

Biomaterials



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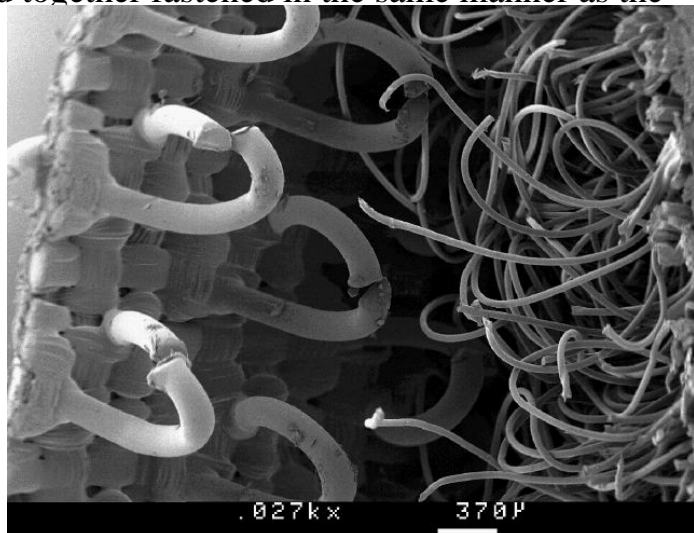


Velcro Biomimetic Principle

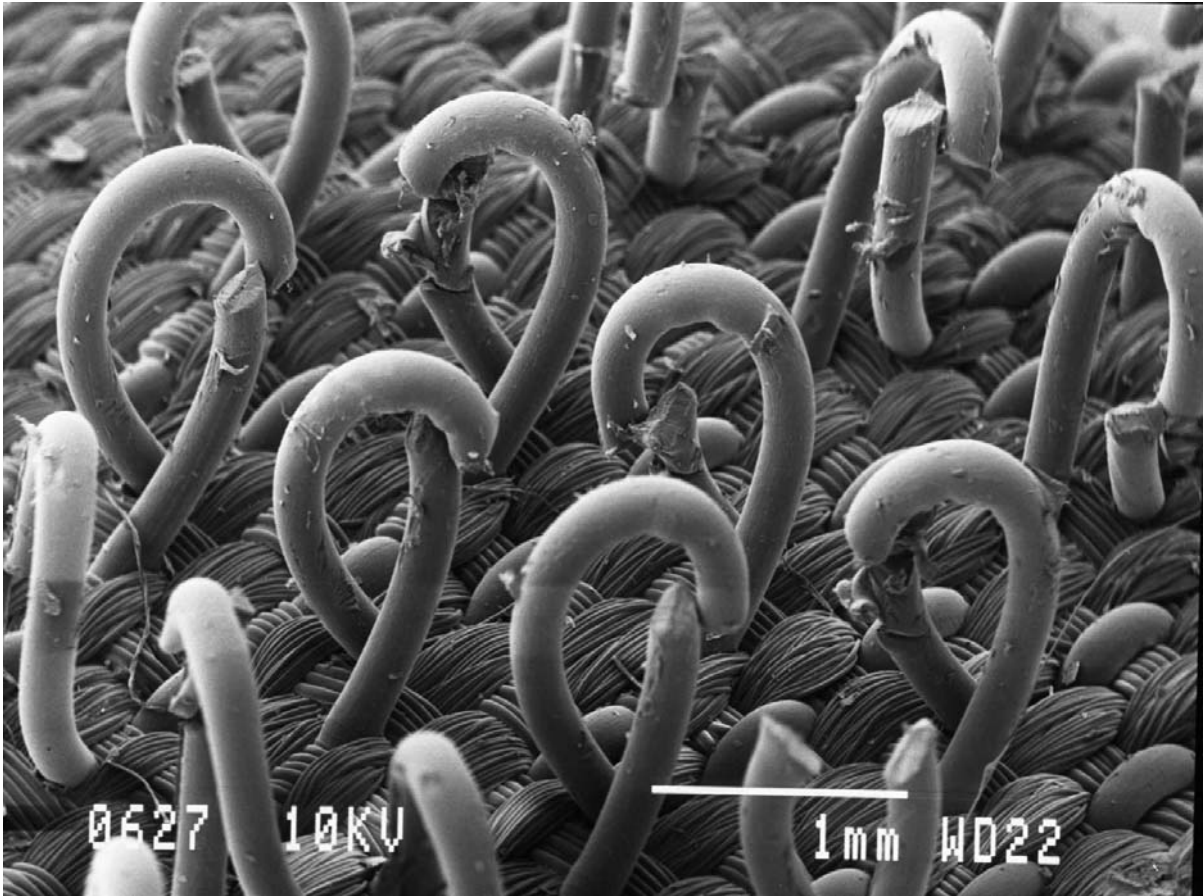
The inventor of Velcro, George Mestral, was working in the machine shop of a Swiss engineering company more than 60 years ago. He examined the burrs that stuck to his dog's fur under a microscope, and saw that they consisted of hundreds of tiny hooks that latched into the soft dog's fur.

He discussed the principle with weaving experts in the French cloth industry, and eventually a weaver produced cotton tapes that when pressed together fastened in the same manner as the teasel and fur.

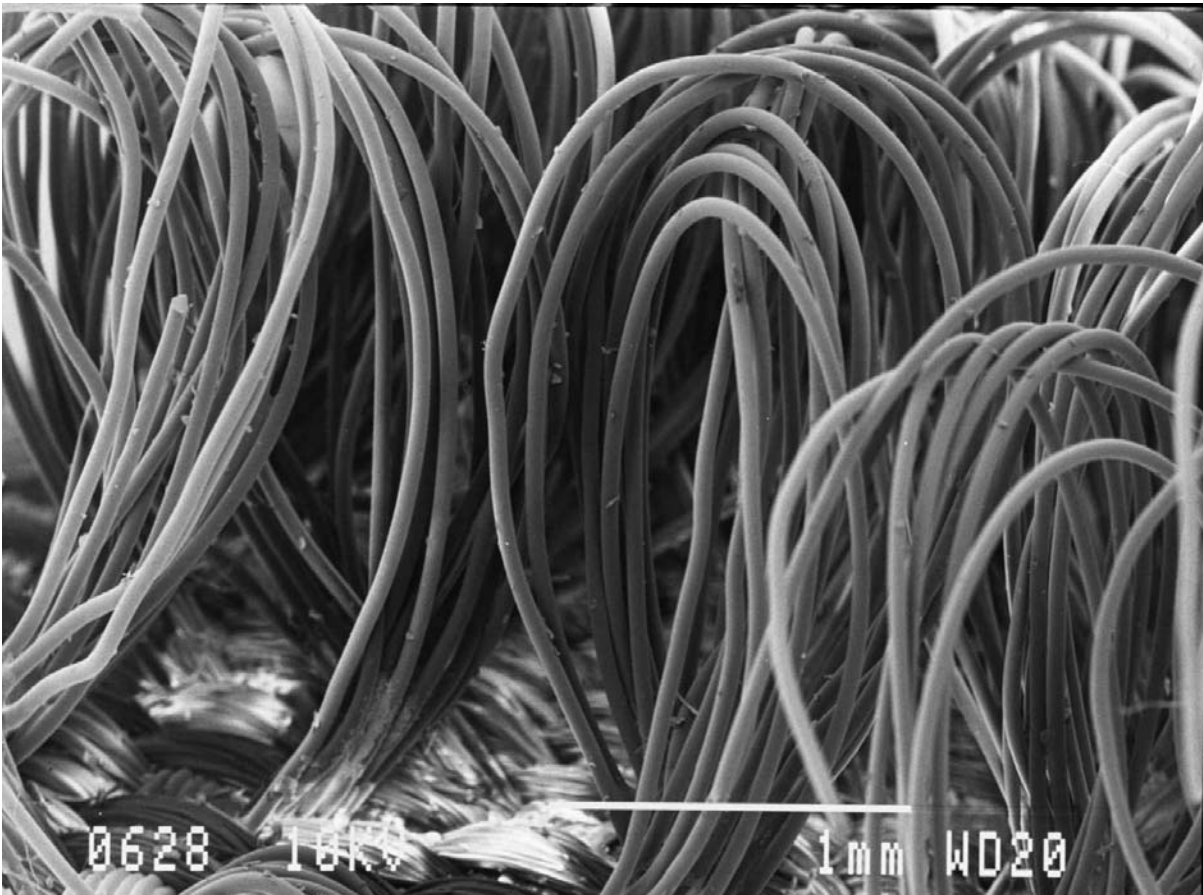
This idea was patented by a Swiss company, Velcro S.A in 1952. These patents covered "the invention and fabrication of special napped piles of man-made material, at least some of these loops having the means of hooking near their ends".



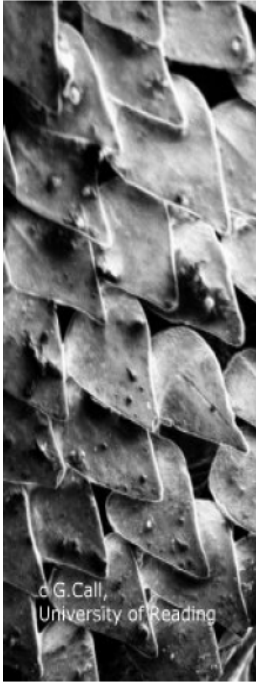
Velcro, SEM



Velcro, SEM



Shark Skin



Shark skin is very rough, in fact so rough that dried shark skin can be used as sanding paper.

- The skin is covered by little V-shaped bumps, made from the same material as sharks' teeth.
- The rough surface has been shown to reduce friction when the shark glides through water, which is why sharks are surprisingly quick and efficient swimmers.



Fabrics modelled on sharkskin designed to reduce drag by channeling the water along grooves in the fabric.

These grooves allow the water to spiral in microscopic vortices, a hydrodynamic advantage.

After looking at shark skin, NASA pioneered the use of longitudinal riblets, ridges perpendicular to surface, to reduce drag on flat surfaces of ships and aircraft. Riblets were used successfully to reduce drag on the 'Stars and Stripes' America's Cup yacht and were thought to offer such an advantage that riblets were banned from competition for subsequent events. Shark skin itself is far more complex than simple longitudinal riblets

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Biomaterials

Solid biomaterials produced by living organisms:

Bones, teeth, spines, shells...

Substances prepared by biomimetic approaches or materials prepared for living/tissue interaction

Biomaterialization:

The mechanism by which living organisms form inorganic solids.

Differences between man-made analogues and "natural" synthesis:

Exceptional control over shape, size and orientation.

Not formed corresponding to thermodynamic/kinetic control as abiogenic materials.

Extreme control over local environments (e.g. chemical composition)

- Mechanical properties
- Chemical storage
- Navigation

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Table 4-2. Important biominerals, their chemical composition, and their function.

Chemical composition	Mineral	Function and examples
<p>Calcium carbonate</p> CaCO_3	<p>calcite</p> <p>aragonite</p> <p>vaterite</p> <p>amorphous</p>	<p>exoskeletons (e.g., egg shells, corals, mollusks, sponge spicules)</p>
<p>Calcium phosphates</p> $\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$ $\text{Ca}_{10-x}(\text{HPO}_4)_x(\text{PO}_4)_{6-x}(\text{OH})_{2-x}$ $\text{Ca}_{10}\text{F}_2(\text{PO}_4)_6$ $\text{Ca}_2(\text{HPO}_4)_2 \cdot 2 \text{H}_2\text{O}$ $\text{Ca}_2(\text{HPO}_4)_2$ $\text{Ca}_8(\text{HPO}_4)_2(\text{PO}_4)_4 \cdot \text{H}_2\text{O}$ $\text{Ca}_3(\text{PO}_4)_2$	<p>hydroxylapatite</p> <p>defect apatites</p> <p>fluoroapatite</p>	<p>endoskeletons (bones and teeth)</p> <p>calcium storage</p>
<p>Calcium oxalate</p> $\text{Ca}_2\text{C}_2\text{O}_4 \cdot (1 \text{ or } 2) \text{H}_2\text{O}$	<p>whewellite</p> <p>wheddellite</p>	<p>calcium storage and passive deposits in plants, calculi of excretory tracts</p>

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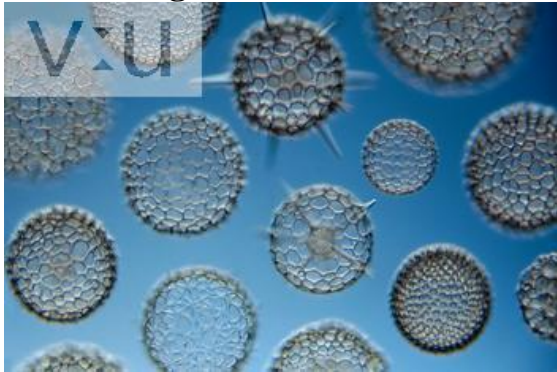
<p>Metal sulfates</p> $\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$ SrSO_4 BaSO_4	<p>gypsum</p> <p>celestite</p> <p>baryte</p>	<p>gravity sensors</p> <p>exoskeletons</p> <p>gravity sensors</p>
<p>Amorphous silica</p> $\text{SiO}_n(\text{OH})_{4-2n}$	<p>amorphous (opal)</p>	<p>defense in plants, diatom valves, sponge spicules, and radiolarian tests</p>
<p>Iron oxides</p> Fe_3O_4 $\alpha, \gamma \text{-FeOOH}$ $5 \text{Fe}_2\text{O}_3 \cdot 9 \text{H}_2\text{O}$	<p>magnetite</p>	<p>chiton teeth, magnetic sensors</p>

Dominant:

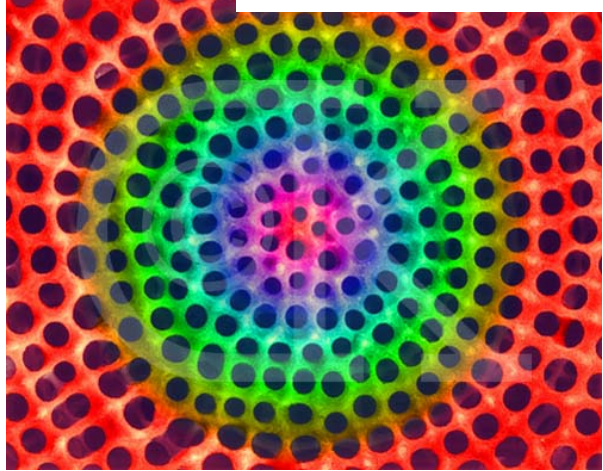
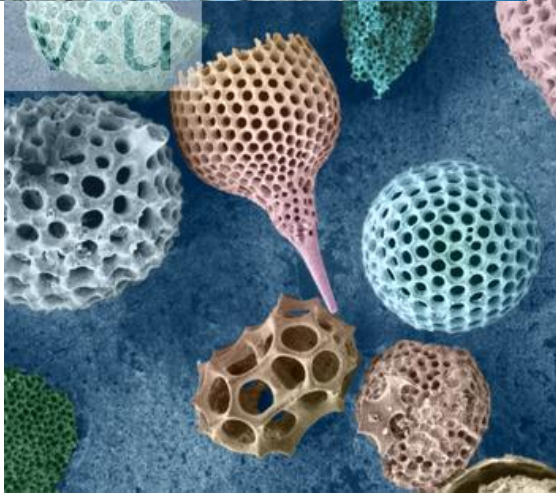
Calcium (due to low solubility)

Silica: stability toward water.

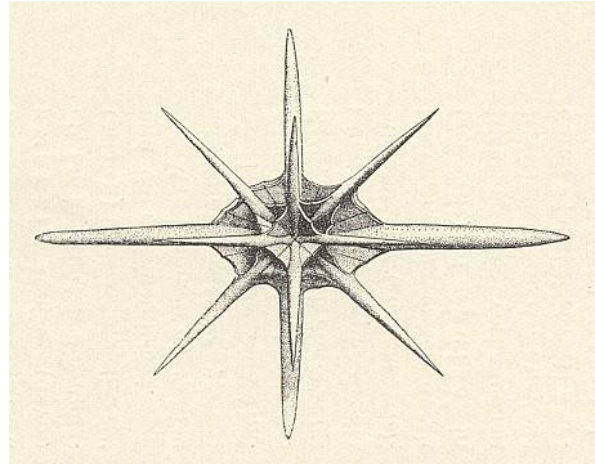
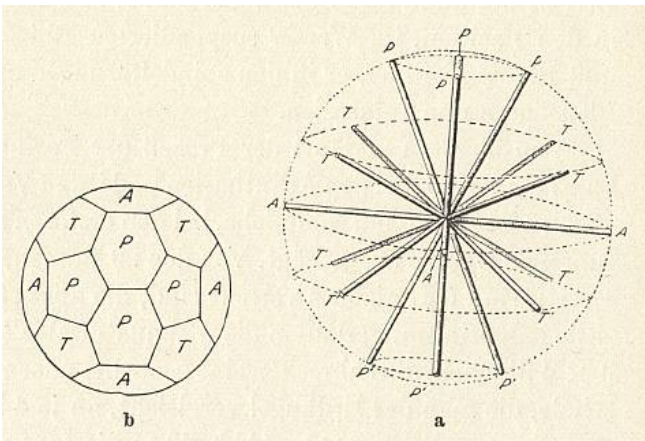
Radiolarians are mostly marine and have glass shells.



Tests (glass shells) of four radiolaria

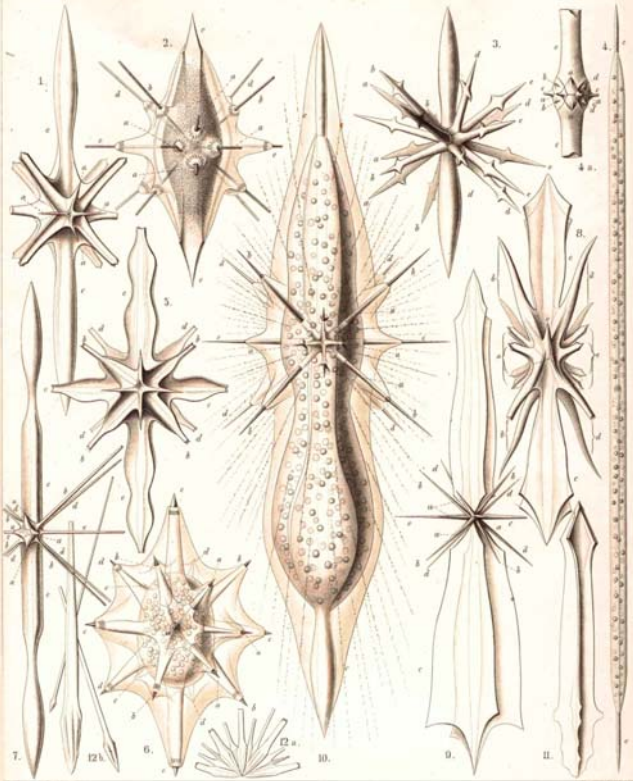


Vectorial (directional) and scalar (numerical) regularity in unicellular organisms : Acantharia (Radiolaria).
 In the above we discussed pattern formation by cell division (and in many cases followed by cell differentiation), and cell migration, and we saw that still some sort of pre-generated vectoriality must be assumed. And this is even more so when we consider *unicellular organisms*, especially those that are not simply drop-like (whose form can possibly be explained by surface tension phenomena), but have a regular form of anisotropy, resulting in certain constant directions being pronounced with respect to other directions. This we see very clearly in the case of the Acantharia which is a group of Radiolarians (The latter are unicellular but complex planktonic marine organisms (smaller than 1mm), in most cases possessing a skeleton (mineral or otherwise), which often is very regular and consists of perforated concentric spheres and/or radially placed needles).
 The skeleton of the Acantharia is made from strontium sulfate (SrSO_4) and consists of 20 needles (often provided with outgrowths) that are arranged according to 'Müller's Law': If we imagine these needles as originating from the center of a sphere (such as the earth), then there are four arctic polar needles (going through the arctic circle), four northern tropic needles (going through the northern tropic), four equatorial needles (going through the equator), four southern tropic needles (going through the southern tropic) and, finally, four antarctic polar needles (going through the antarctic circle).



The Voyage of H.M.S. 'Challenger'

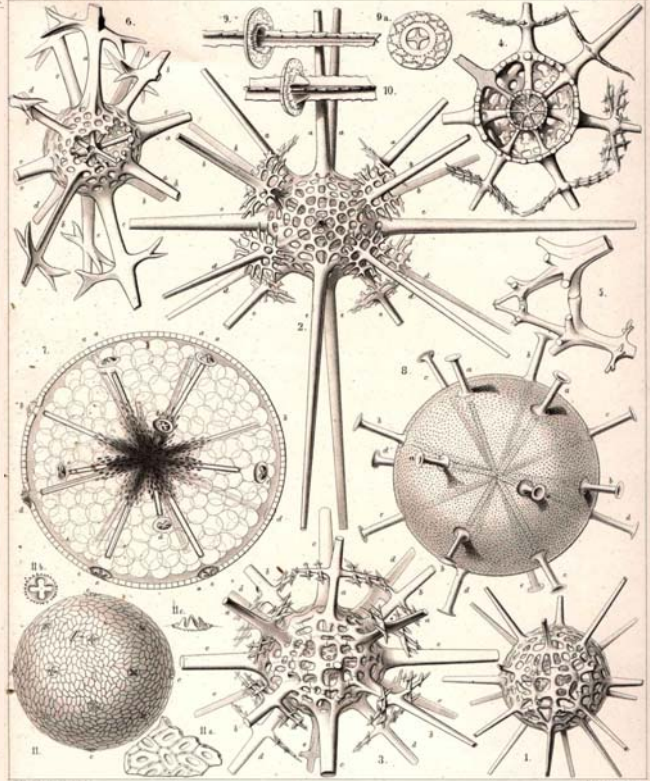
Radiolaria Pl. 132.



1-6. AMPHILONCHE, 7. 8. ACANTHOLONCHE, 9-12. AMPHIBELONE.

The Voyage of H.M.S. 'Challenger'

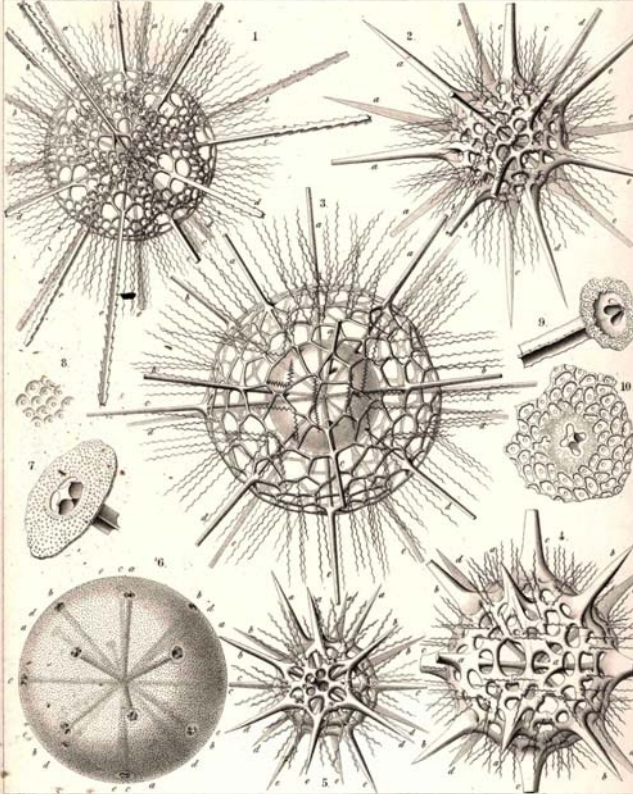
Radiolaria Pl. 133.



1-5. PHRACTOPELTA, 6. QROPHASPIS, 7. POROCAPSA, 8. CANNOCAPSA,
9. 10. ASTROCAPSA, 11. CENOCAPSA.

The Voyage of H.M.S. 'Challenger'

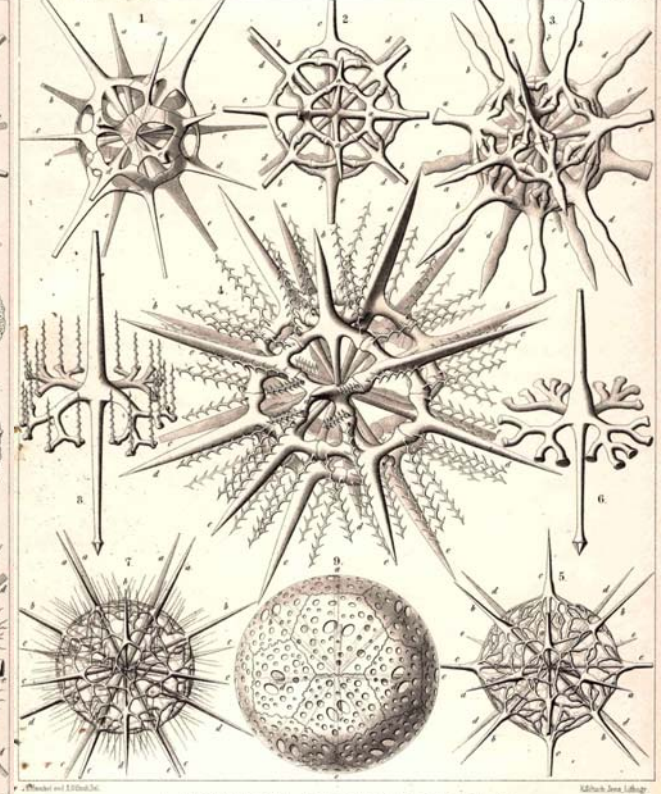
Radiolaria Pl. 135



1-5 LYCHNASPIS, 6-10 SPHAEROCAPSA.

The Voyage of H.M.S. 'Challenger'

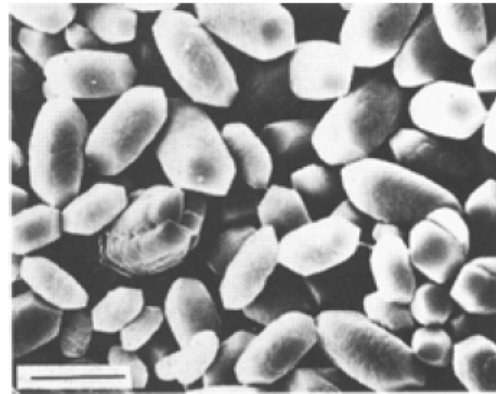
Radiolaria Pl. 137.



1-3 PHRACTASPIS, 4. PLEURASPIS, 5. 6. STAURASPIS,
7. 8. ECHINASPIS, 9. DORATASPIS.

Gravity sensors

- Aragonite & calcite used as gravity sensors in both land and marine animals
 - Statoliths, statoconia, otoliths or otoconia
- Function by transferring linear acceleration to hair-like extensions on sensory cells → electrical signal
- Akin to fluid in the semicircular canals which are for angular momentum

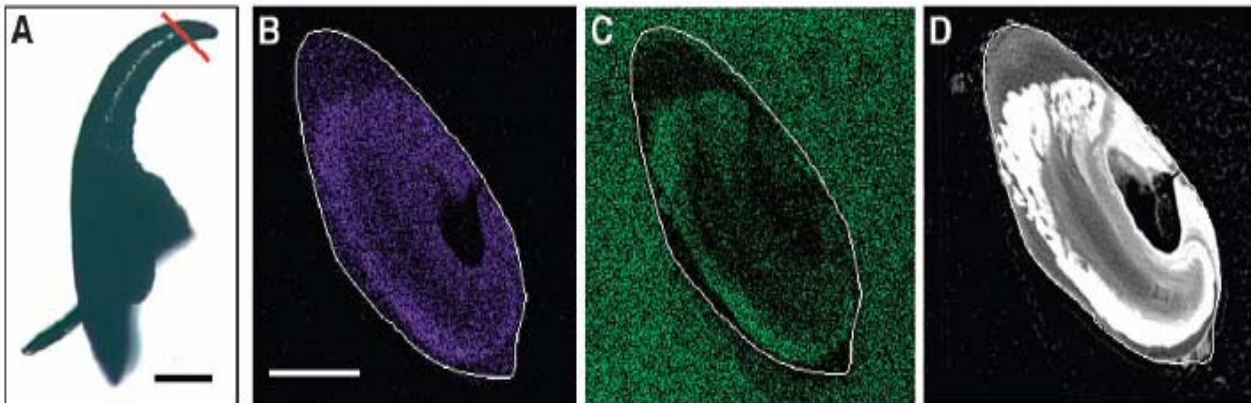
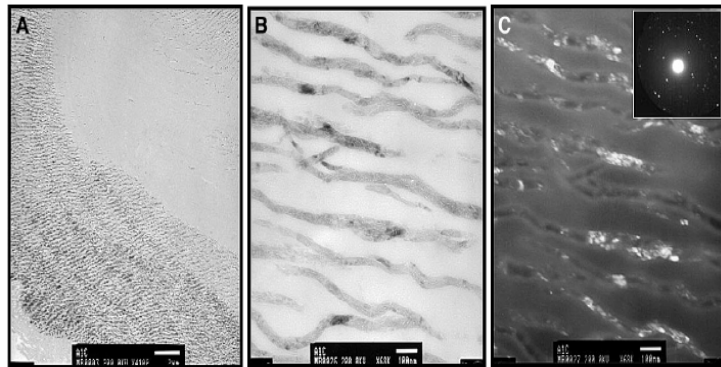


8 μ m

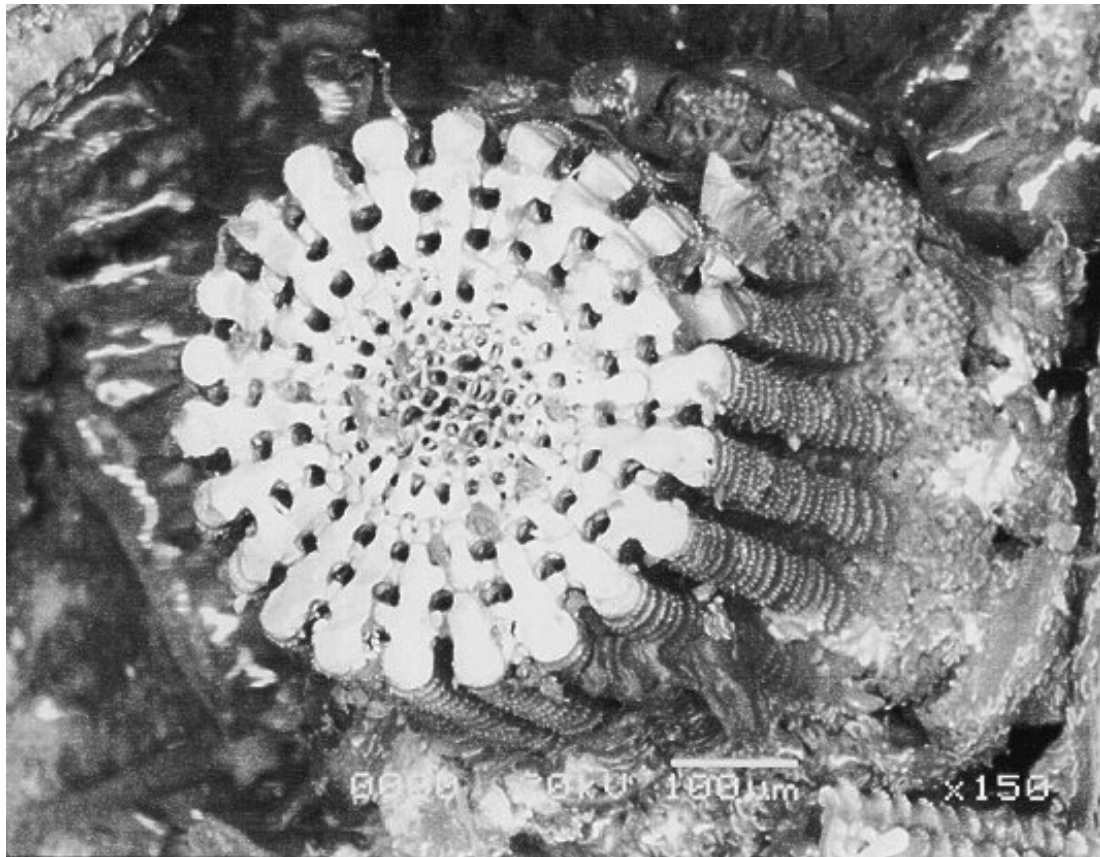
In humans (above) calcite is used in form of spindle shaped crystals

Kemi 27 lecture 2

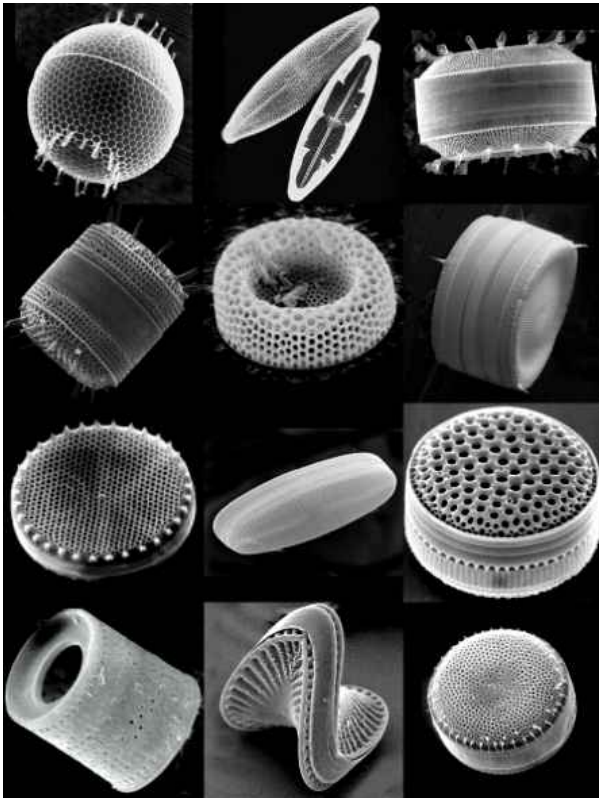
Bloodworm teeth: $\text{Cu}_2(\text{OH})_3\text{Cl}$, atacamite



Sea Urchin spine



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Diatoms

Microscopic unicellular algae.
Exoskeleton of amorphous SiO_2
Deposits on ocean floor: used
commercially (shoe polish, cosmetics...)

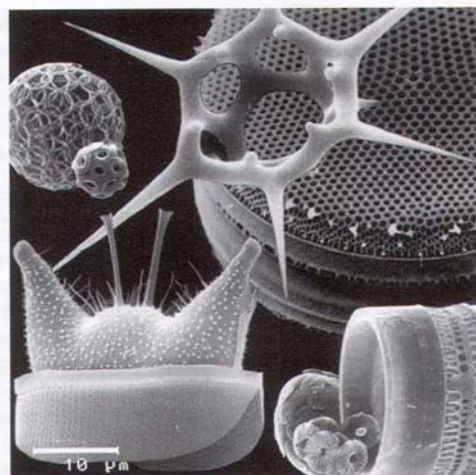
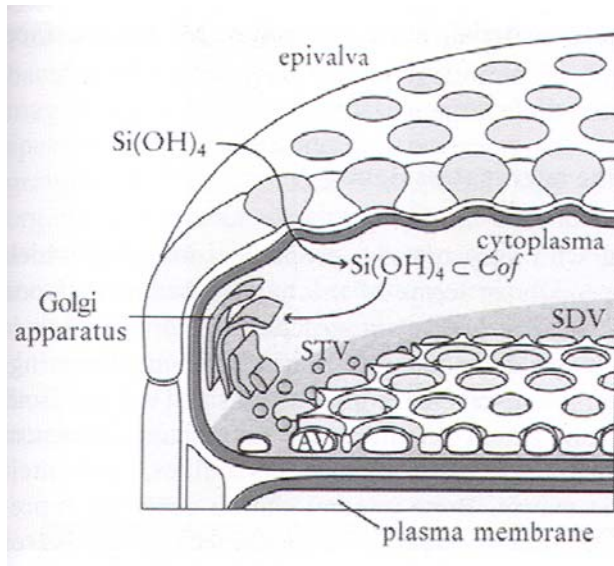
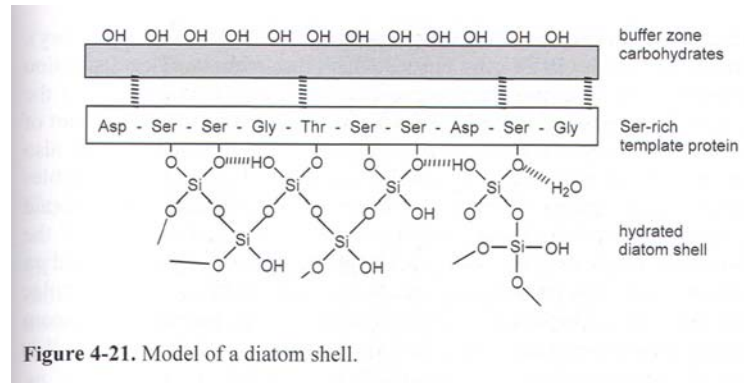


Figure 4-20. Diatom impressions – the fascinating world of diatoms in the micron range.

Exoskeleton formation

Si undersaturated in sea water. Must be actively transported into the cell (monomeric).



Polycondensation is suppressed by a Cofactor (Cof) (unknown)

Silica transport vesicles (STV) transport the silica to the cell wall and mineralization takes place in silica deposition vesicles (SDV)

Patterning is used to define the shape (mold-prepattern hypothesis)

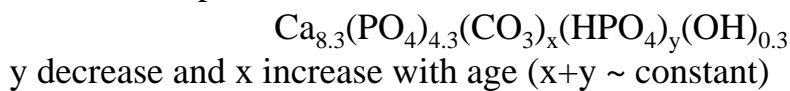
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Bone: ordered mesoscopic crystalline aggregates

Structural material and ion reservoir.

Both functions depend on the exact size, shape, chemical composition, and crystal structure of the mineral component, and on their arrangement in the organic matrix.

General composition:



Nanocomposite material, different layers of organization from the nanoscopic to the macroscopic structure:

- **Lowest: Crystals and the organic framework (collagen fibrils) and their relationship**
- **Tens of microns: longer range organization of collagen and associated crystals**
- **Highest: macroscopic structure of bones. Dense outer layers surrounding a less dense, porous tissue.**

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Crystalline materials

Transition metals: Mainly iron (some manganese) play a role in biomineralization. Dominated by redox properties (energy source), an affinity for O, S and OH, and ease of hydrolyzation.

Magnetic properties of mixed valent iron phases are used e.g. for navigation. Magnetite, Fe_3O_4 or greigite, Fe_3S_4 . Size and shape is controlled by organic membranes.

Aligned, single magnetic domain particles (40-80nm, ferromagnetic). Smaller crystals would be superparamagnetic, larger would be multidomain.

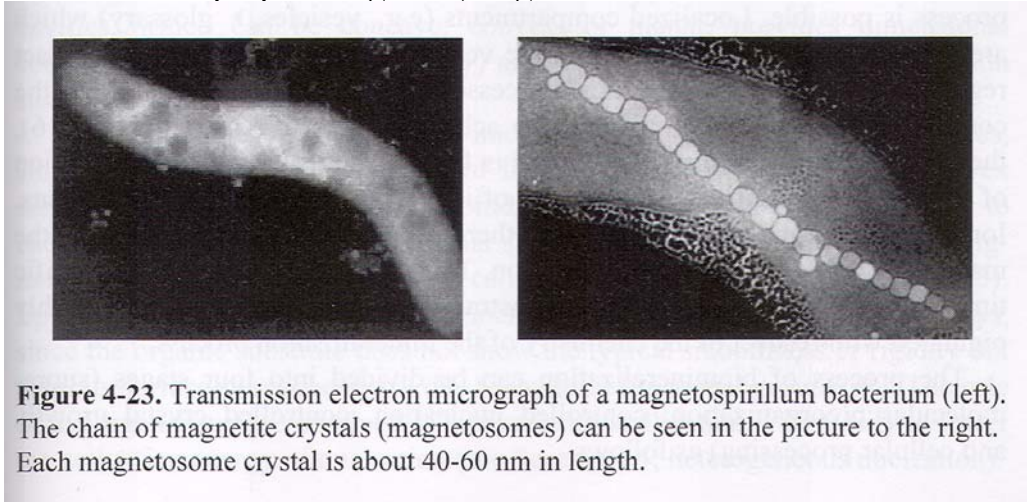


Figure 4-23. Transmission electron micrograph of a magnetospirillum bacterium (left). The chain of magnetite crystals (magnetosomes) can be seen in the picture to the right. Each magnetosome crystal is about 40-60 nm in length.

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Mineralization processes

Much is still unknown about the molecular interaction in the formation mechanisms of biominerals.

Again, precipitation is easy, but controlling size, shape, orientation and assembly of the crystals is not...

In biomineralization, the concentration and the nature of the interfaces (mineral-organic matrix and mineral-environment) are of extreme importance.

Mineralization takes place in open systems far from equilibrium!

Localized compartments (vesicles) surrounded by lipid membranes are very common.

Active accumulation of ions against concentration gradient require ion specific pumps or channels.

- **Supramolecular preorganization**
- **Controlled nucleation**
- **Controlled crystal growth**
- **Cellular processing**

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Supramolecular preorganization

e.g. supramolecular reaction compartment. The mineralization zone is isolated from the cellular environment.

- On or in the membrane wall of bacterial cells (epicellularly)
- Outside the cell. (e.g. collagen matrix of bone) Many shells or teeth are constructed within lamellar, columnar or reticular frameworks.
- Intracellularly by self-assembly. Construction of compartments are mainly based on balancing hydrophilic-hydrophobic interactions.

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Controlled nucleation by interfacial molecular recognition

Controlled nucleation into the framework organized in the first stage. One of the key points in biomineralization.

The organized pre-structures consist of functionalized surfaces. Blueprints for site directed inorganic nucleation.

Electrostatic, structural, and stereo chemical recognition.

Charge and polarity distribution, curvature...

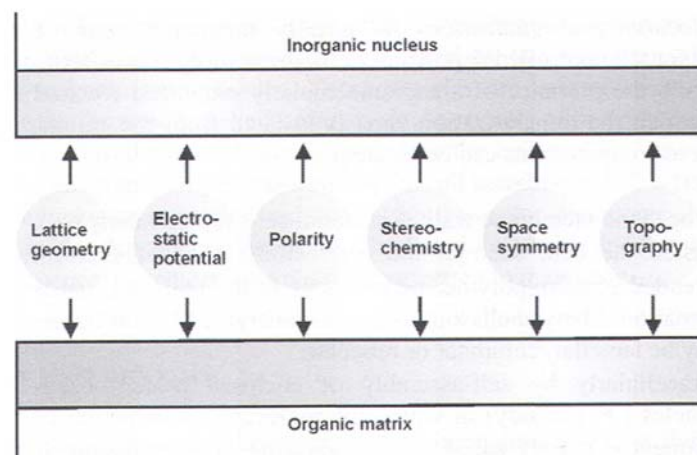


Figure 4-24. Possible modes of molecular complementarity at inorganic-organic interfaces.

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Concave surfaces are more active due to high concentration of active groups.
Planar surfaces allow “biological epitaxy”:

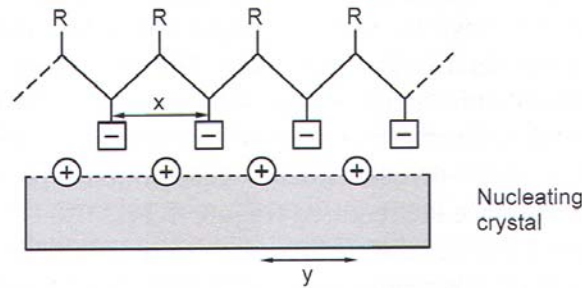


Figure 4-25. The concept of epitaxy as applied to biomineralization. Geometric matching must exist at the interface between a structured organic surface and nuclei of the inorganic crystal. Cation–cation distances in one specific crystal face are commensurate with the spacing of periodic binding sites on an organic surface (i.e., $x \approx y$).

Sometimes larger periodic structures may control inorganic nucleation.
e.g. collagenes: Bone crystals nucleate in the interstices of crystalline
assembly of collagen fibrils..

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Controlled crystal growth

Nucleation and growth in a supramolecular confined host may result in size limitations, but would not control the morphology

Morphology may be controlled by strict control of localized chemical environment.

Sometimes different polymorphs are grown in the same system, e.g. Fe_2O_3 , $n\text{H}_2\text{O}$, $\gamma\text{-FeOOH}$ and Fe_3O_4 or calcite and aragonite in some shells.

Spatial localization of ion pumps in the compartment may shape the growing crystal by turning on and off ion flows.

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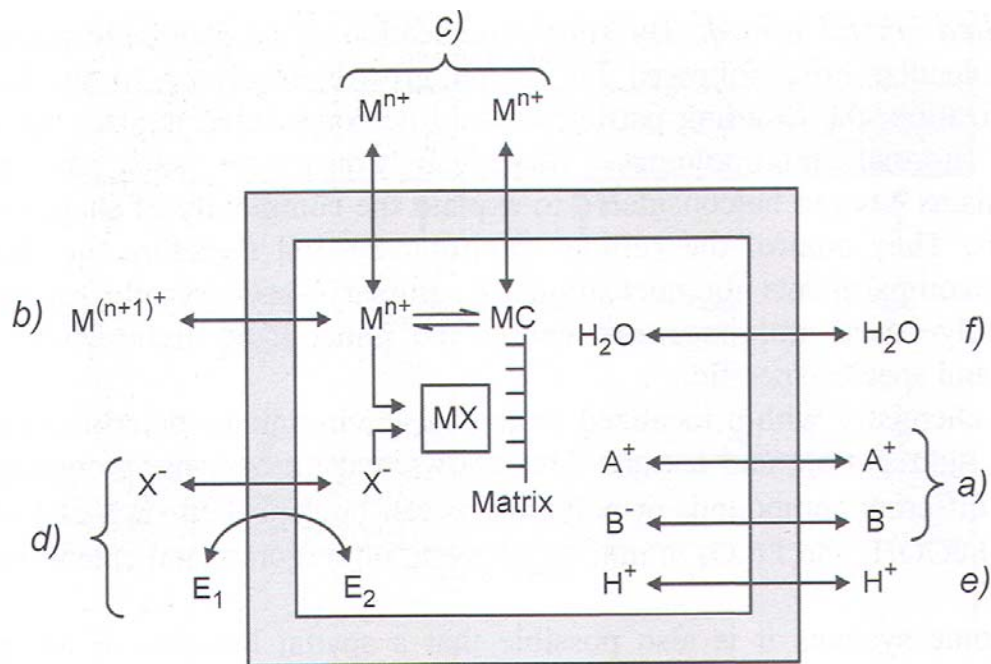


Figure 4-26. Control mechanisms involved in biomineralization processes (MX = biomineral; for an explanation of (a-f) see text).

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Cellular processing

Construction of higher order architectures.

Example: Organized architecture found in nacre in shells. Plate-like aragonite crystals are organized with layers of sheet-like organic compounds. The organic layers are secreted out periodically during mineralization, resulting in a well organized lamellar structure.

Details unknown...

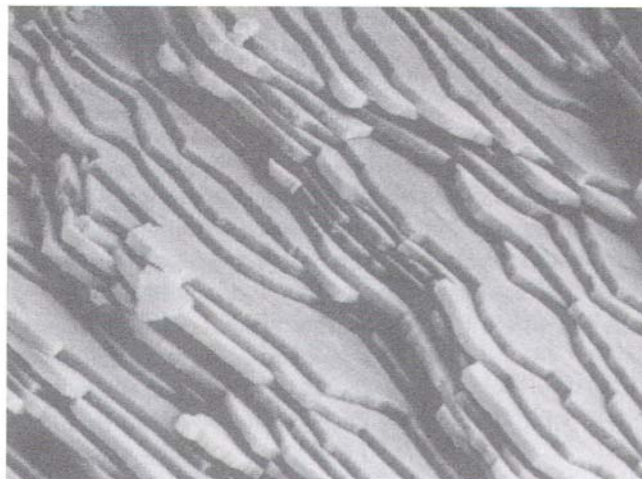


Figure 4-27. Scanning electron microscope image of the fracture of red abalone shell (*Halitoides rufescens*) showing multiple tiling of $\approx 200\text{--}500$ nm-thick aragonite (CaCO_3) crystals. Organic layers between the tiles (<10 nm-thick) are not discerned at this resolution.

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Synthetic biominerals

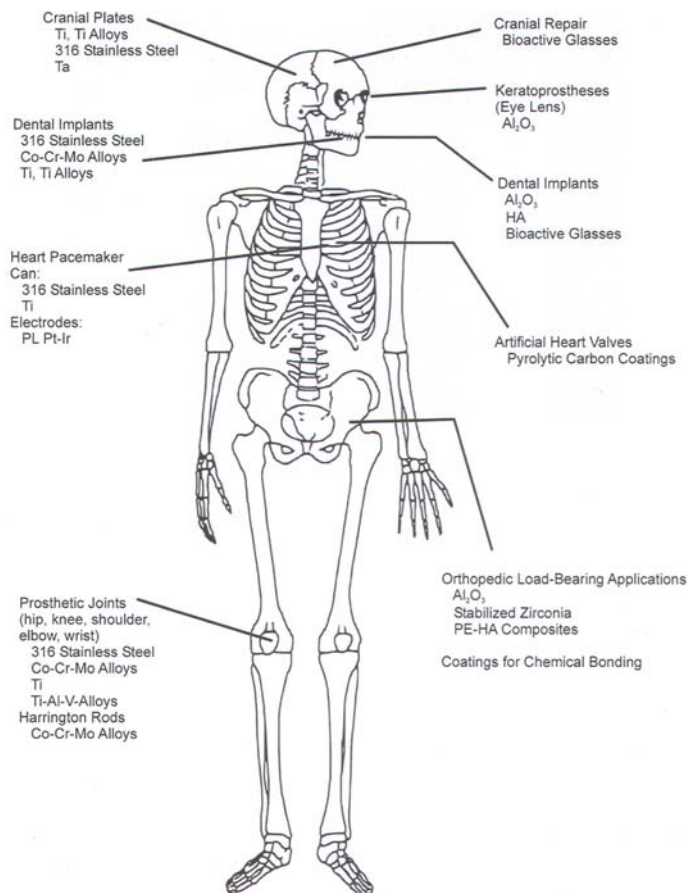
Implants or prostheses: attempts to replicate biological architecture.

Currently not possible: Materials must be found to substitute biological materials.

Interaction between tissue and biomaterials:

- **Bioinert materials.** Minimal interaction with neighbouring tissue. Implants made of metal and porous alumina: cementing or screwing (*morphological fixation*)
- **Biocompatible materials:** Interact (positively) with neighboring tissue. Enhances the mechanical stability of the implant. (hydroxyapatite implants are mechanically attached by ingrowth) (*biological fixation*)
- **Bioactive materials:** Increase recovering and growth. Resorbable bioactive materials will be slowly replaced by bone. Bioactive, dense, nonporous surface reactive ceramics, glasses and glass ceramics. Attached by chemical bonding. (*bioactive fixation*)

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Materials

Figure 4-28. Examples for clinical uses of some biomaterials.

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Bioactive ceramics and glasses

Typical chemical compositions: Na_2O , K_2O , MgO , CaO , Al_2O_3 , SiO_2 , P_2O_5 , CaF_2
 Low silica and presence of calcium and phosphate: rapid ion exchange, rapid nucleation and crystallization of hydroxycarbonate apatite. (bone mineral)

Stages 1-5 fairly well understood... 6-11 not really

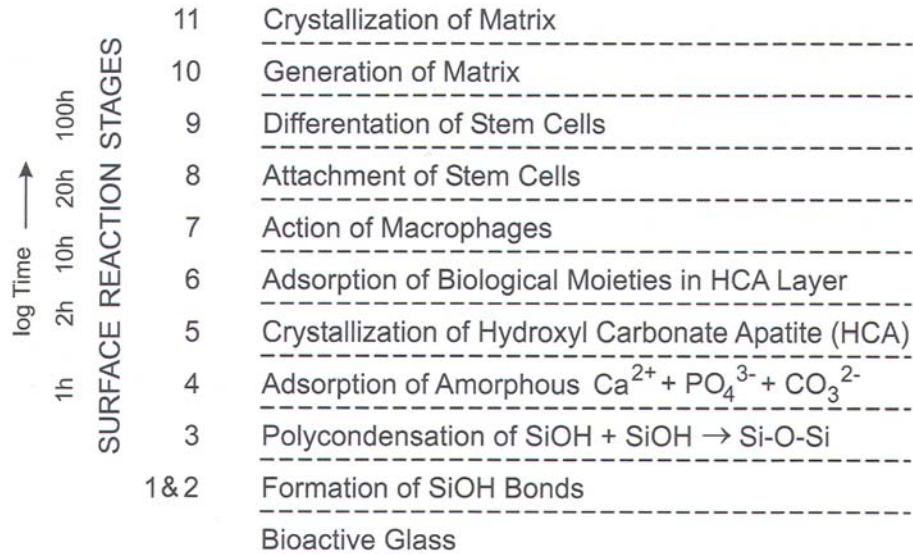


Figure 4-29. Proposed sequence of interfacial reactions involved in forming a bond between tissue and bioactive glass.

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Joint prostheses

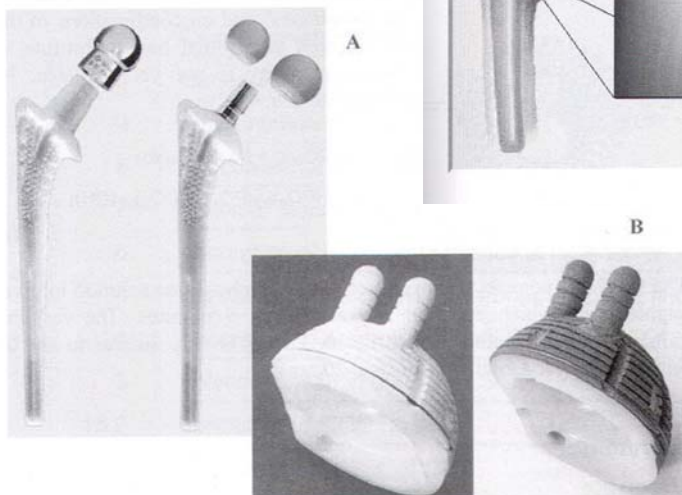


Figure 4-30. Artificial hip joint (two-part device). A. The ball portion with the shank. B. The socket portion with two pins for fixation and holes for screws. For a better biocompatibility with the tissue, the prosthesis is coated with either hydroxylapatite (B; left) or titanium powder (B; right).

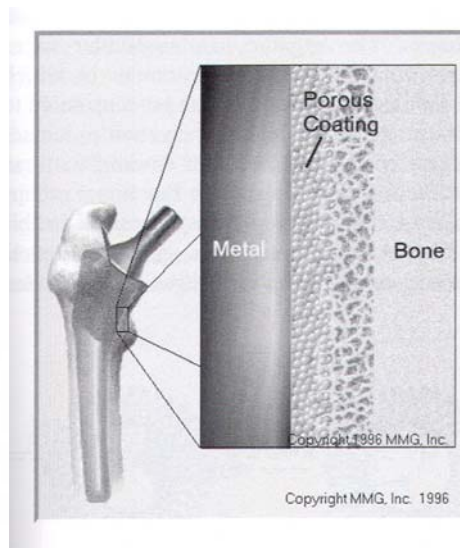


Figure 4-31. Scheme of the artificial hip joint coated with a porous coating.

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Biomimetic materials chemistry

Bioinspired materials processing

Complex structured composites; difficult to mimic. (so far very limited success.)
No system has yet shown the level of control and complexity that is found in biogenic materials.

Would be a significant step towards synthesis of “smart” materials.

Example: Microemulsion, phospholipid vesicles, proteins and reverse micelles.
Formed by surfactant-water mixtures. Used for producing nanoparticles.

e.g. magnetite crystals (Fe_3O_4)

Variable dimensions (1-500nm), surface functional groups may be modified.

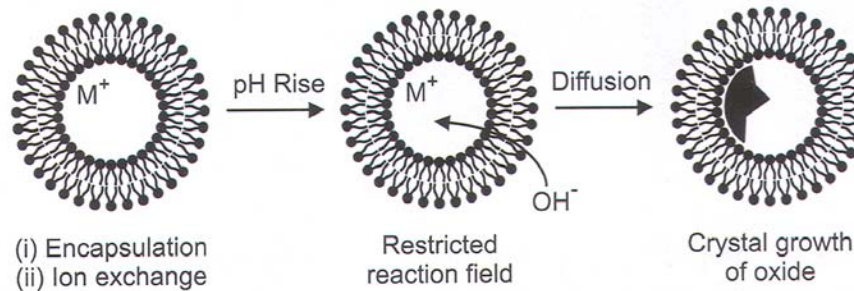
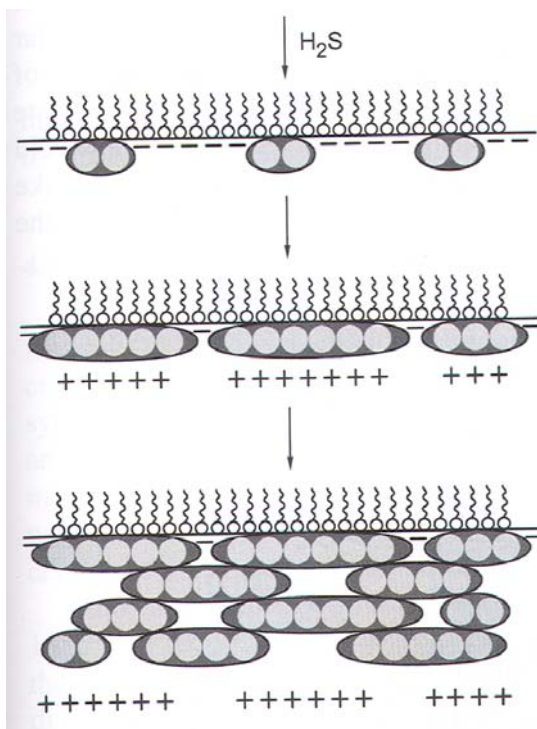


Figure 4-32. Membrane-mediated precipitation of metal oxides in phospholipid vesicles. The chemical reaction is as previously discussed (Eq. 4-10).

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Synthetic surfaces

Synthetic surfaces used for initializing nucleation. Use of surfactant monolayers or surfaces: functionality and packing may be tuned.



Example: formation of thin films and size controlled microcrystals of semiconducting sulfides.

Diffusion of H_2S through a surfactant monolayer on an aqueous solution of a metal salt.

Film formation in a layer-by-layer way. (CdS ~ 30 nm, ZnS ~ 350 nm)

Figure 4-33. Schematics of the growth of nanoparticulate metal sulfide films under monolayers. The time of hydrogen sulfide treatment increases from top to bottom.

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BaSO₄

Normally rectangular tablets are obtained by precipitation of baryte, BaSO₄.

When precipitated in the presence of a monolayer of *n*-eicosyl sulfate (C₂₀H₂₁OSO₃⁻) a morphological change is seen

Monolayers of *n*-eicosyl sulfate BaSO₄ nucleate with the (100) face parallel to the monolayer. The arrangement of sulfate groups simulates the arrangement in baryte, leading to oriented nucleation

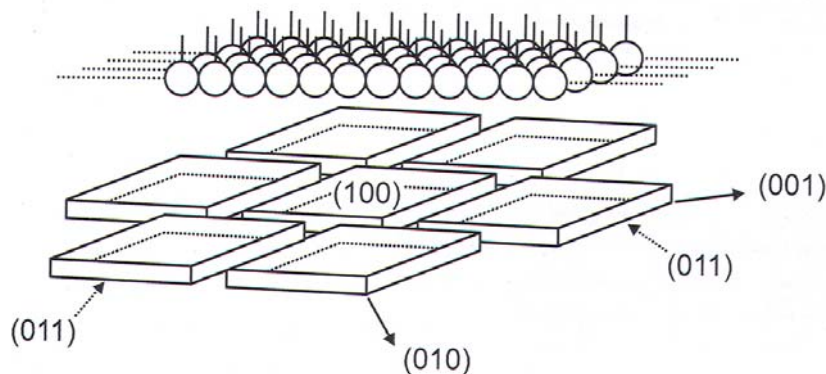


Figure 4-34. Scheme of barium sulfate precipitation in the presence of a monolayer of *n*-eicosyl sulfate.

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Fusion of Seashell Nacre and Marine Bioadhesive Analogs: High-Strength Nanocomposite by Layer-by-Layer Assembly of Clay and L-3,4-Dihydroxyphenylalanine Polymer**

By Paul Podsiadlo, Zhongqiang Liu, David Paterson, Phillip B. Messersmith,
and Nicholas A. Kotov*

Adv. Mater. **2007**, *19*, 949–955

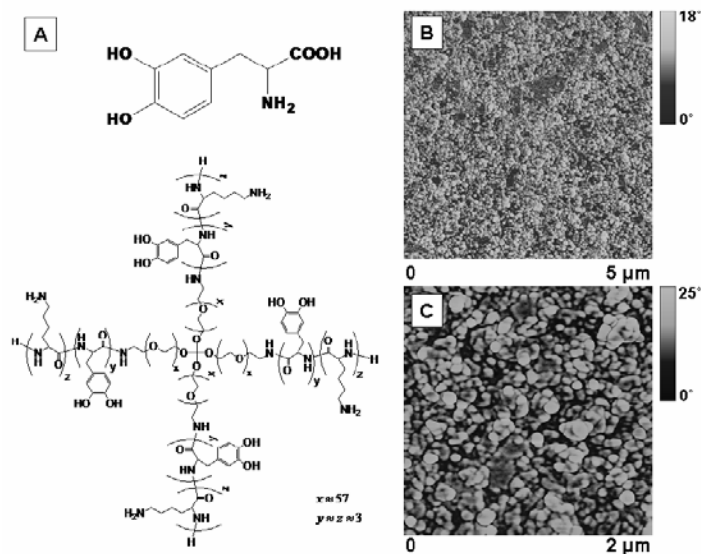


Figure 1. A) Molecular structure of a single DOPA molecule and DOPA-Lys-PEG polymer. B,C) phase AFM images of a single layer of C platelets adsorbed on a layer of DOPA-Lys-PEG polymer. The surface roughness (root mean square) is 1.695 nm in (B) and 1.429 nm in (C).

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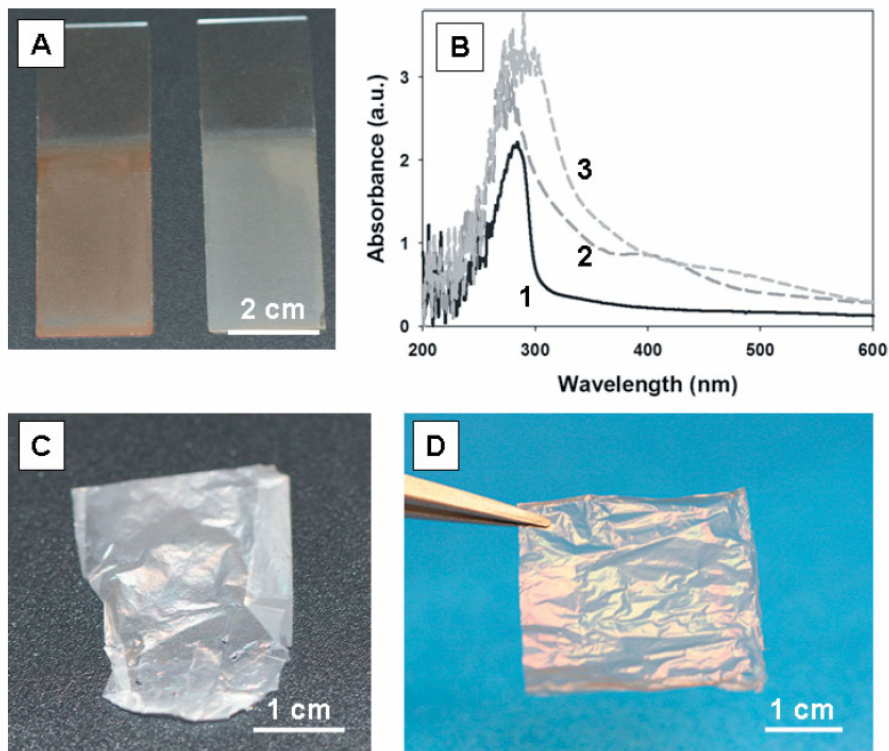


Figure 3. A) Digital photograph of 300 bilayer DOPA-Lys-PEG/C films on microscope glass slides with (left) and without (right) Fe^{3+} crosslinking, B) UV-vis spectra of 300 bilayer films of DOPA-Lys-PEG/C at different stages of DOPA:Fe complexation: 1) plain film, 2) pH ~ 3, and 3) pH ~ 8, C) digital photograph of a 300 bilayer DOPA-Lys-PEG/C free-standing film after separation from the glass slide, and D) digital photograph of a Fe^{3+} crosslinked 300 bilayer DOPA-Lys-PEG/C free-standing film.

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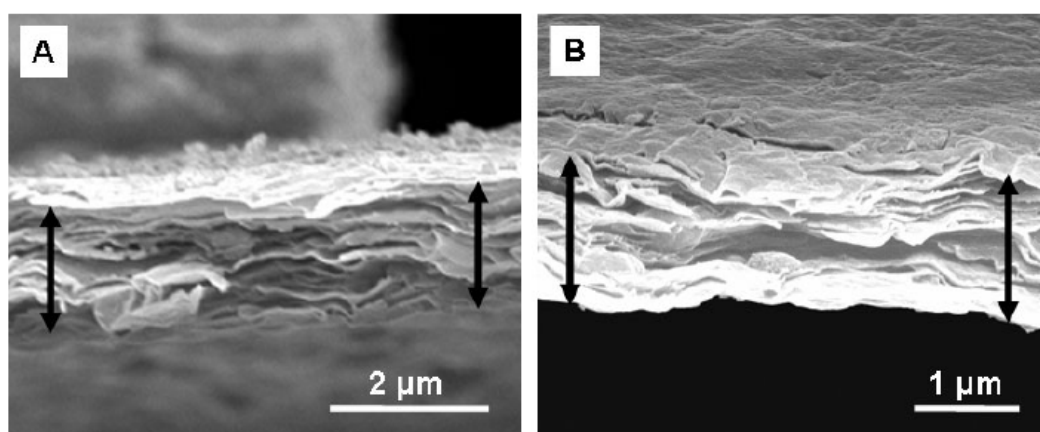


Figure 4. SEM cross-sectional view of 300 bilayer, Fe^{3+} crosslinked films of A) DOPA-Lys-PEG/C and B) Lys-PEG/C. Arrows indicate the cross section of the films. The slight separation of the layers seen in (B) is caused by a shearing force resulting from cutting samples with a razor blade during sample preparation.

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