Cellular Solids: Structure, Properties and Applications

Lorna J. Gibson
Materials Science & Engineering
MIT

Cork: Robert Hooke

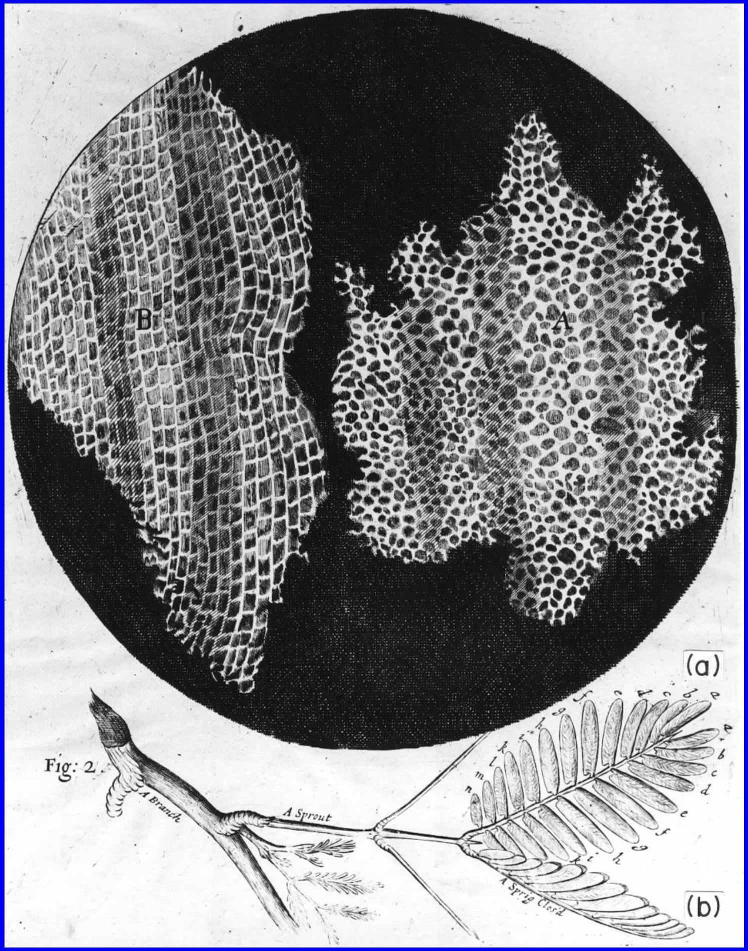


Image is in the public domain. Source Wikimedia Commons.

"I no sooner discerned these (which were indeed the first microscopical pores I have ever saw…) but me thought I had with the discovery of them, perfectly hinted to me the true and intelligible reason for all the phenomena of cork"

Micrographia (1665)

Hooke: first to use the term "cell", from Latin "cella" a small compartment

Cellular Solids

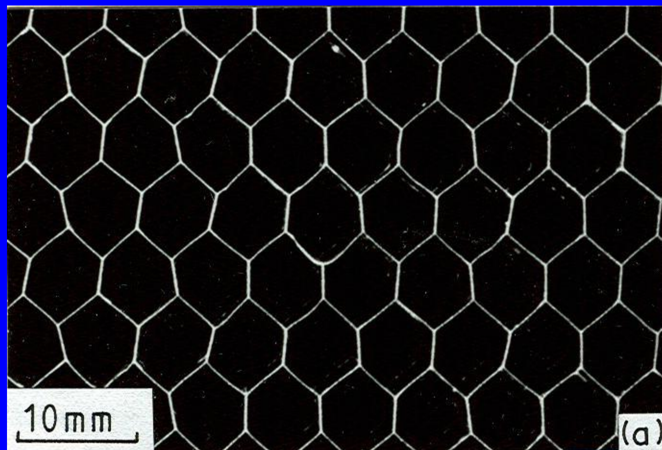
- Engineering cellular solids
  - Honeycombs: 2D prismatic cells
  - Foams: 3D polyhedral cells
  - Applications: sandwich panels, energy absorption, insulation
- Cellular materials in medicine
  - Trabecular bone, osteoporosis
  - Tissue engineering scaffolds; cell-scaffold mechanics
- Cellular materials in nature
  - Honeycomb-like: wood, cork
  - Foam-like: trabecular bone, plant parenchyma, sponges
  - Cellular/solid structural components in nature
    - Sandwich panels (leaves, skulls)
    - Radial density gradients (palm stems, bamboo)
    - Cylindrical shells with compliant cores (plant stems, animal quills, toucan beak)

Cellular Solids

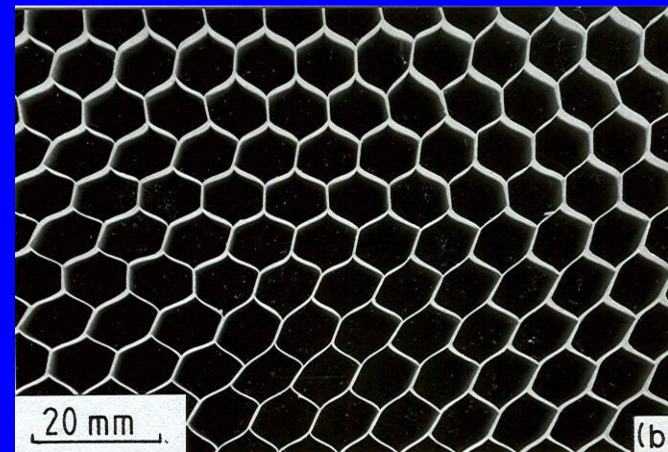
- Identify mechanisms of deformation and failure
- Structural analysis to obtain bulk mechanical properties such as moduli, strength, fracture toughness
- Microstructural design of cellular solids
- Selection of cellular materials in engineering design

Engineering Cellular Solids

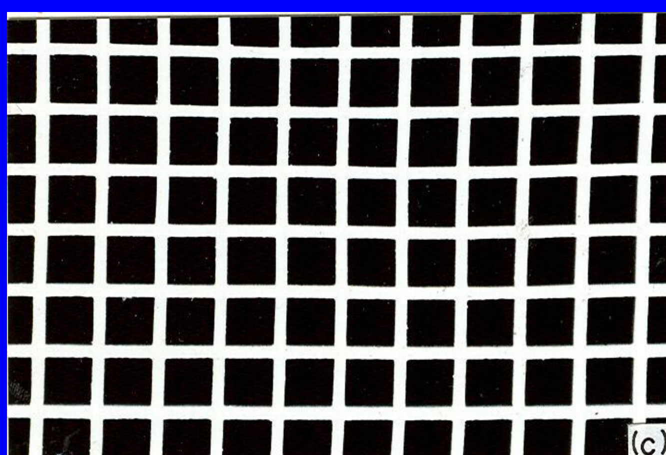
Engineering Honeycombs



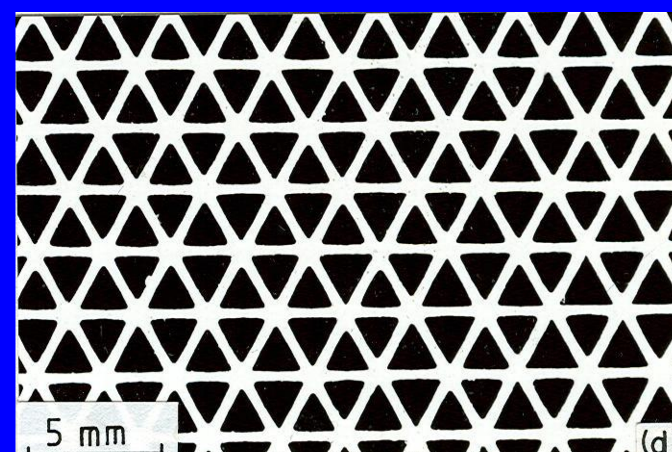
Aluminum



Paper - resin



Ceramic



Ceramic

Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press. © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

Engineering Foams

Polyurethane

Polyethylene

Nickel

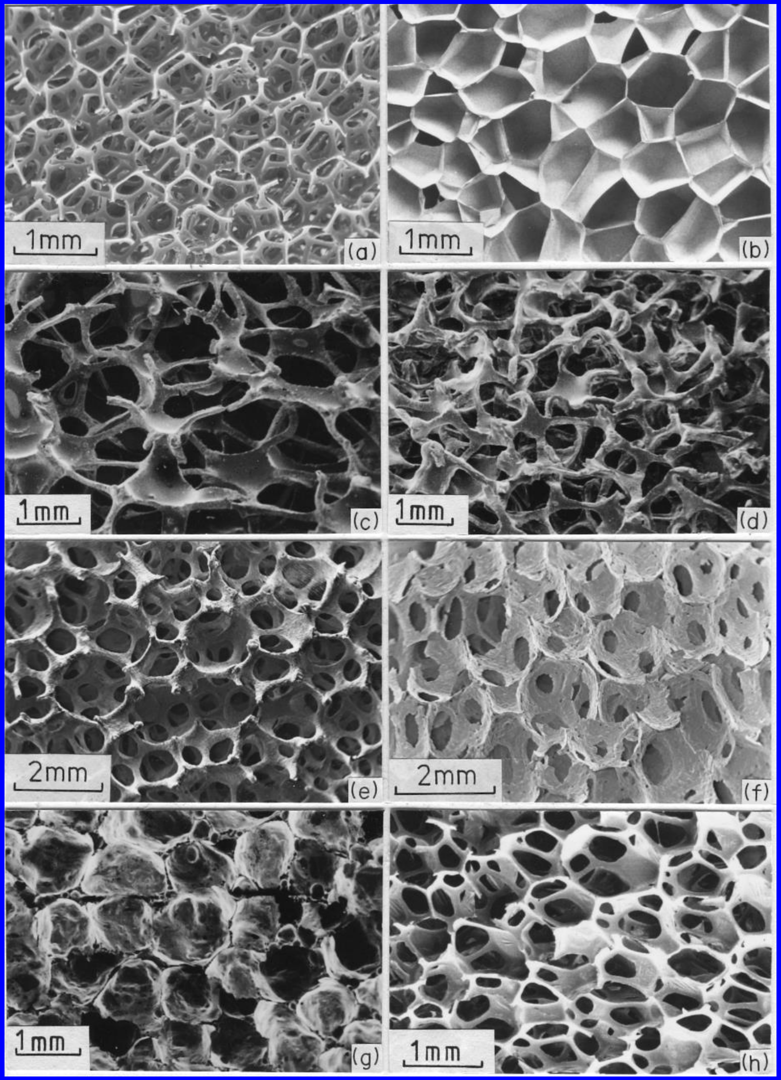
Copper

Zirconia

Mullite (combination of alumina and silica)

Glass

Polyether



Food Foams

Bread

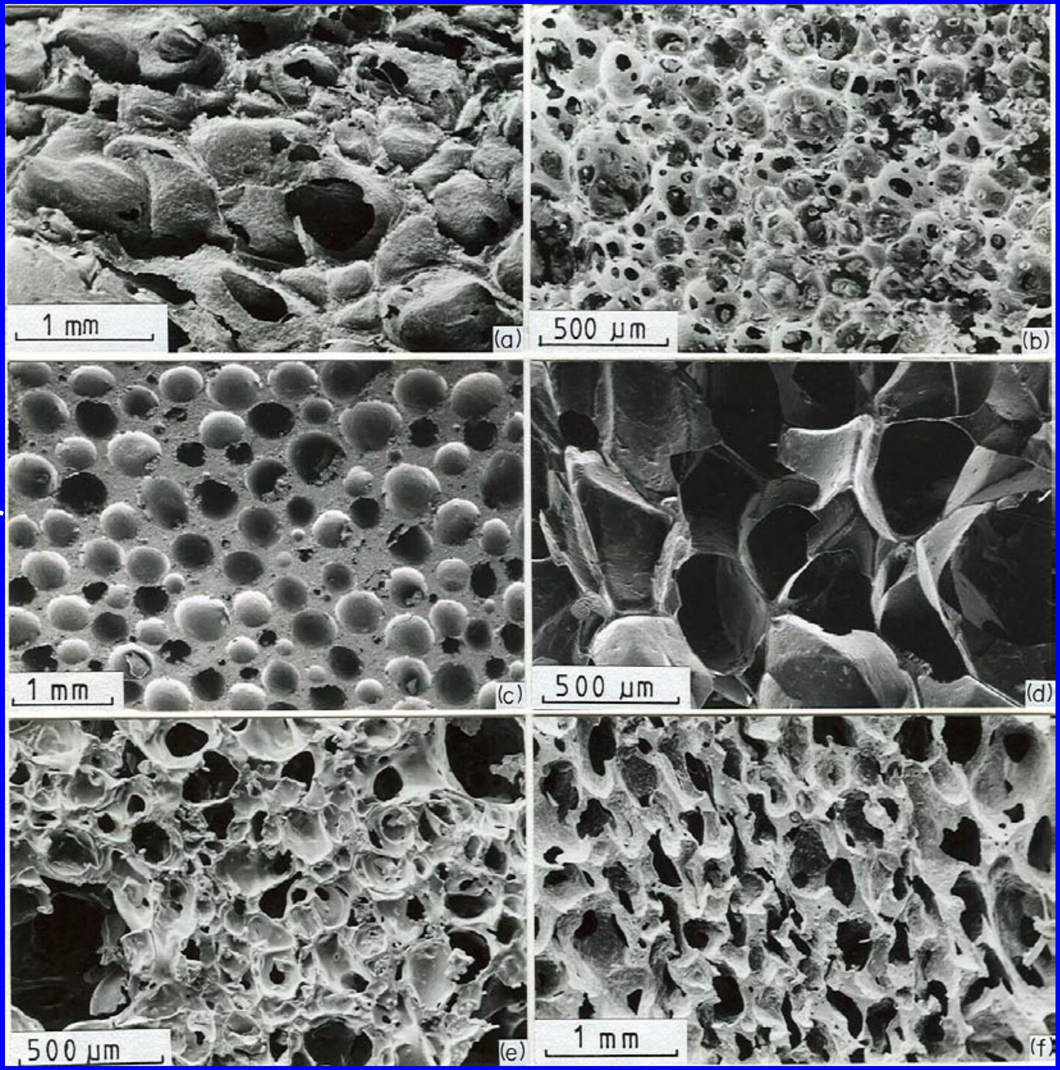
Meringue

Aero chocolate bar

Potato chip

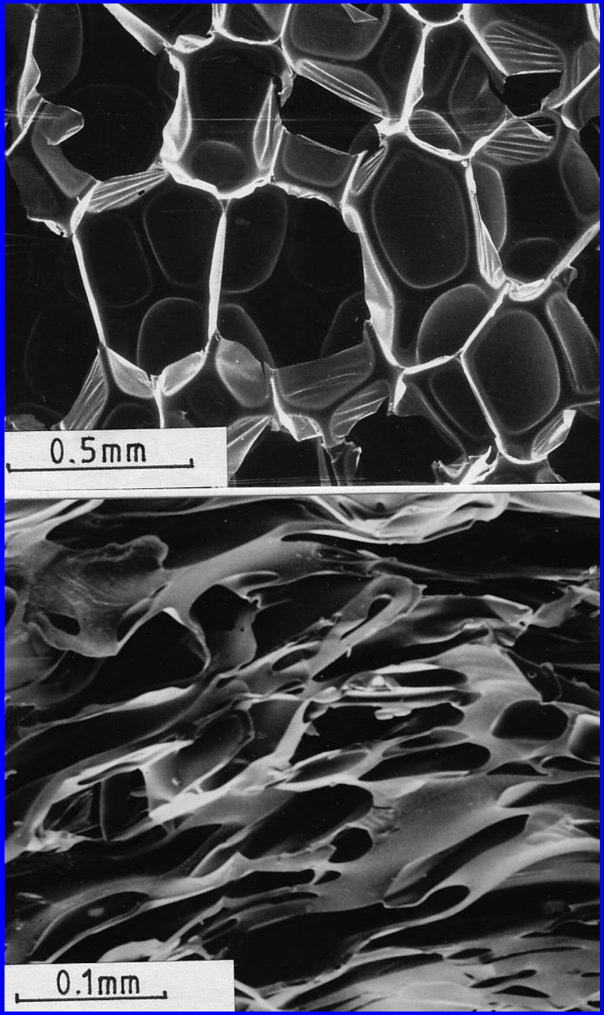
Malteser

Jaffa cake



Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press. © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

Anisotropy

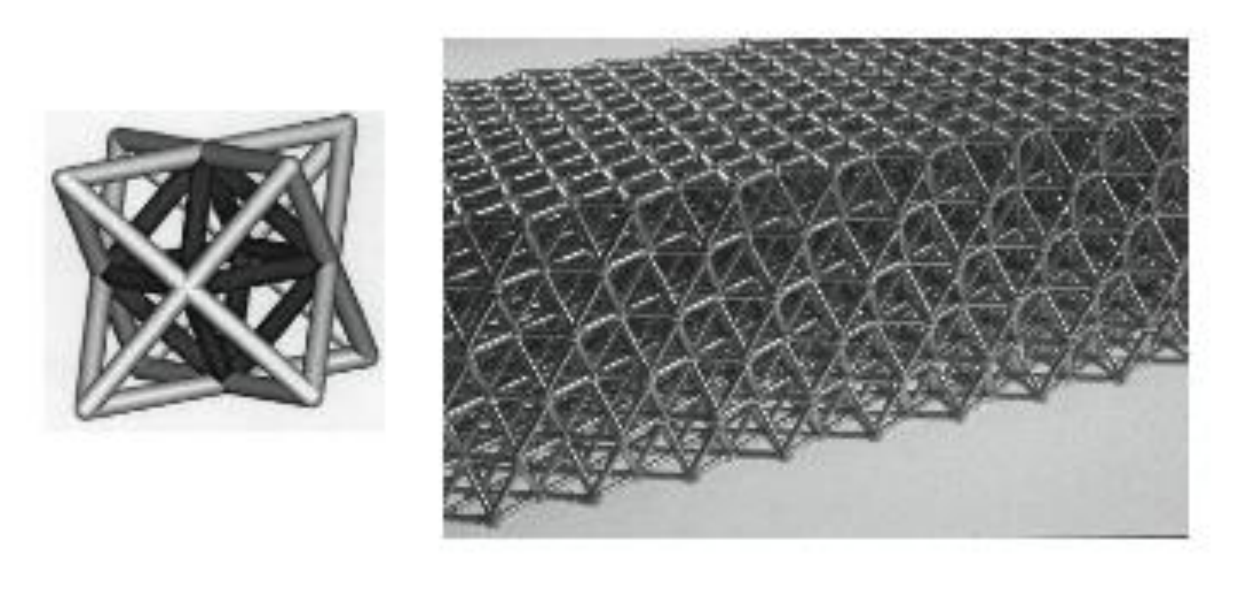


Polyurethane foam

Pumice

Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press. © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

3D Lattice Structures
3D Trusses



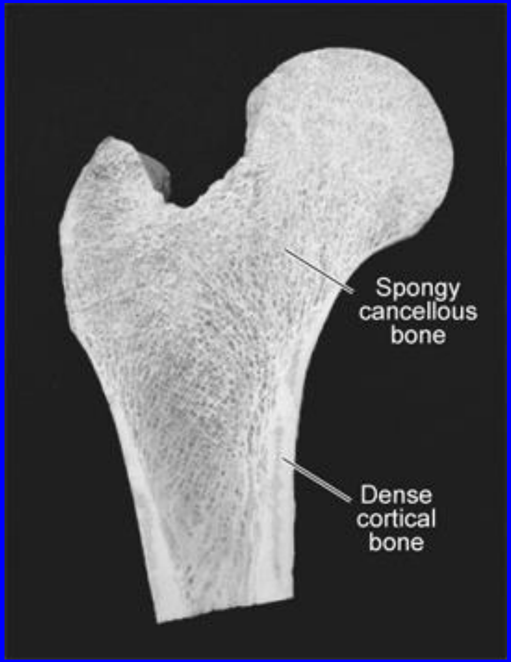
Triangulated structures: Trusses

Cellular Solids: Properties and Applications

- Low weight
  - structural sandwich panels, buoyancy devices
- Can undergo large deformations (80-90%) at roughly constant (low) stress
  - energy absorption devices (e.g. helmets)
- Low thermal conductivity
  - insulation
- Large surface area
  - carriers for catalysts (e.g. catalytic converters)

Cellular Materials in Medicine

Trabecular Bone



Femoral head

Tibia

Vertebral body

Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press. © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

Trabecular Bone: Osteoporosis

Figure removed due to copyright restrictions. See Figure 1: Vajjhala, S., A. M. Kraynik, et al. "A Cellular Solid Model for Modulus Reduction due to Resorption of Trabecular Bone." *Journal Biomedical Engineering* 122 (2000): 511–15.

Trabecular Bone: Microstructure

Images removed due to copyright restrictions.

1mm

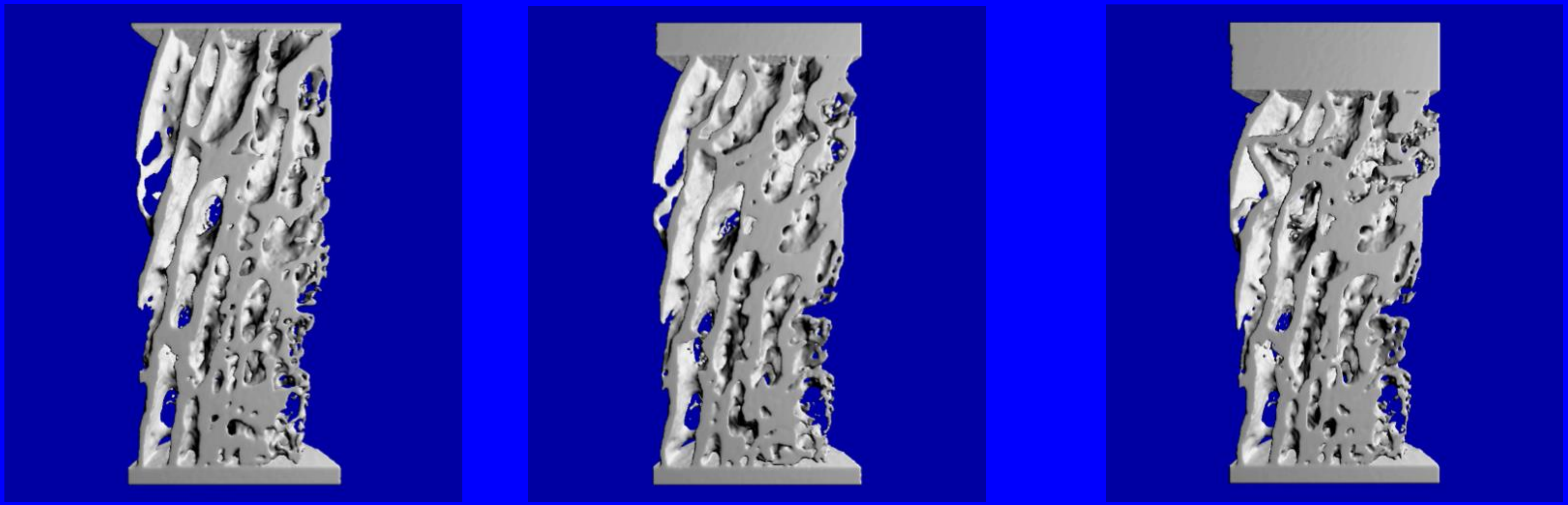
Lumbar spine
42 year old male
11.1% dense

Femoral head
37 year old male
25.6% dense

Lumbar spine
59 year old male
6.1% dense

Ralph Muller, ETH Zurich

Trabecular Bone: Deformation



$\varepsilon = 0\%$ 8% 16%

Source: Nazarian, A., and R. Müller. *Journal of Biomechanics* 37 (2004): 55-65. Courtesy of Elsevier. Used with permission.
http://www.sciencedirect.com/science/article/pii/S0021929003002549

Bending and buckling of whale vertebra

Nazarian and Muller (2004) J. Biomech. 37, 55.

Metal (Ti, Ta) Foams for Implant Coatings

Replica of polymer foam

Slurry infiltration of polymer foam, then heating

Fugitive phase method

Foaming agent

Argon gas expansion

Freeze-casting

Selective laser sintering

High temperature synthesis

(Sources in Cellular Solids in Nature and Medicine)

Tissue Engineering Scaffolds

Collagen based (freeze-drying)

Polymer (foaming)

Polymer (salt leaching)

Polymer (electrospinning)

Polymer (selective laser sintering)

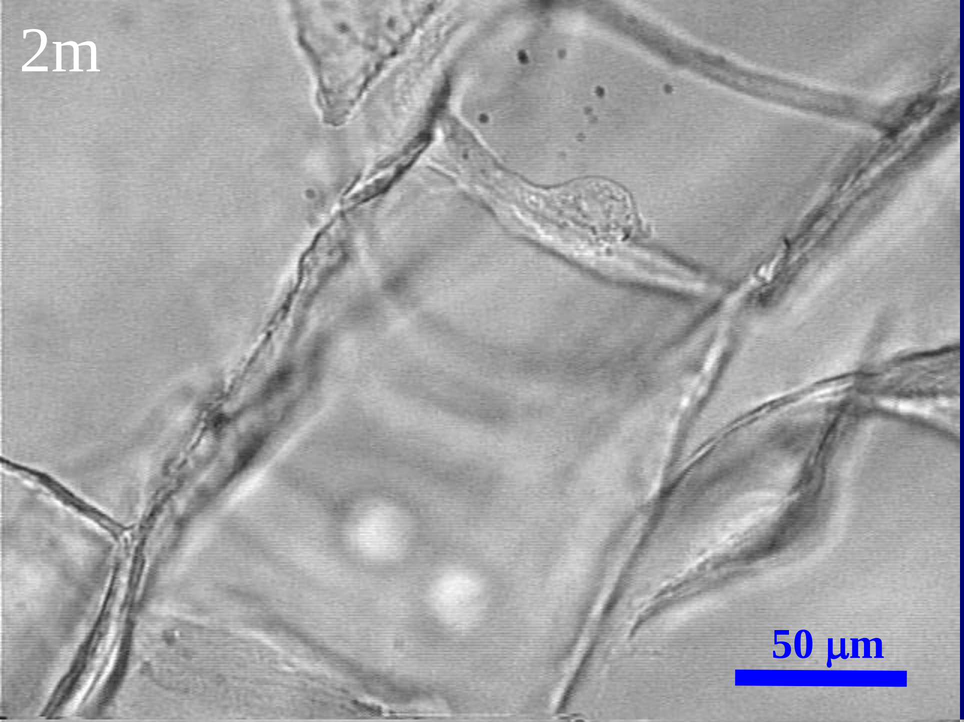
Acellular elastin (ECM with cells removed)

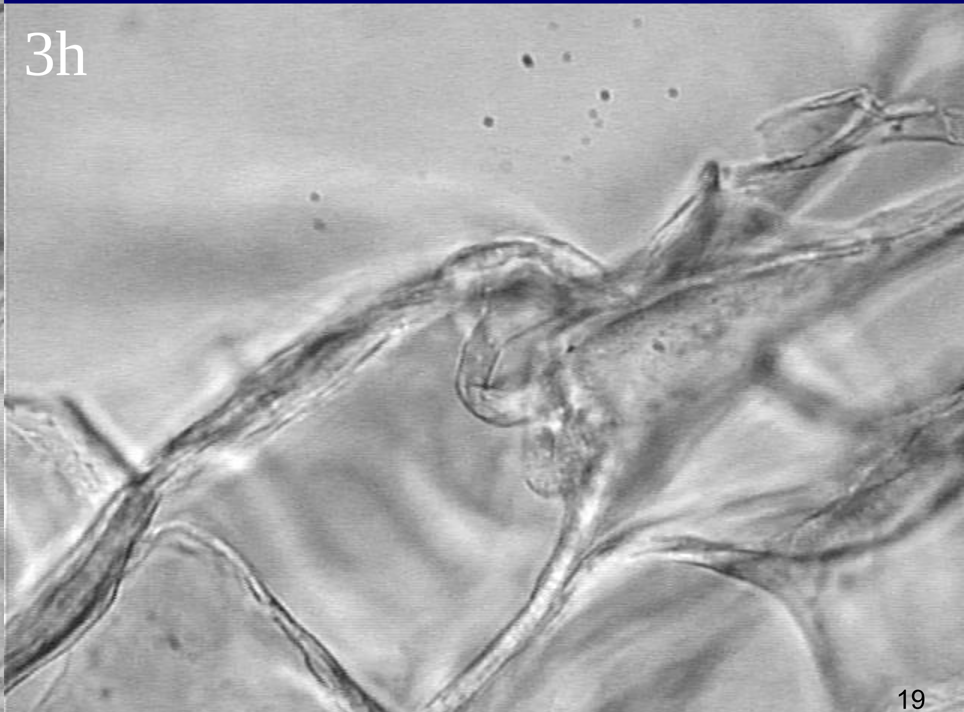
Acellular elastin (ECM with cells removed)

(Sources in Cellular Solids in Nature and Medicine)

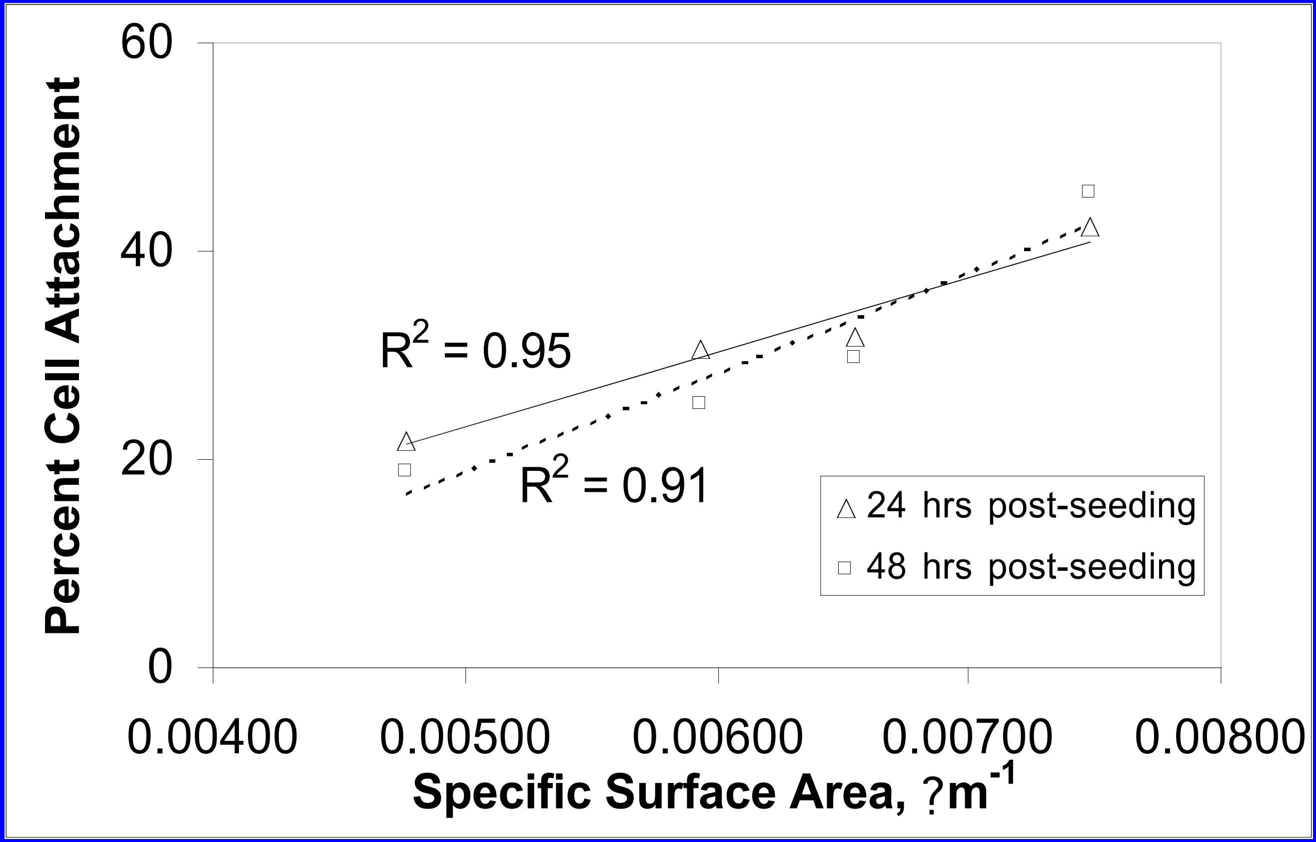
Cell Contraction of Scaffold

Freyman





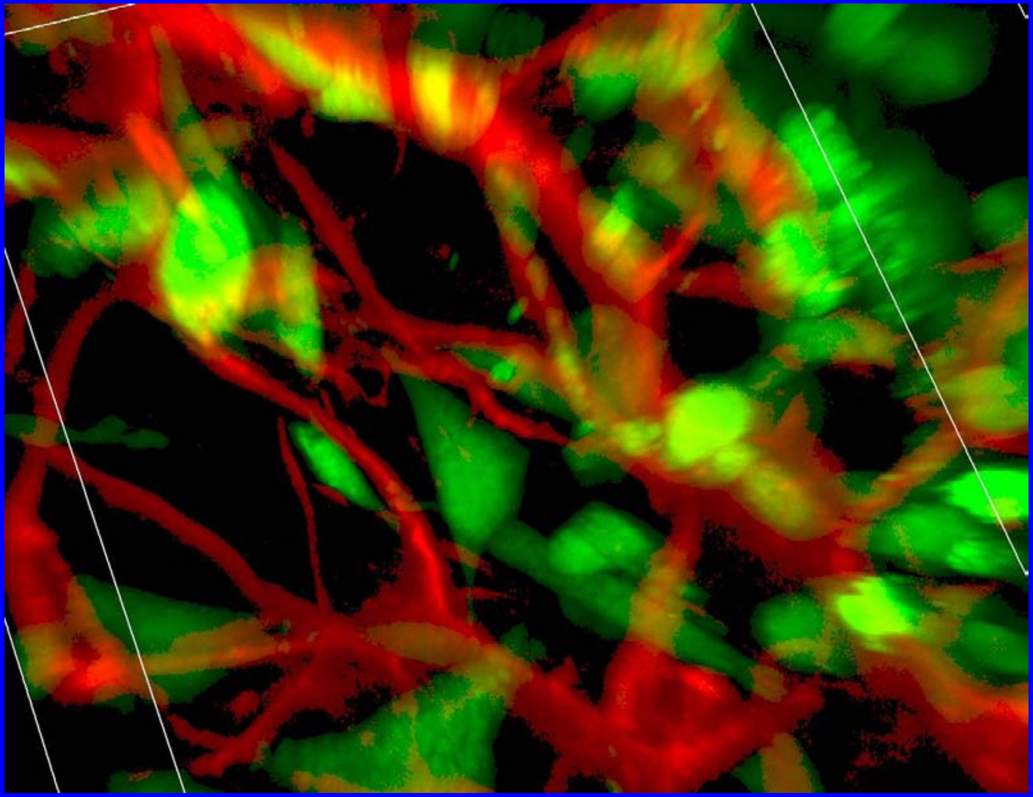
Cell Attachment



O'Brien, B. A. Harley, I. V. Yannas, et al. *Biomaterials* 26 (2005): 433-41. Courtesy of Elsevier. Used with permission.
http://www.sciencedirect.com/science/article/pii/S0142961204002017

Mouse MC3T3 osteogenic cells
(O' Brien)

Cell Migration: Fibroblasts in Scaffold



Courtesy of Brendan Harley. Used with permission.

Confocal Microscopy

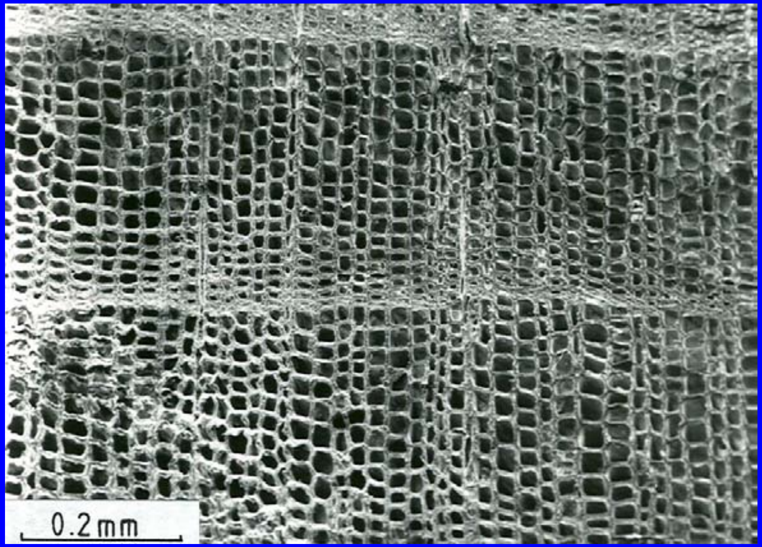
NR6 Fibroblasts
CMFDA Live Cell Tracker

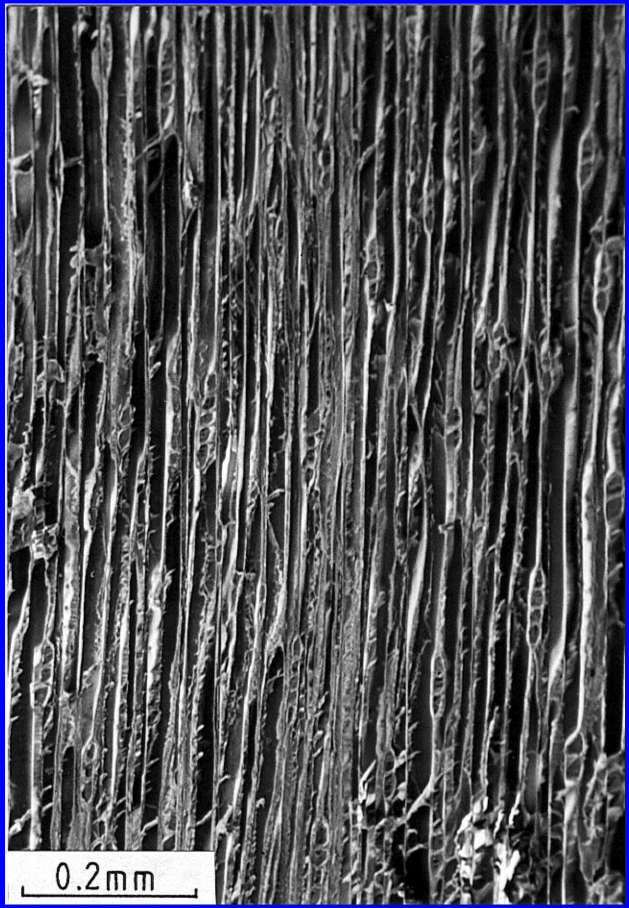
CG Scaffold
Alexa Fluor 633 Stain

Harley

Cellular Materials in Nature

Wood





Cedar

Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press. © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

Wood

Figure removed due to copyright restrictions. See Figure 7: Easterling, K. E., R. Harrysson, et al. "On the Mechanics of Balsa and Other Woods." *Proceedings of the Royal Society A* 383 (1982): 31-41.

Wood

Image removed due to copyright restrictions. See Figure 5.14: Dinwoodie, J. M. *Timber: Its Nature and Behaviour.* Van Nostrand Reinhold, 1981.

Images removed due to copyright restrictions. See Figures 1, 3: Kučera, L. J., and M. Bariska. "On the Fracture Morphology in Wood." *Wood Science and Technology* 16 (1982): 241-59.

From Dinwoodie (1981) and Bariska and Kucera (1982)

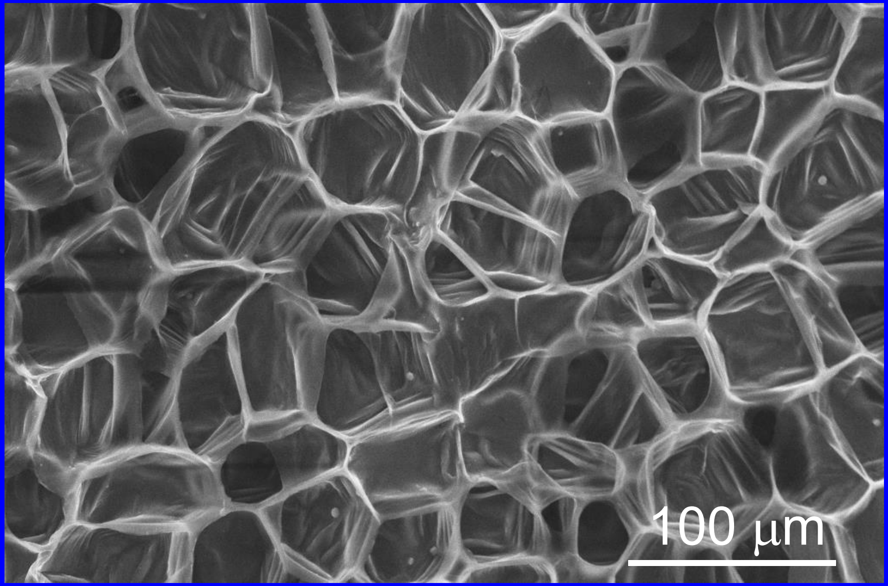
Cork

Images removed due to copyright restrictions. See Figure 5: Gibson, L. J., K. E. Easterling, et al. "The Structure and Mechanics of Cork." *Proceedings of the Royal Society A*377 (1981): 99-117.

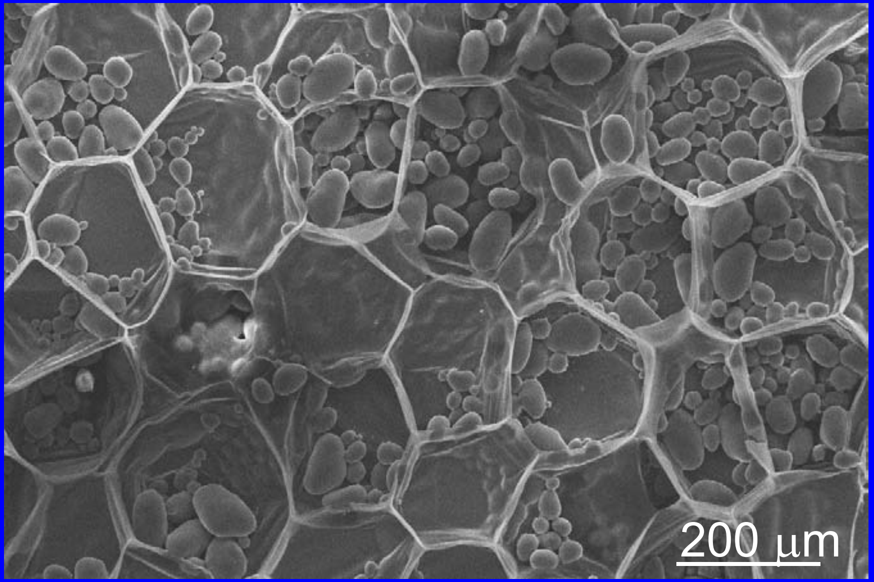
Cork

Images removed due to copyright restrictions. See Figure 11: Gibson, L. J., K. E. Easterling, et al. "The Structure and Mechanics of Cork." *Proceedings of the Royal Society A* 377 (1981): 99-117.

Plant Parenchyma: Liquid-Filled Closed-Cell Foam



Carrot



Potato

Venus Flower Basket Sponge

Image removed due to copyright restrictions. See Figure 1a: Aizenberg, J., et al. *Science* 309 (2005): 275-78.
http://chemstone.net/Materials/Sponge.htm

Cellular/Solid Structures in Nature

- Sandwich structures
- Density gradient structures
- Tubes with cellular core

Sandwich Structures: Leaves

Sandwich Structures: Bird Skulls

Sandwich Structures: Horseshoe Crab

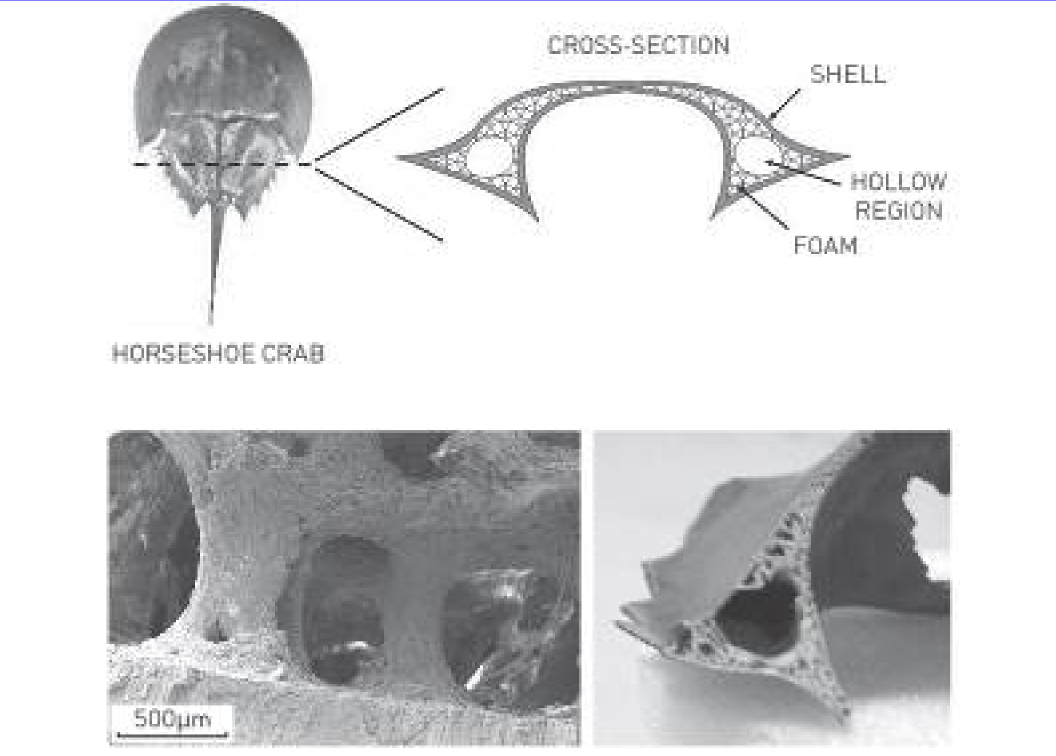


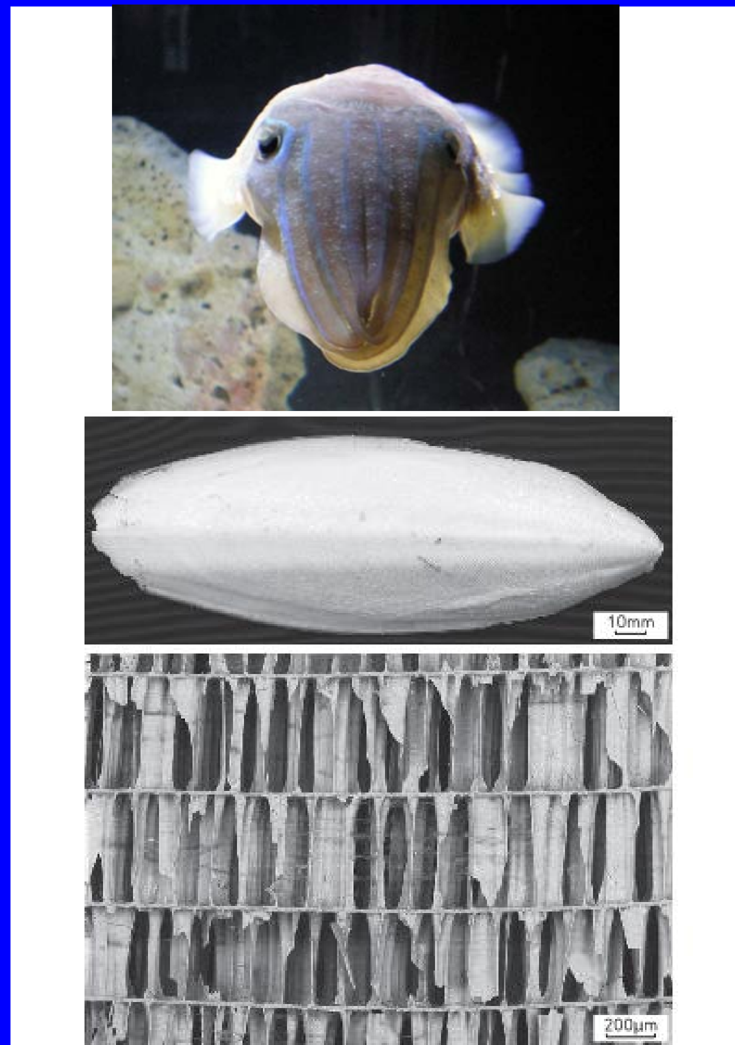
Figure 148: M. A. Meyers, P.-Y. Chen, et al. *Progress in Materials Science* 53 (2008): 1–206.

http://www.sciencedirect.com/science/article/pii/S0079642507000254

From Meyers et al. (2008)

Sandwich Structures: Cuttlefish Bone

Image is in the public domain.
Source: Wikimedia Commons.



Radial Density Gradient: Palm

- Stem has constant diameter: r = constant
- As palm grows taller, it increases the density of the material towards its periphery
- Cell wall thickness increases towards periphery of stem and towards the base of the stem E = E (r, z)

Coconut Palm
http://en.wikipedia.org/wiki/Image:Palmtree_Curacao.jpg

Radial Density Gradient: Palm

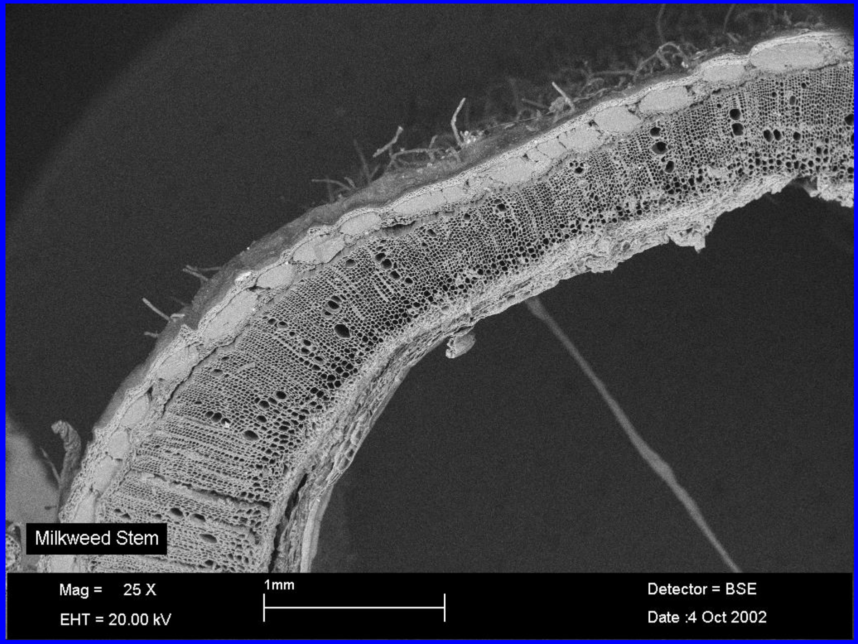
Images removed due to copyright restrictions. See Figures 22 and 23: Rich, P. M. *Am. Journal of Botany* 74 (1987): 792-802.
http://www.jstor.org/discover/10.2307/2443860

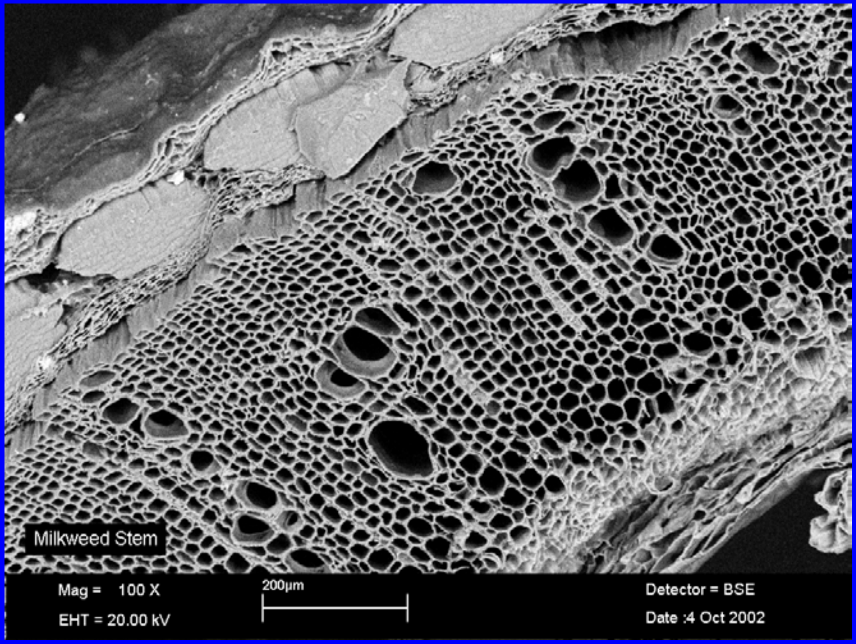
Figures removed due to copyright restrictions. See Figure 1e, f: Kuo-Huang, L. -L., et al. IAWA J. 25 (2004): 297-310.
http://booksandjournals.brillonline.com/content/journals/10.1163/22941932-90000367

Radial Density Gradient: Bamboo

Figure removed due to copyright restrictions. See Figure 6b: Gibson, L. J., et al. *Proceedings of the Royal Society A* 450 (1995): 141-65.

Cylindrical Shell with Compliant Core: Plant Stems

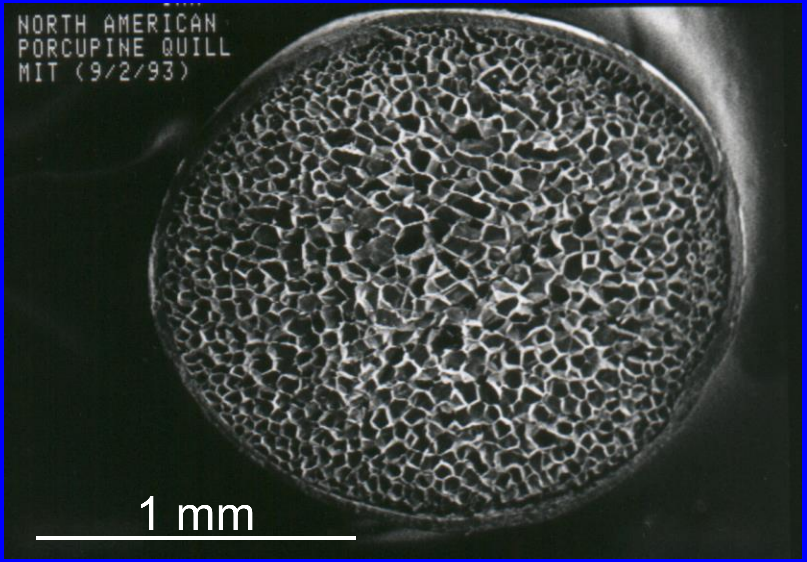




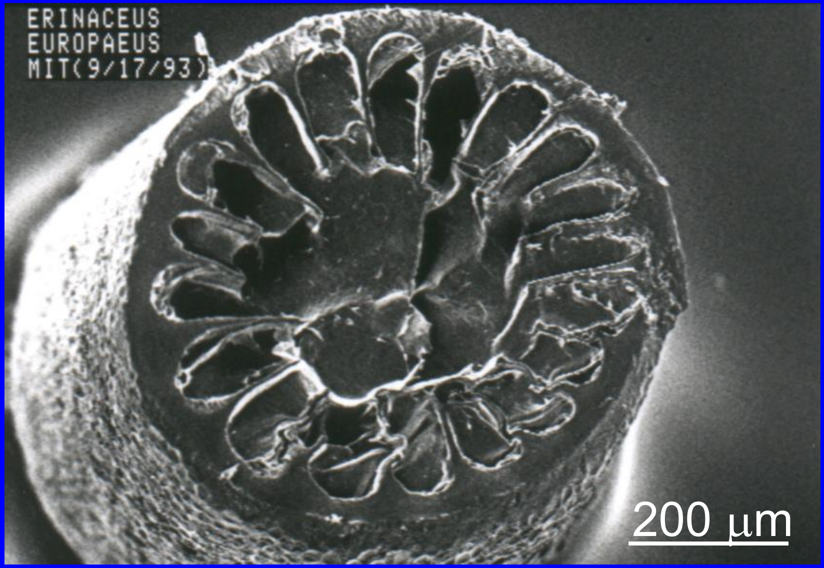
Milkweed

Gibson, L. J., M. Ashby, et al. *Cellular Materials in Nature and Medicine*. Cambridge University Press, © 2010. Figure courtesy of Lorna Gibson and Cambridge University Press.

Cylindrical Shell with Compliant Core: Animal Quills



Porcupine



Hedgehog

Source: Karam, G. N., and L. J. Gibson. *International Journal of Solids and Structures* 32 (1995): 1259-83.

http://www.sciencedirect.com/science/article/pii/002076839400147O

Acknowledgements

- Mike Ashby, Ken Easterling, Hugh Shercliff, Tom McMahon, Toby Hayes, Brendan Harley

- Ed Guo, Matt Silva, Surekha Vajjhala, Phoebe Cheng, Gebran Karam, Toby Freyman, Brendan Harley,Fergal O'Brien, Biraja Kanungo, Matt Dawson, Tessa Shercliff, Ros Olive, Ulrike Wegst

- Figures: Justin Breucop, Don Galler, Beth Beighlie

- Financial support: NSF, NIH, Salapatas Professorship at MIT