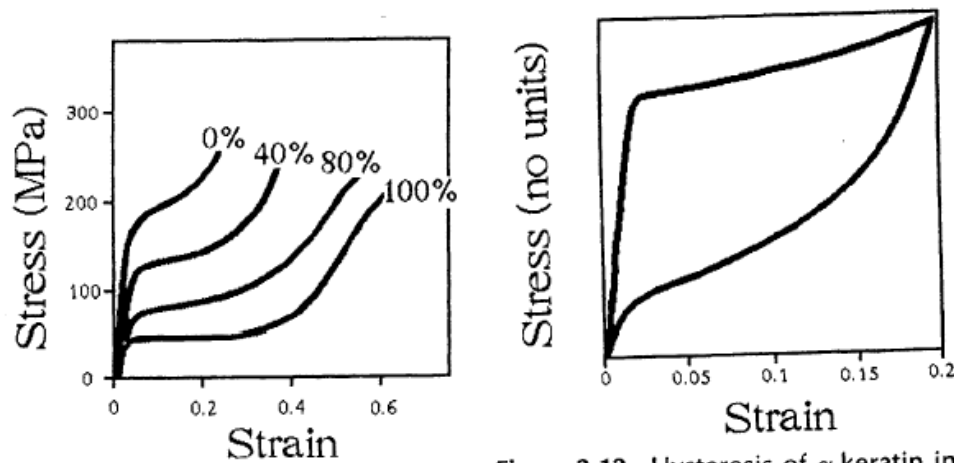


Figure 2.12 Hysteresis of α -keratin in hair.

2. Resilin: protein or polysaccharide? Where does it occur?

Resilin is a protein rubber of very high resilience occurring in insects.

Bioceramics

Control mechanisms in biomineralization

1. **Chemical:** The thermodynamic conditions for precipitation of mineral from solution is strictly controlled. Chemical conditions (e.g. pH, temperature) determine solubility and supersaturation.
2. **Structural:** The mineral structure is determined by an organic template. Interfacial molecular recognition causes selected crystallographic orientation or specific crystal structure (polymorph).
3. **Morphological:** Control of shape by controlled deposition of the mineral and selective growth inhibition.
4. **Spatial:** Mineralization is confined to vesicles or porous organic frameworks (supramolecular preorganization of organic molecules).

What is tanning? Name two types of tanning in insects.

Tanning is the slow process of chemically hardening the exocuticle through cross-linking of cuticular matrix proteins with oxidized phenols (sclerotization). An only hardly cross-linked matrix protein is the hydrophilic, highly elastic resilin. After cross-linking it becomes hydrophobic, stiff sclerotin. The cuticle is stiffened with two strategies:

1. Quinone tanning (results in darker color)

2. β -sclerotization (results in lighter color)

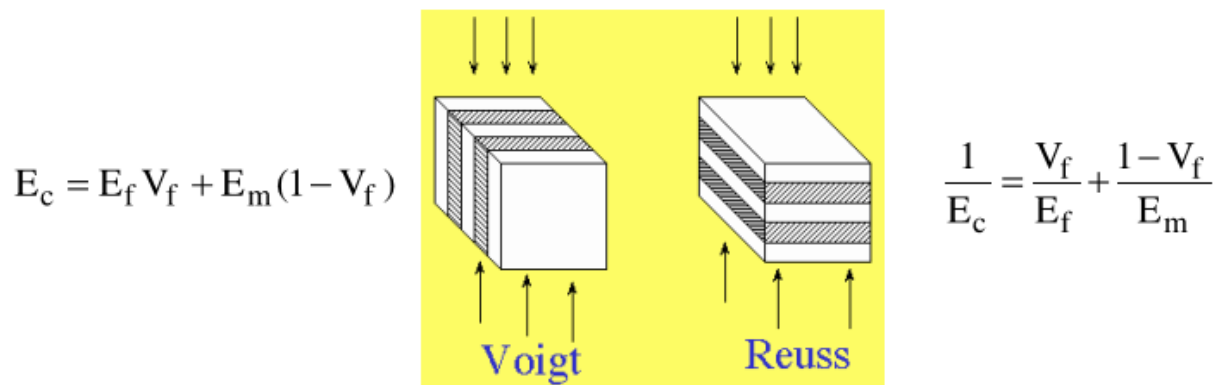
Name two examples for biomineralization.

- Controlled growth of aragonite platelets in nacre.
- Controlled growth of silica around diatoms.

Composite materials

Stiffness of a composite (*This was marked as important, but did not appear in any exams*)

The stiffness of a composite is highly dependent on orientation of the composite components with respect to the applied force.



E_c : Young's modulus (elastic modulus, stiffness) of composite

E_f , E_m : Young's moduli of stiff phase ("fiber") and soft phase ("matrix")

V_f : Volume fraction of stiff phase, $1 - V_f$: volume fraction of matrix

Summaries of the slides

1. Introduction

Biomaterials are....

- made from metabolically cheap substances
- light weight (efficient design)
- able to respond to changes of conditions by adaptive growth
- mechanically optimized to specific loading pattern
- structured on many different length scales (hierarchical architecture)
- designed to grow while keeping full functionality

2. Elements of biological materials

Primary structure: proteins consist of amino acids.

Secondary structure: proteins form helices or sheets

Tertiary structure: folding of protein

Quaternary structure: assembly of large functional units:
example: hemoglobin

Keratin:

- hair keratin: 2 alpha helices, contains cysteine (forms disulphide bonds -> hairstyling)
- feather keratin: made from beta-sheets

Silk:

- silkworm silk: mostly Ala and Gly (regular sequence); sheet-like arrangement
- spider silk: high strength and toughness, partly crystalline; spinning and drawing process at the same time -> water soluble precursor, water-insoluble final product

Collagen:

typical sequence: (Gly-X-Y)_n

triple helix

regular stacking of collagen molecules -> gap-overlap zones

associates to collagen fibrils

Polysaccharides are chains of sugars

Cellulose:

found in plant cell walls;

consists of cellobiose units (disaccharide from 2 glucose units);

cellulose molecules associate to build crystalline cellulose fibrils;

Chitin:

found in insect cuticle;

consists of acetylglucosamine units (otherwise similar to cellulose);

molecules associate to build stiff fibrils

Polysaccharide gels: pectin, carrageenan, alginates, hyaluronic acid, etc.

3. Self-assembly and growth

Self assembly of identical parts reduces info needed for construction plan

Self assembly is governed by 'weak' interactions:
van der Waals, electrostatic, hydrophilic-hydrophobic

LCs (liquid crystals) are an extremely common motif in self-assembled materials (not only biological ones). They consist of elongated units that assemble into (quasi)ordered structures.

Examples: liquid crystalline display (LCD), spider silk

Proteins:

primary structure is coded for (AA sequence), secondary+tertiary structure by self-assembly:

- keratin: double helix
- collagen triple helix
(stabilized by hydrophilic-hydrophobic interactions)

Special examples of self assembly of larger structures:
viral capsids (icosahedral virus, tobacco mosaic virus)

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4. Mechanical concepts in biomaterials

Rubber elasticity in biology: elastin, resilin, abductin are exceptions!!
most biomaterials are highly viscoelastic (e.g. hair keratin)

Mechanical properties are *not constant*: change with hydration
(material may become weaker *or* stronger upon addition of water);

Main issues:



fracture toughness

- composite materials
- fiber pull-out
- crack deviation
- etc. etc.

efficiency

- light weight structures (economic use of material, cellular materials, optimized shapes)
- optimization through microstructure

5. Soft tissues: skin, cartilage, glue

Skin: extensibility due to network-like arrangement of collagen fibers

Cartilage:

layered structure of collagen fibers

proteoglycan (macromolecules of protein + sugar) network:
holds huge amounts of water (gel)-> shock absorber

Pedal mucus: highly strain sensitive material (non fibrous protein + sugar)

Mussel glue:

cross-linking through oxidization and metal binding of Dopa

6. Engineering with fibers

Tendons: collagen fiber composite of hierarchical structure. Shows typical toe-heel curve upon deformation.

Artery walls: collagen fibers wound concentrically around blood vessel, layers with different orientation, high toughness and crack tolerance.

Muscle: skeletal muscle is a protein fiber composite from mainly myosin and actin. Muscle contraction: relative movement of thick filament (myosin) and thin filament (actin) through movement of myosin head ("myosin motor").

Insect cuticle: chitin fibers in protein matrix. Huge variation in stiffness at very similar composition. Mechanical tuning by fiber orientation, water content and tanning.

7. Bioceramics

Controlled deposition:

1. **chemical:** amorphous/crystalline/crystalline polymorph: e.g. rust to magnetite in magnetic bacteria
2. **structural:** control of crystal polymorph in nacre (aragonite instead of calcite), strict orientation of CaCO_3 in sea urchin spine
3. **morphological:** e.g. sea urchin larval spicules, coccoliths
4. **spatial control:** bone formation in osteocyte vesicle

Matrix mediated biomineralization:

biomineral deposition on structural framework, e.g. tooth enamel

- **Nacre** (mother of pearl): consists of CaCO_3 tablets, stacked like coins, with thin sheath of organic glue in between -> 3000 fold increase of toughness as compared to pure calcium carbonate mineral

- **Calcitic lenses in brittlestar:** oriented with main axis in direction of entering light (avoid birefringence); shape optimized to avoid aberration in thick lens

- **Human (and vertebrate) teeth:**

dentin (inner part): similar to bone in composition (about 65% mineral)

enamel (hard coating of teeth): cross running mineral rods, heavily mineralized tissue (about 95% mineral)

- **Transition metal-based teeth:**

Fe-based teeth of chitons and limpets: crystallites arranged such that a continuously sharp cutting edge is ensured.

The poisonous marine worm *Glycera* contains copper-mineralized teeth: copper mineral atacamite embedded in dark protein matrix in form of fibers reinforcing the jaw tip

8. Bone

Bone is a **composite material** of collagen and hydroxyapatite mineral; efficient combination of organic and inorganic: strength of bone (130 MPa) higher than strength of both components (collagen 50 MPa, HAP 100 MPa)

The **structure** of bone is **strictly hierarchical**: nanocomposite, lamellar structure, osteons, trabecular structure

Mechanical properties are highly **dependent on strain rate** (viscoelastic material, on **hydration** (normal working conditions of bone in moist environment), on **direction of loading** (anisotropic material).

Material properties (hardness, stiffness, toughness) depend on **degree of mineralization** (very high in whale bulla, enamel; low in antler).

Adaptive growth of bone: material laid down where needed, removed where not needed (balance of bone deposition by osteoblasts and bone resorption by osteoclasts)

Examples of diseased bone: osteoporosis, osteogenesis imperfecta

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9. Wood

Wood is **light weight material** optimized to support its own weight without buckling.

Hierarchical architecture: tree rings, cellular structure, nanocomposite of cellulose fibers (stiff, partially crystalline) and matrix (amorphous, hemicellulose/lignin).

Growth of tree: by adding material only! (no change of existing material).
Growth zone: cambium (between wood and bark)

Wood cells arrange to build up complex vessel system: bordered pits act as valves between cells.

Ultrastructure and mechanical properties:

Microfibril angle (MFA) influences stiffness, extensibility and toughness of wood.

Optimization of different parts of tree:

branches, wood near pith: large MFA (toughness, flexibility)

large stems: small MFA (stiffness)

10. Smart materials – adaptive growth

Start design: safety factor depends on expected load conditions.

Adaptation of bone:

- Wound healing: spongy bone formed first, turns into cortical bone later, bone callus: over-reaction: more bone is formed than before to avoid another breakage;
- Bone responds to increased/decreased strain by adding/reducing bone mass
- Design adapted to load: trabeculae follow principal load directions (Wolff);
- Hip implants: exact fit is essential, problem of decreased load in upper part of femur;
- Osteoporosis: can occur in old age or due to missing strain (astronauts)

Adaptation of wood:

- Adaptive growth only through selective addition of material (no remodeling);
- Goal: evenly distribute stress (avoid stress concentrations);
- Reaction to bending stresses (wind or gravity in leaning stems): growth of reaction wood (tension wood in deciduous trees, compression wood in conifers);
- Optimization to stiffness or flexibility through variations in ultrastructure

11. Biomimetic and bio-inspired materials

Imitating biological *materials*:

- Bioduplication: artificial spider silk and resilin
- Bio-inspired: Velcro, lotus effect, moth eye

Imitating biological *processes*:

- synthesis of nanoparticles
- bio-inspired mineralization
- motion: smart polymers