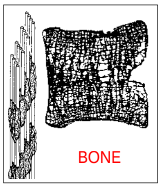
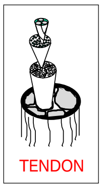
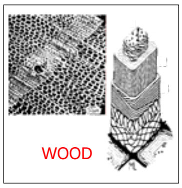
Nature's Adaptive Materials

Adaptive Materialien der Natur







DEEP SEA SPONGE

(VENUS FLOWER BASKET)

Peter Fratzl

Max Planck Institute of Colloids and Interfaces

WIAS-Kolloquium, 19. 6. 2006, Berlin

Biological Material	Engineering Material
Few Chemical Elements dominate: C, N, O, H, Ca, P, S, Si….	**Large Variety** of Elements: Fe, Cr, Ni, Al, Si, C, N, O, …
Growth by biologically controlled self-assembly (approximate design)	**Fabrication** from melts, powders, solutions, etc. (exact design)

Same Engineering Design

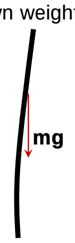
Same Genetic Code

Biological Material	Engineering Material
Few Chemical Elements dominate: C, N, O, H, Ca, P, S, Si….	**Large Variety** of Elements: Fe, Cr, Ni, Al, Si, C, N, O, …
Growth by biologically controlled self-assembly (approximate design)	**Fabrication** from melts, powders, solutions, etc. (exact design)

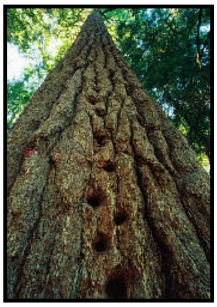
Hierarchical Structure at all size levels	**Form** (of the part) and **Micro-structure** (of the material)
Adaptation of form and structure to the function	**Design** of the part and **Selection** of material according to function
Modeling and Remodeling: Capability of adaptation to changing environmental conditions.	**Secure Design** of the part and secure materials selection (considering possible maximum loads as well as fatigue)
Healing: Capability of self-repair	

Highest column with lowest amount of material

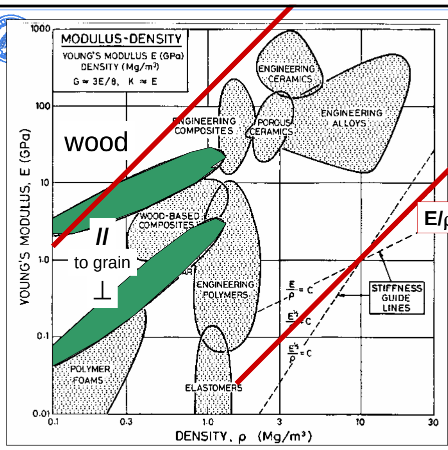
buckling due to own weight



solution = **E / ρ^2** maximum

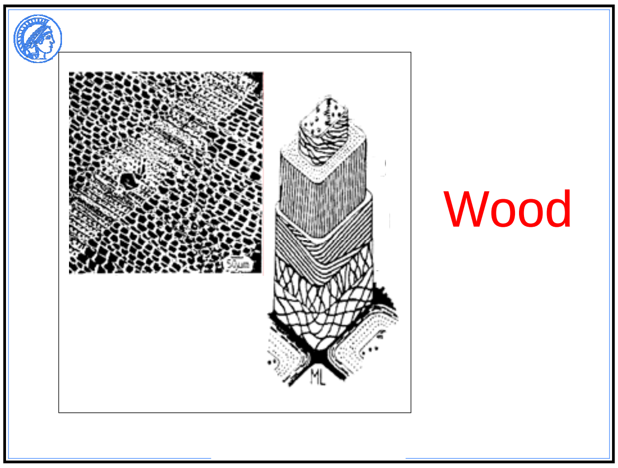


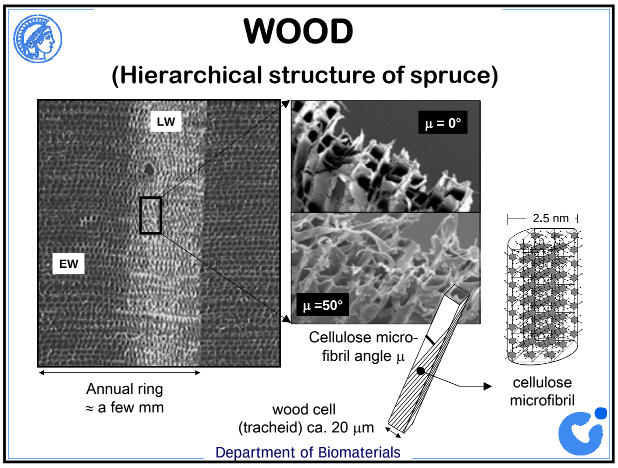
(**E** = Young's modulus, ρ = density)

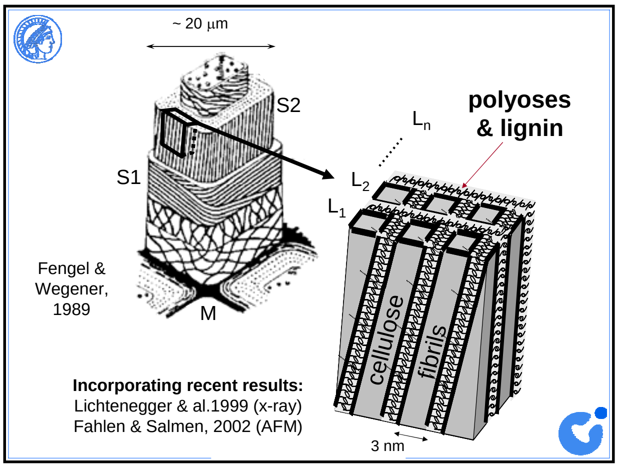


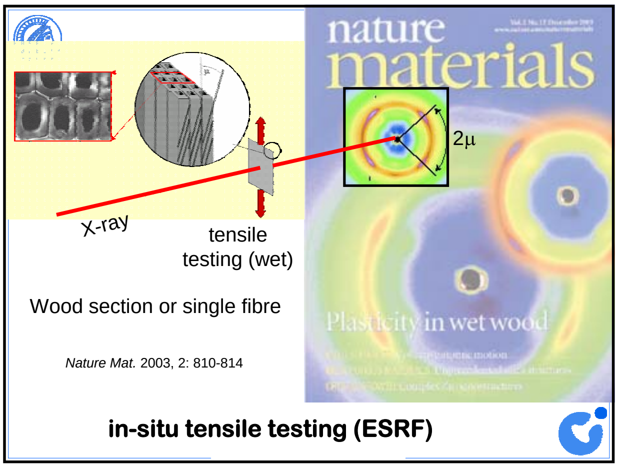
Ashby-map

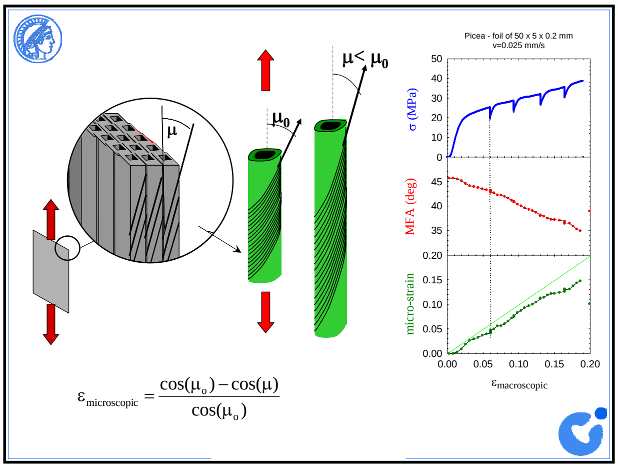
E/ρ^2 = const.

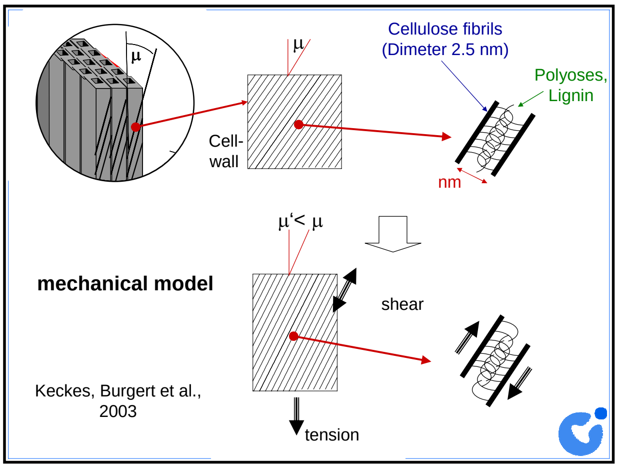

Wood
ML


WOOD
(Hierarchical structure of spruce)
LW
EW
μ = 0°
μ =50°
2.5 nm
Cellulose micro-
fibril angle μ
cellulose
microfibril
Annual ring
≈ a few mm
wood cell
(tracheid) ca. 20 μm
Department of Biomaterials


~ 20 μm
S2
S1
M
Fengel &
Wegener,
1989
polyoses
& lignin
Ln
L2
L1
cellulose
fibrils
3 nm
Incorporating recent results:
Lichtenegger & al.1999 (x-ray)
Fahlen & Salmen, 2002 (AFM)


x-ray
tensile
testing (wet)
Wood section or single fibre
Nature Mat. 2003, 2: 810-814
nature
materials
2μ
Plasticity in wet wood
in-situ tensile testing (ESRF)

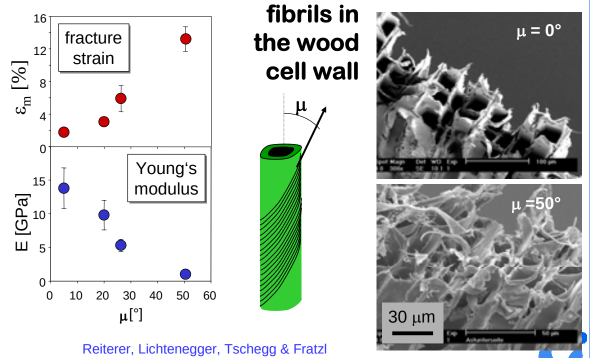

μ
μ0
μ< μ0
Picea - foil of 50 x 5 x 0.2 mm
v=0.025 mm/s
σ (MPa)
MFA (deg)
micro-strain
ε macroscopic
0.00
0.05
0.10
0.15
0.20
$$\varepsilon_{microscopic} = \frac{\cos(\mu_o) - \cos(\mu)}{\cos(\mu_o)}$$


μ
Cellulose fibrils
(Dimeter 2.5 nm)
Polyoses,
Lignin
Cell-
wall
nm
μ'< μ
mechanical model
shear
Keckes, Burgert et al.,
2003
tension

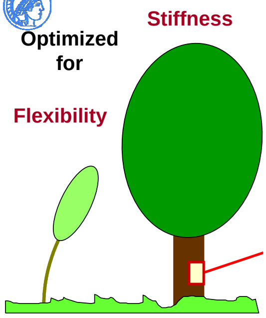
Mechanical Function

Adaptivity

Mechanical function of the spiral angle of cellulose



Reiterer, Lichtenegger, Tschegg & Fratzl
Phil. Mag. (1999); *J. Mater. Sci.* (2001)



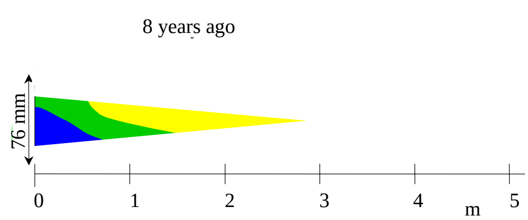
La loi du chêne et du roseau

(the oak and the reed)

d'après
Jean de La Fontaine
(1621-1695)

H. Lichtenegger et al., *J. Struct. Biol.* (1999)
A. Reiterer et al., *Wood Sci. Tech.* (1999)

Microfibril angle distribution in the vertical section of a spruce branch



J. Färber *et al., J. Mater. Sci.* (2001)

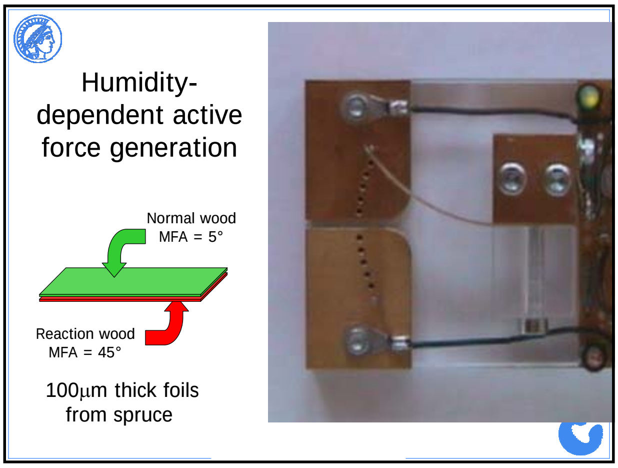
Active Force

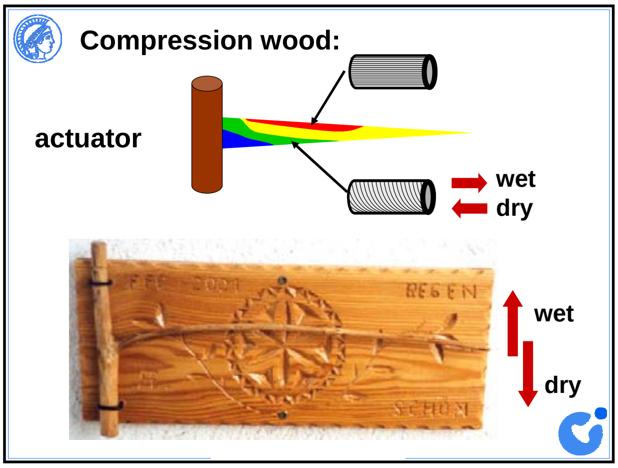
Generation

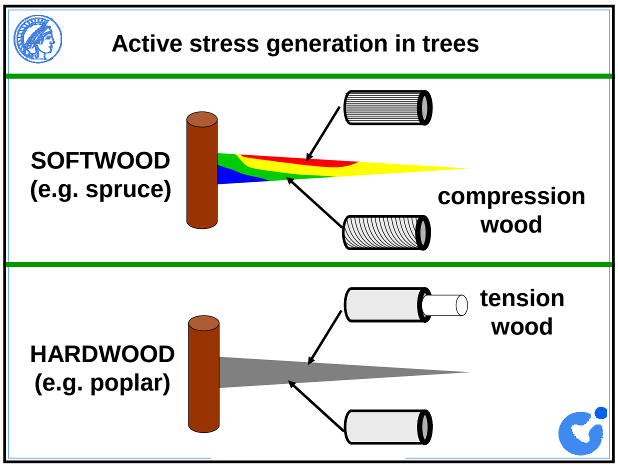
„Hygrometer"

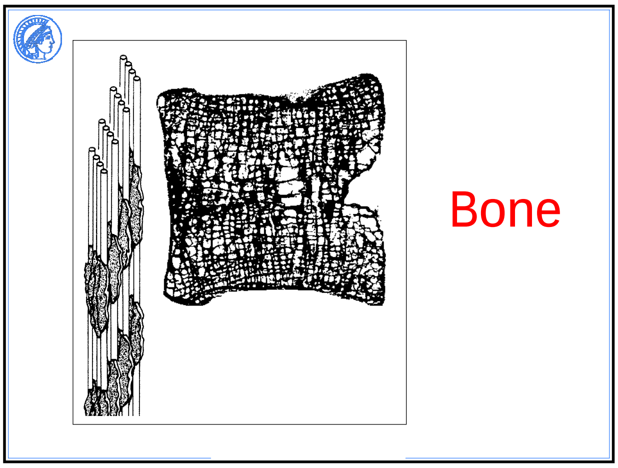
(Leoben, Austria)

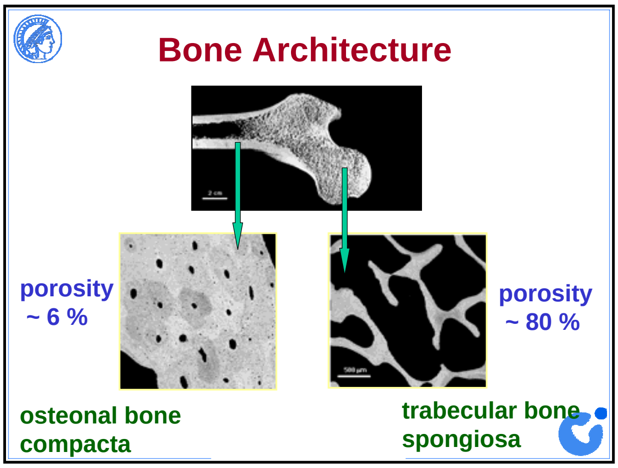
Photographs
H.P. Stüwe
2001

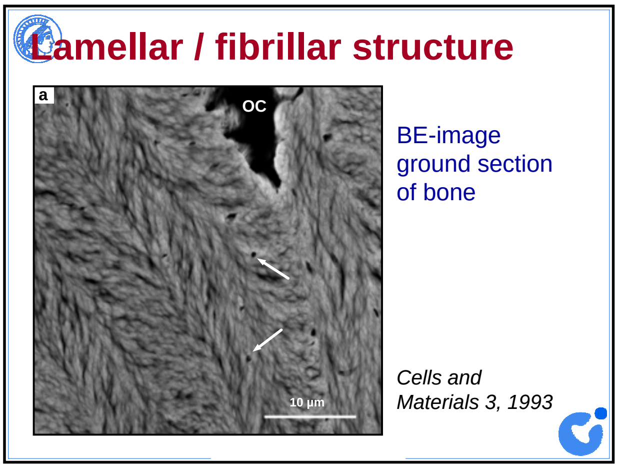

Humidity-dependent active force generation
Normal wood
MFA = 5°
Reaction wood
MFA = 45°
100µm thick foils from spruce


Compression wood:
actuator
wet
dry
wet
dry


Active stress generation in trees
SOFTWOOD (e.g. spruce)
compression wood
tension wood
HARDWOOD (e.g. poplar)

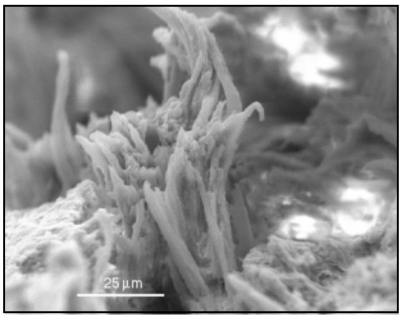

Bone


Bone Architecture
porosity ~ 6 %
porosity ~ 80 %
osteonal bone compacta
trabecular bone spongiosa


Lamellar / fibrillar structure
a
OC
10 µm
BE-image ground section of bone
Cells and Materials 3, 1993

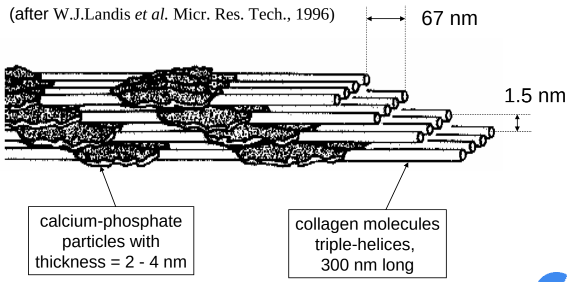
Mineralized Collagen Fibrils

SE-image of ruptured bone



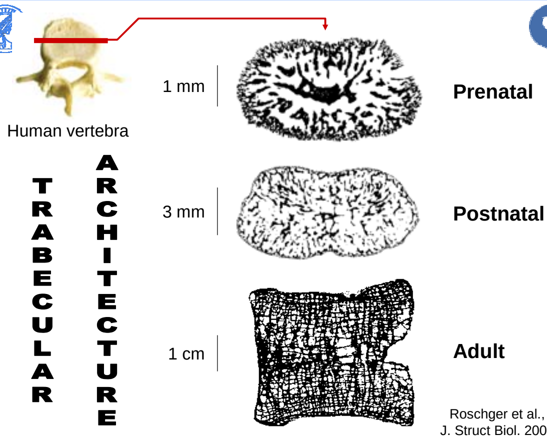
Internal Structure of Mineralized Collagen Fibril

(after W.J.Landis *et al.* Micr. Res. Tech., 1996)



Adaptation at all levels of hierarchy

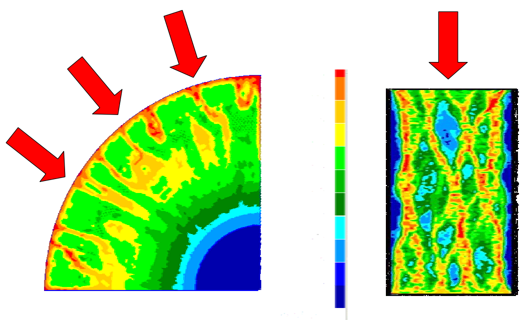
Tissue level

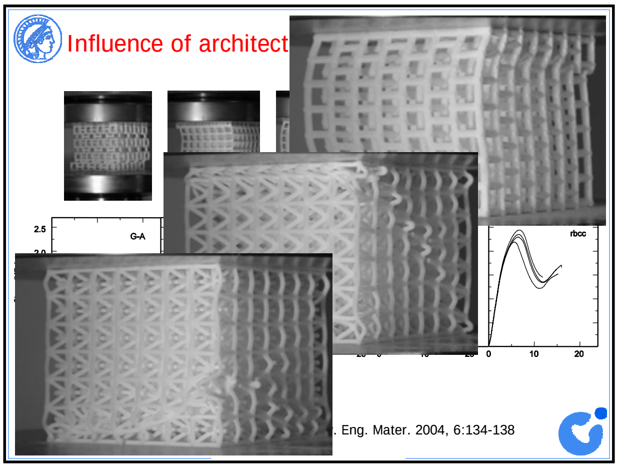


Roschger et al., J. Struct Biol. 2001

Mehrphasen-Topologieoptimierung

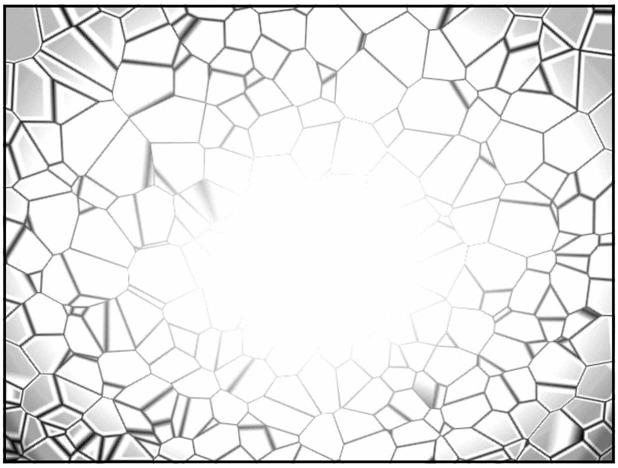
Andreas Burblies, Fraunhofer IFAM Bremen

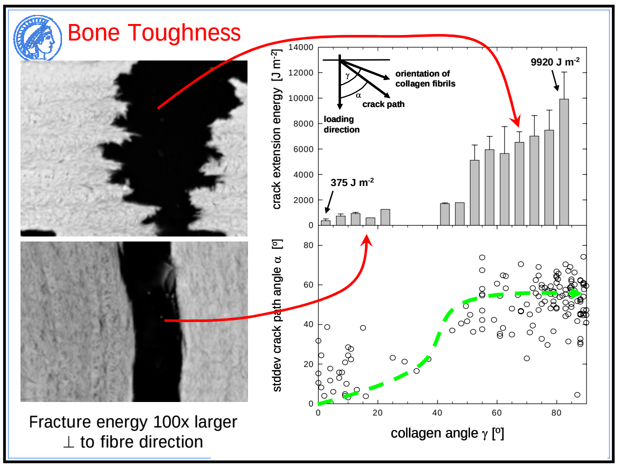


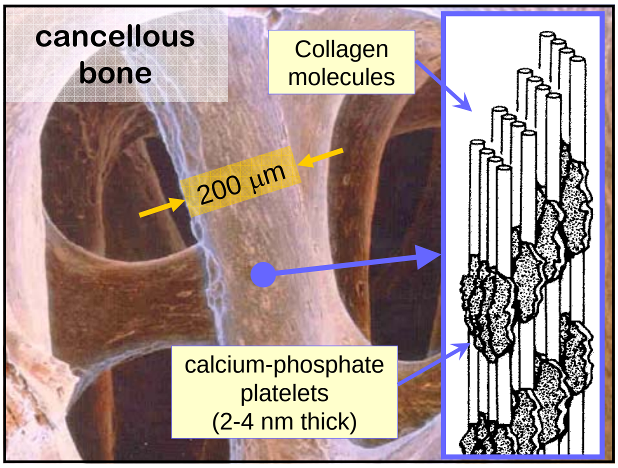


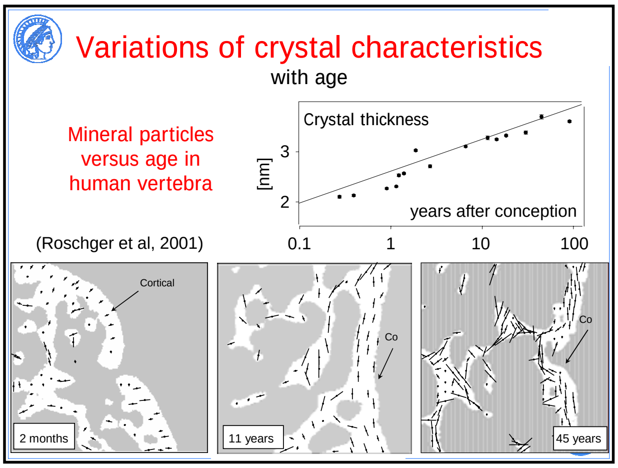
Composite

Level





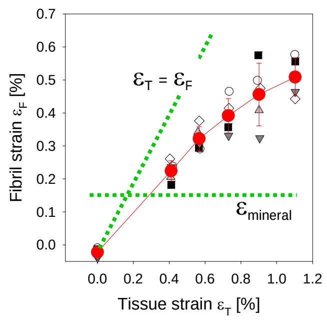


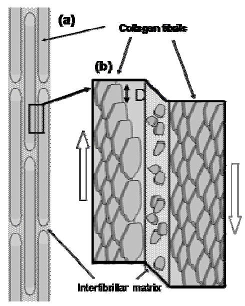


Fibril

Level

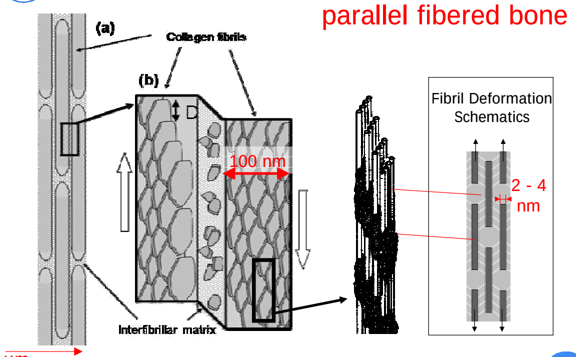
Hierarchical Deformation in Parallel Fibered Bone





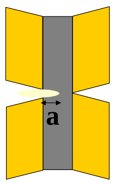
Gupta et al. Nanoletters 2005

Three levels of deformation in parallel fibered bone



shear between fibrils and between mineral particles

Why nano ?



stiffness of particles

interface energy

$$\sigma_P^* = \sqrt{\frac{2 E_p \gamma}{\pi a}}$$

strength

(Griffith)

crack length

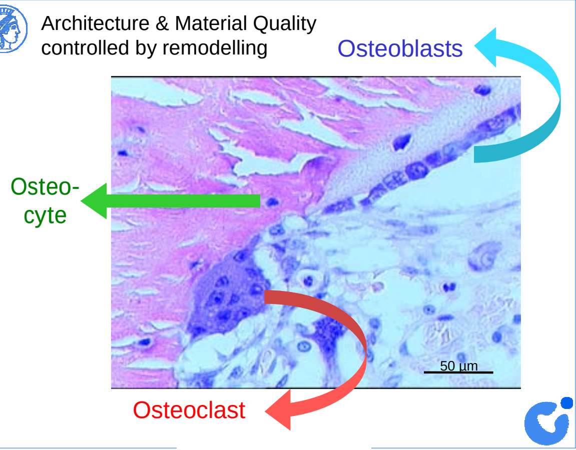
The finer the structure, the higher the strength

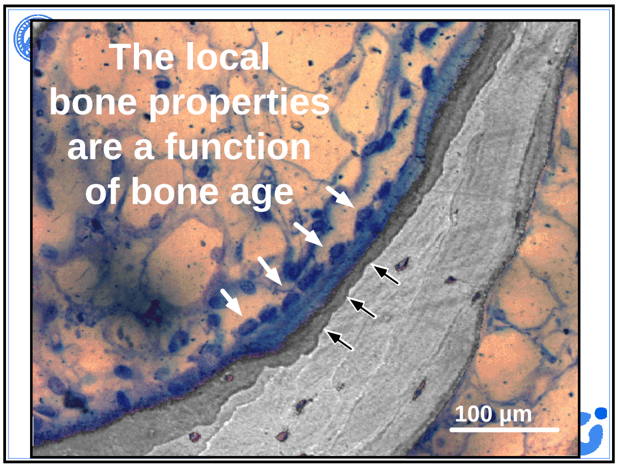
H. Gao, B. Ji, I.L. Jäger, E. Arzt, P. Fratzl, PNAS 100:5597-5600 (2003)

(Re)modeling

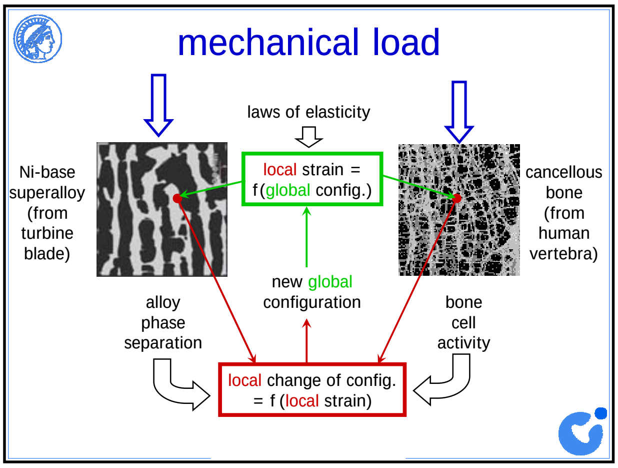
→ Bone is heterogeneous in space and time

Architecture & Material Quality controlled by remodelling

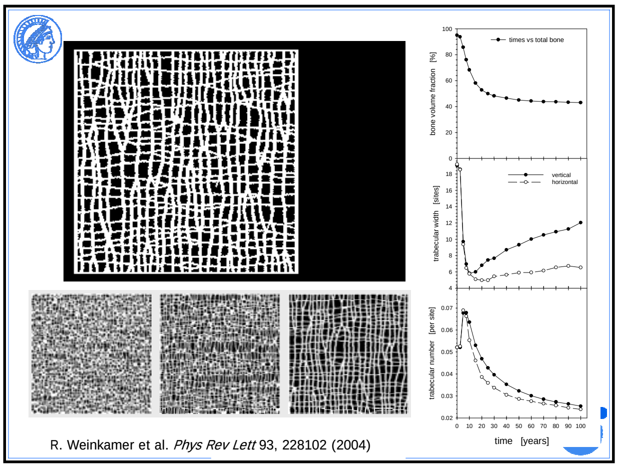




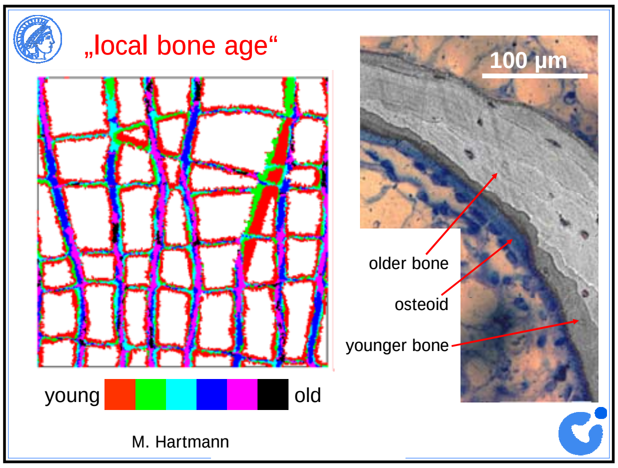
The local bone properties are a function of bone age
100 µm



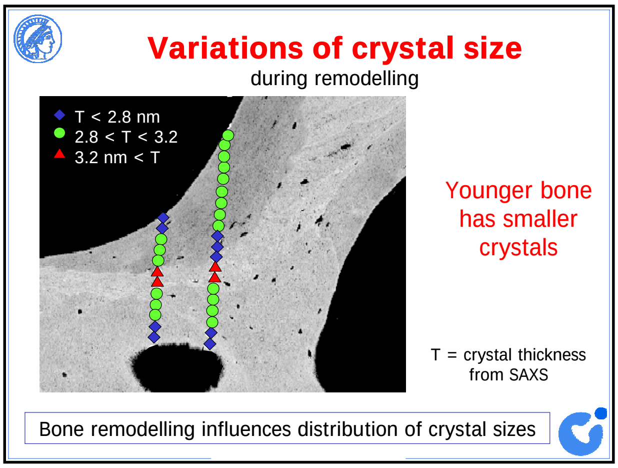
mechanical load
laws of elasticity
Ni-base superalloy (from turbine blade)
local strain = f(global config.)
cancellous bone (from human vertebra)
new global configuration
alloy phase separation
bone cell activity
local change of config. = f (local strain)



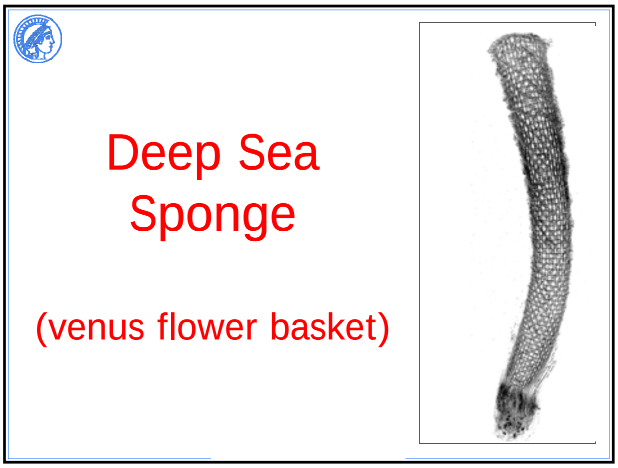
bone volume fraction [%]
trabecular width [sites]
trabecular number [per site]
time [years]
R. Weinkamer et al. Phys Rev Lett 93, 228102 (2004)



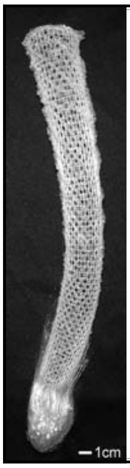
„local bone age“
100 µm
older bone
osteoid
younger bone
young
old
M. Hartmann



Variations of crystal size
during remodelling
T < 2.8 nm
2.8 < T < 3.2
3.2 nm < T
Younger bone has smaller crystals
T = crystal thickness from SAXS
Bone remodelling influences distribution of crystal sizes

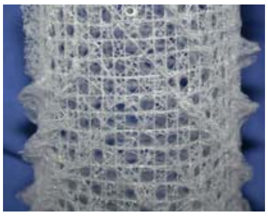


Deep Sea Sponge
(venus flower basket)

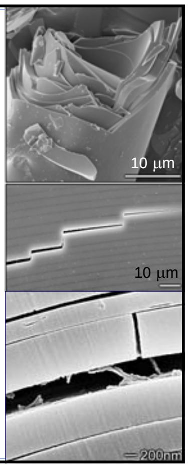


Glass which does (almost) not break

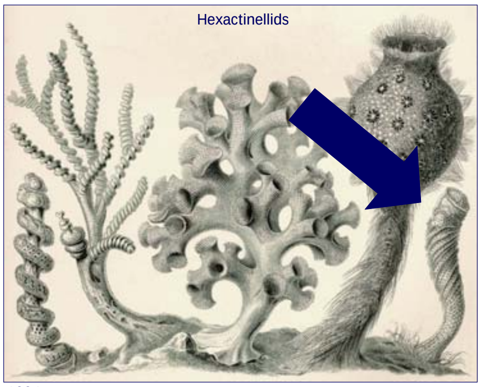
Hierarcical structure of glass sponge Euplectella sp



J. Aizenberg, J. C. Weaver, M. S. Thanawala, V. C. Sundar, D. E. Morse, P. Fratzl
Science **309**, 275 - 278 (2005)

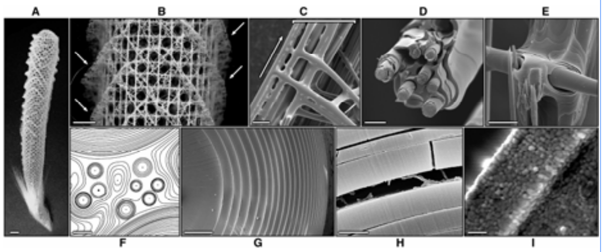


Euplectella aspergillum – Venus's Flower Basket – Cage of Love



Haeckel, 1904

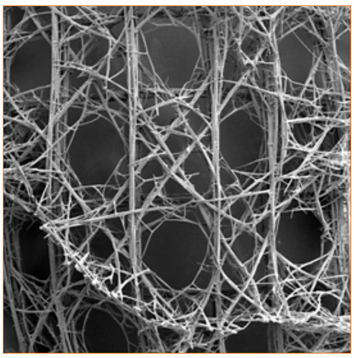
Euplectella sp. (venus flower basket)



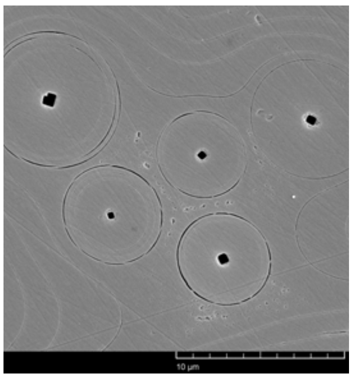
Almost pure silica
Glass-“cage“

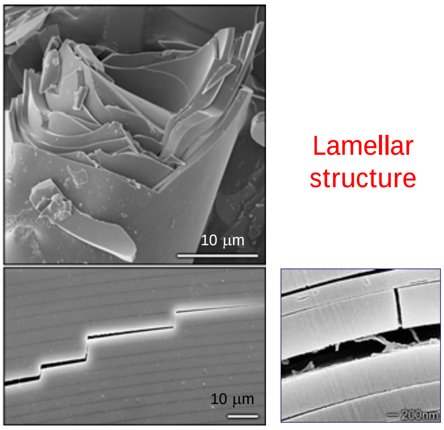
Seven levels of hierarchy

architecture and mechanical properties



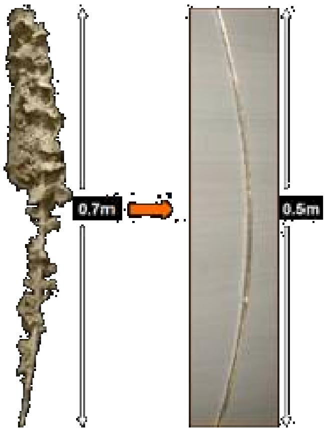
© James Weaver, UCSB



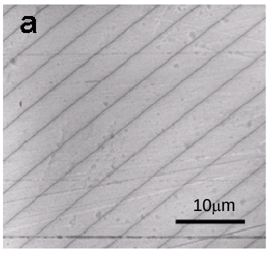


Lamellar structure

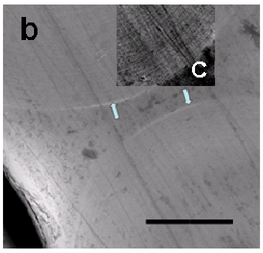
Monorhaphis Chuni



Layered structure of silica spicules

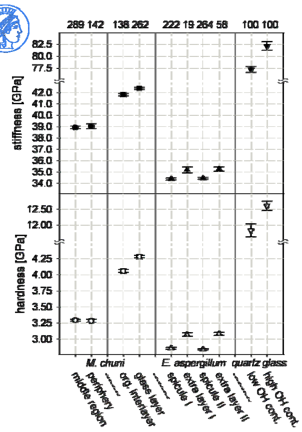


Monorhaphis chuni

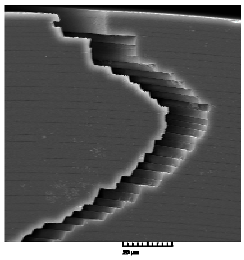


Euplectella aspergillum

A. Woesz et al., 2005

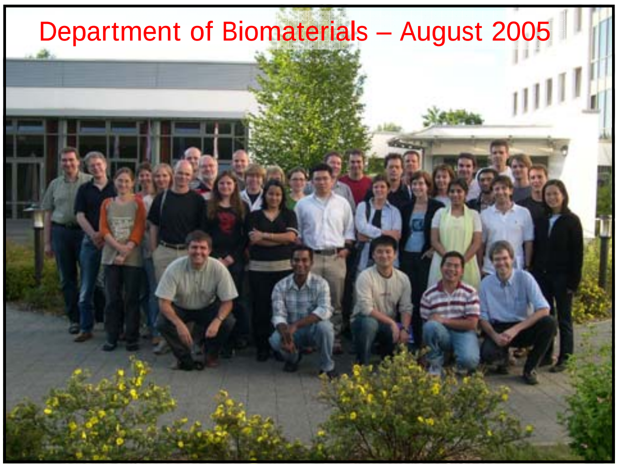


Why bio-silica spicules are tough



Woesz et al. 2005

Department of Biomaterials – August 2005

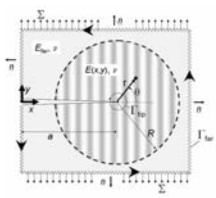


Offene Probleme (Modellierung)

- Rissausbreitung in inhomogenen Medien (J-integral Berechnungen,...) – mit FD Fischer

$$f_{inh} = \int_{-\pi}^{\pi}\left(\frac{E_0}{E(R\cos\theta)} - \frac{E_0}{E(0)}\right)\frac{p(\cos\theta)}{2\pi\cos\theta}\,d\theta$$

  optimale Funktion E(x) mit <E> = E_0



- Knochenadaptierung → Gittermodelle, Zellulare Automaten, ... (Weinkamer, Hartman, Dunlop...) – adaptive zellulare Materialien
- Mineralisationskinetik im Knochen u. ä. (Weinkamer, Ruffoni,...) –
- Biomimetische Nukleation von anorganischen Kristallen (WW Kristalle mit Polymeren).