01.110: Computational Fabrication

Week 7: Advanced materials

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Acknowledgement
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Established in collaboration with MIT

Learning Objectives

- Smart materials
- Advanced materials
  - Cellular materials
    - Metamaterials
  - Composite materials
    - Piezoelectric composites
    - Functionally graded materials
    - Robotic materials
  - Biomimetic/Bio-inspired materials
  - Materials with structural hierarchy

Types Of Materials

MATERIALS

- **Wood**
- **Metals**
- **Polymers**
- **Ceramics**
- **?**

Smart materials

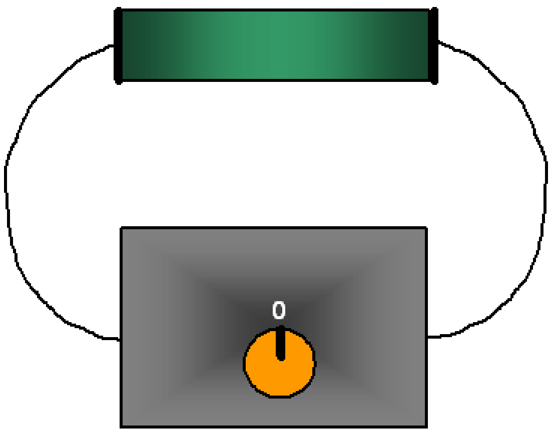
Input \ Output	Strain	Electric charge	Magnetic flux	Temperature	Light
Stress	Elasticity	Piezo-electricity	Magneto-striction		Photo-elasticity
Electric field	Piezo-electricity	Permittivity			Electro-optic effect
Magnetic field	Magneto-striction	Magneto-electric effect	Permeability		Magneto-optic
Heat	Thermal expansion	Pyro-electricity		Specific heat	
Light	Photostriction	Photo-voltaic effect			Refractive index

https://www.youtube.com/watch?v=_QwRsVyk7us

Catarina Mota: Play with smart materials

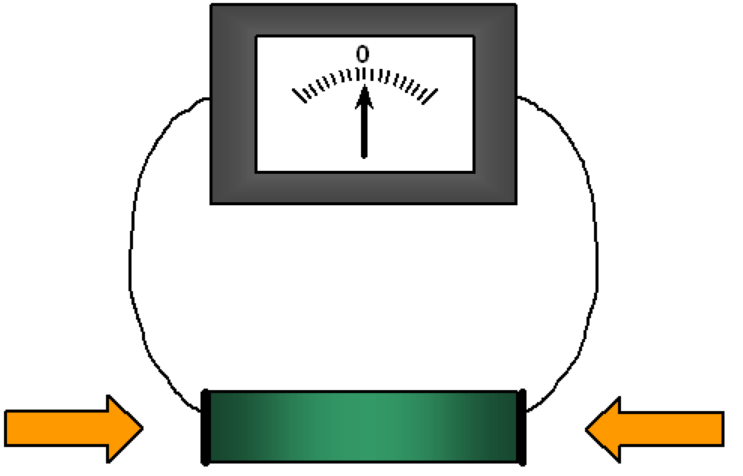
Piezoelectric Material

- Inverse piezo effect



(Actuating functions)

- Direct piezo effect



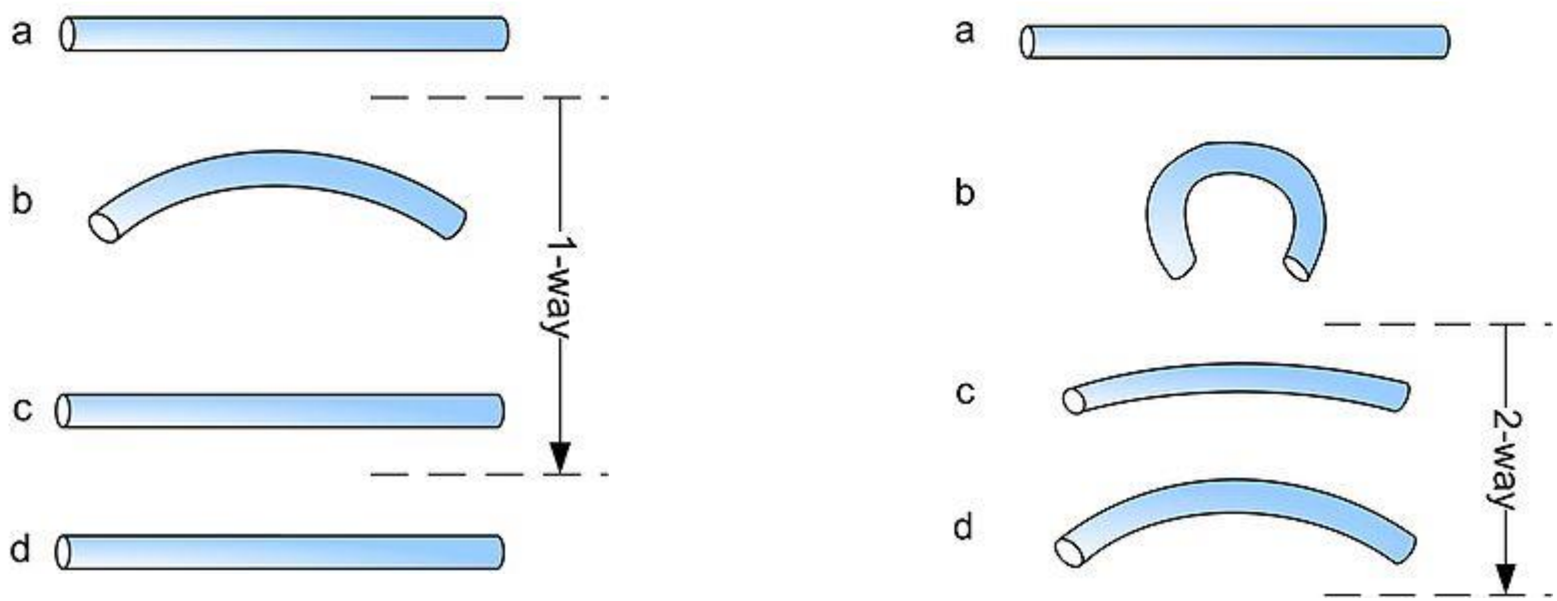
(Sensing functions)

Shape-memory alloy

- A shape-memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated.
- https://www.youtube.com/watch?v=QYp9rIJRM8s

Shape-memory alloy

- One-way vs. two-way shape memory



Smart materials

- Home Activity: choose a smart material, think how it works and cite two applications
- For example:
  - **Piezoelectric material**
  - **Magnetostrictive**
  - **Magneto-rheological**
  - Thermoelectric
  - Thermochronic
  - **Shape memory alloy**
  - Shape memory polymer
  - Dielectric elastomer
  - etc

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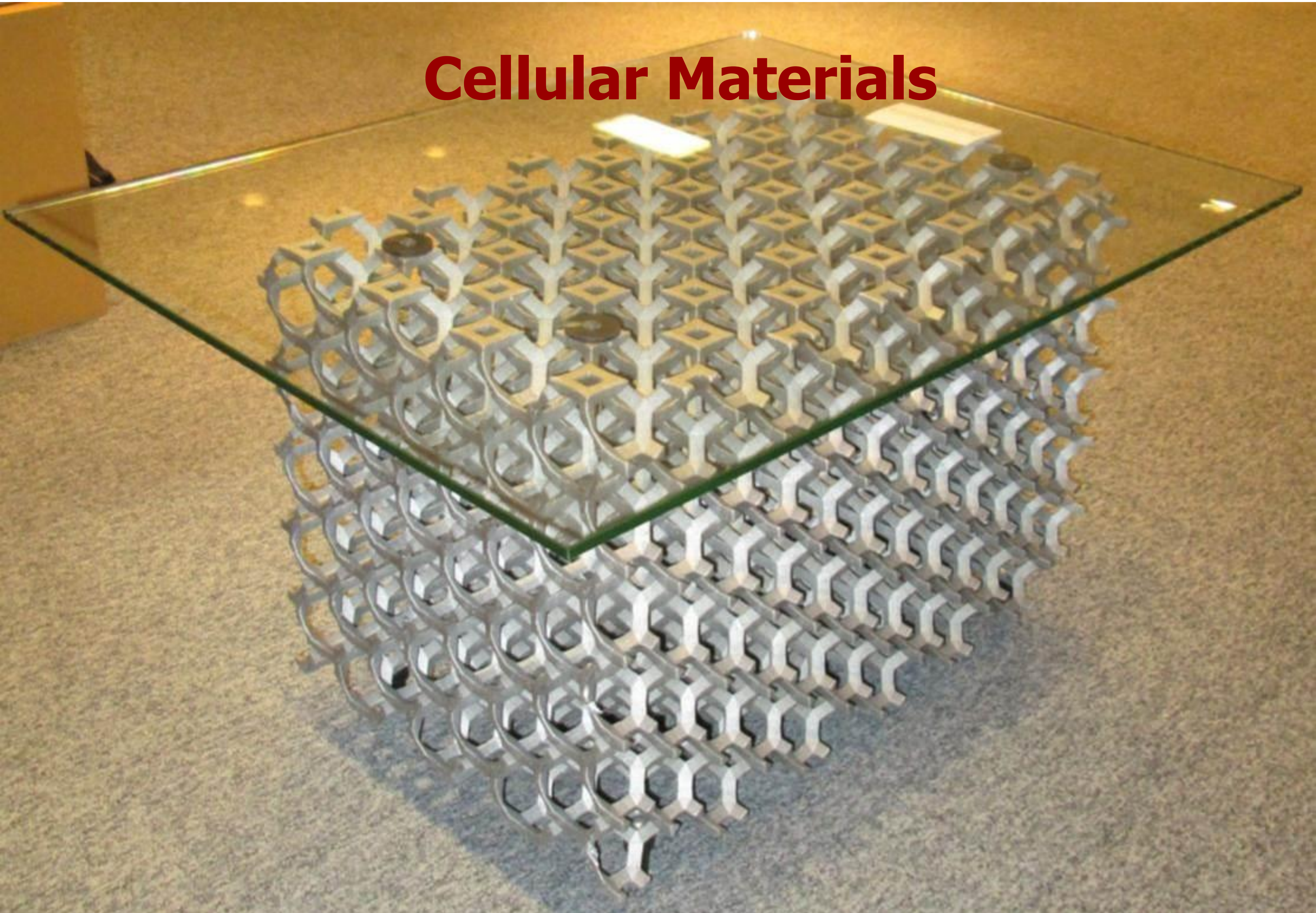
Cellular Materials



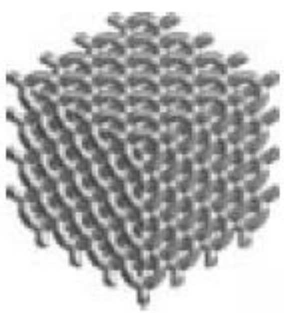
Cellular Materials

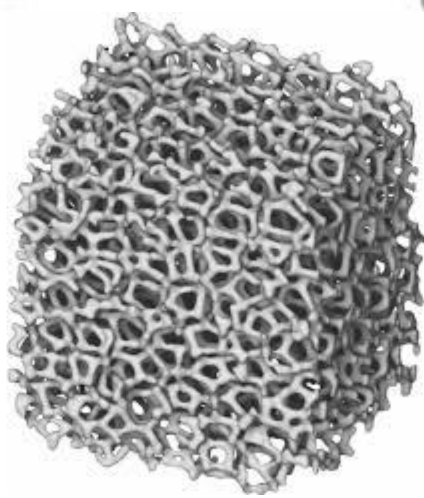
- What is the difference between Eiffel Tower and Washington Monument

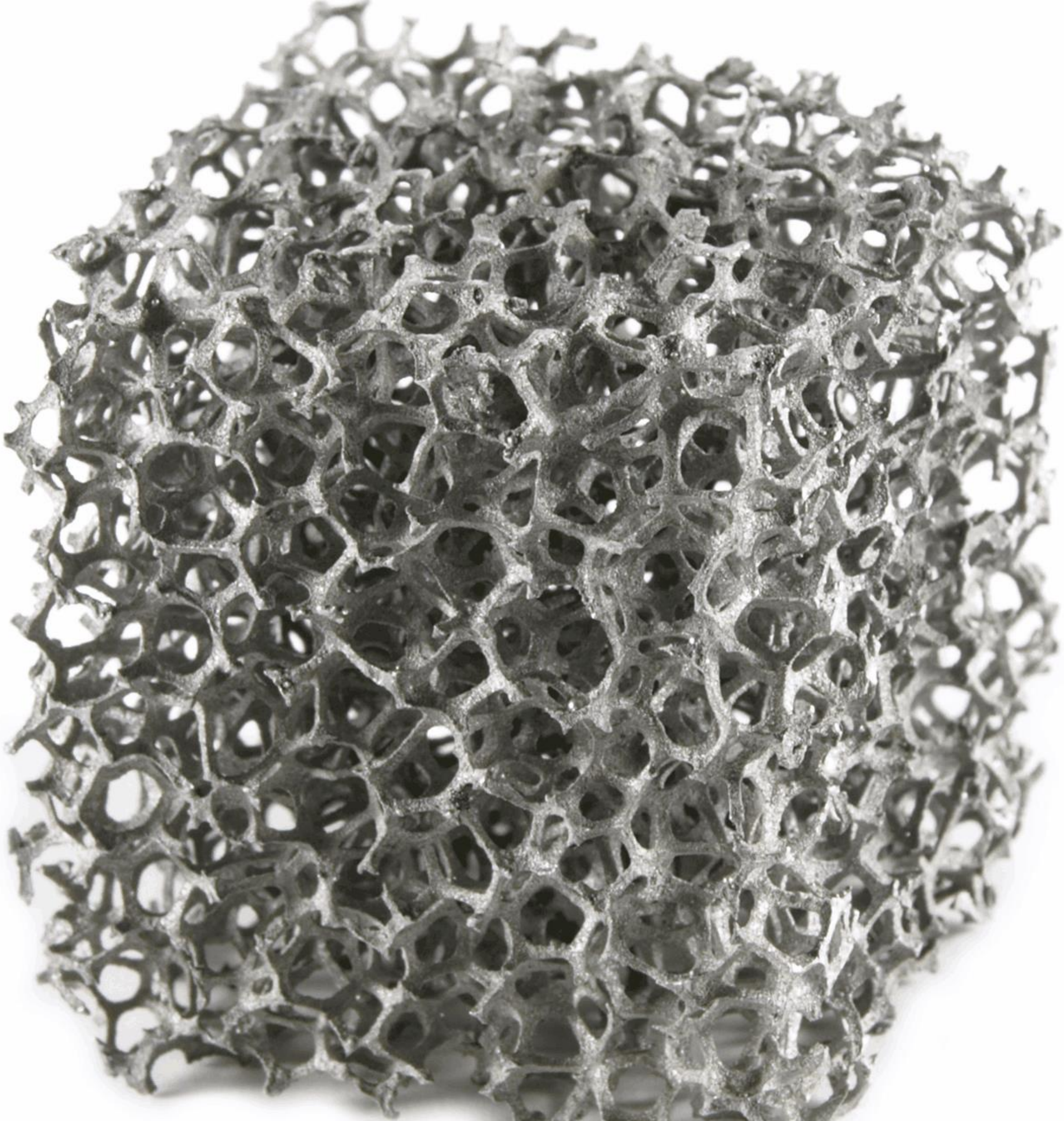
Home activity

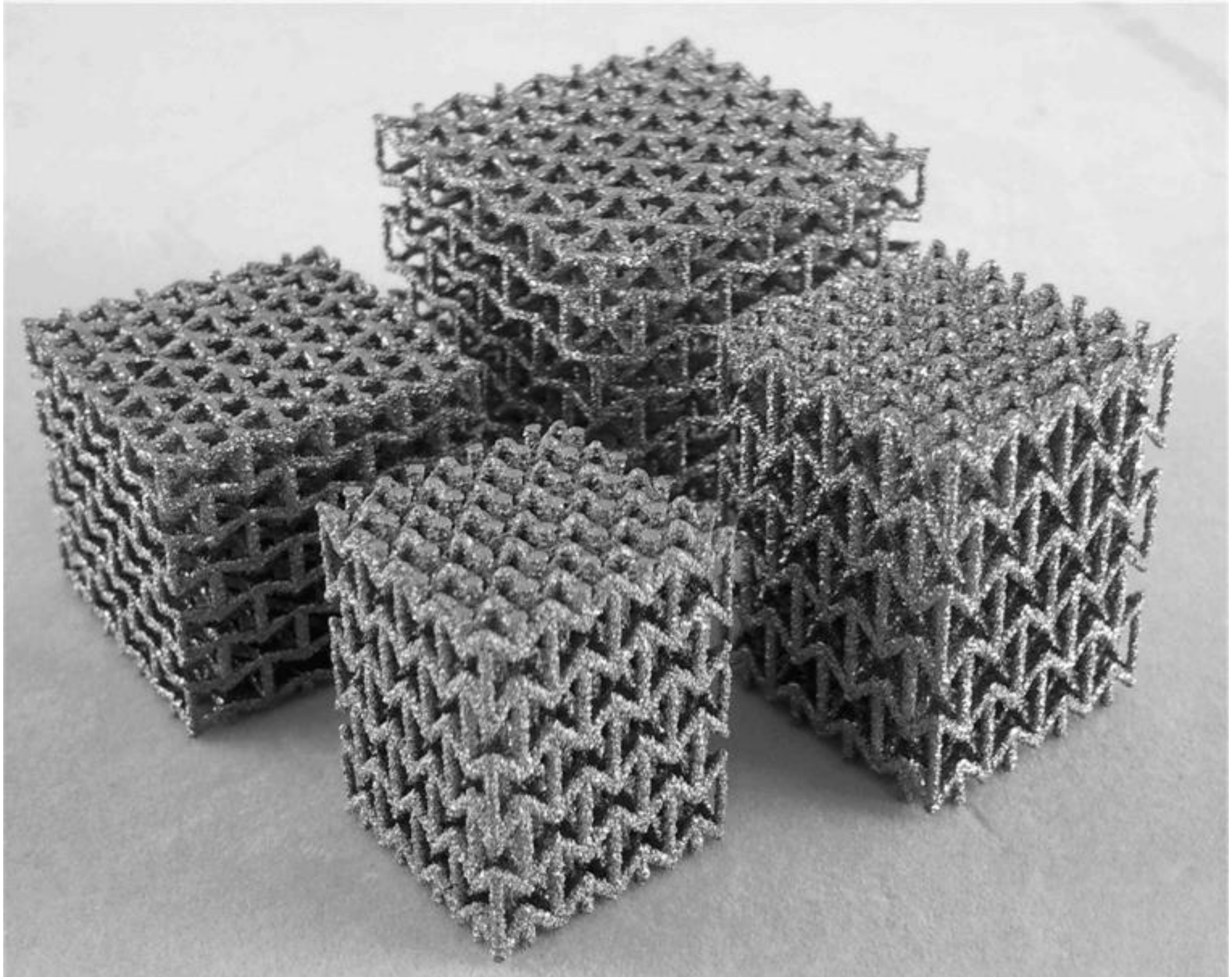
Cellular Materials

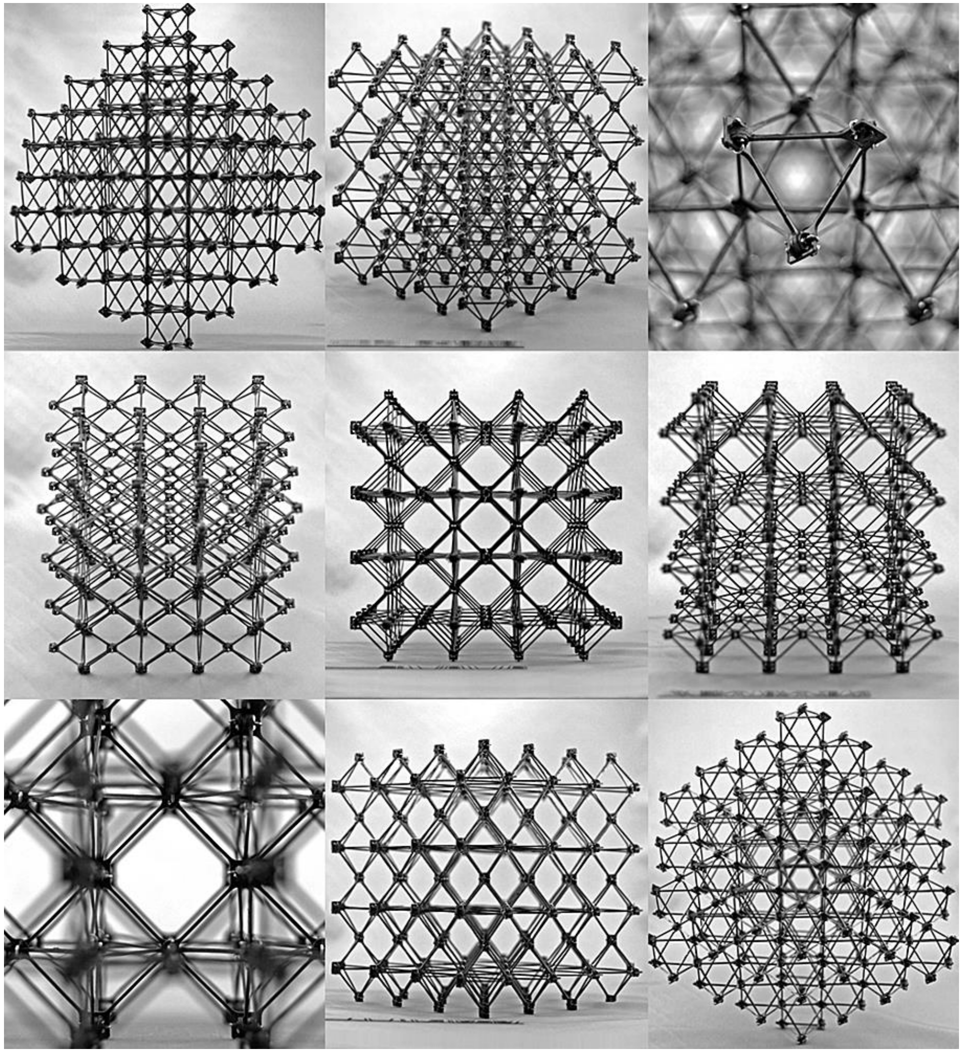
- **Cellular Materials** are any material that contains many cells (either open or closed, or both) dispersed throughout the mass.



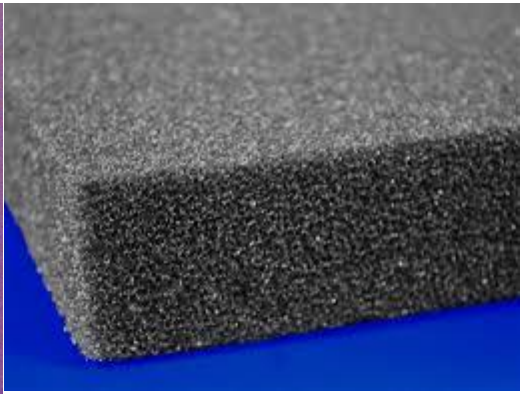








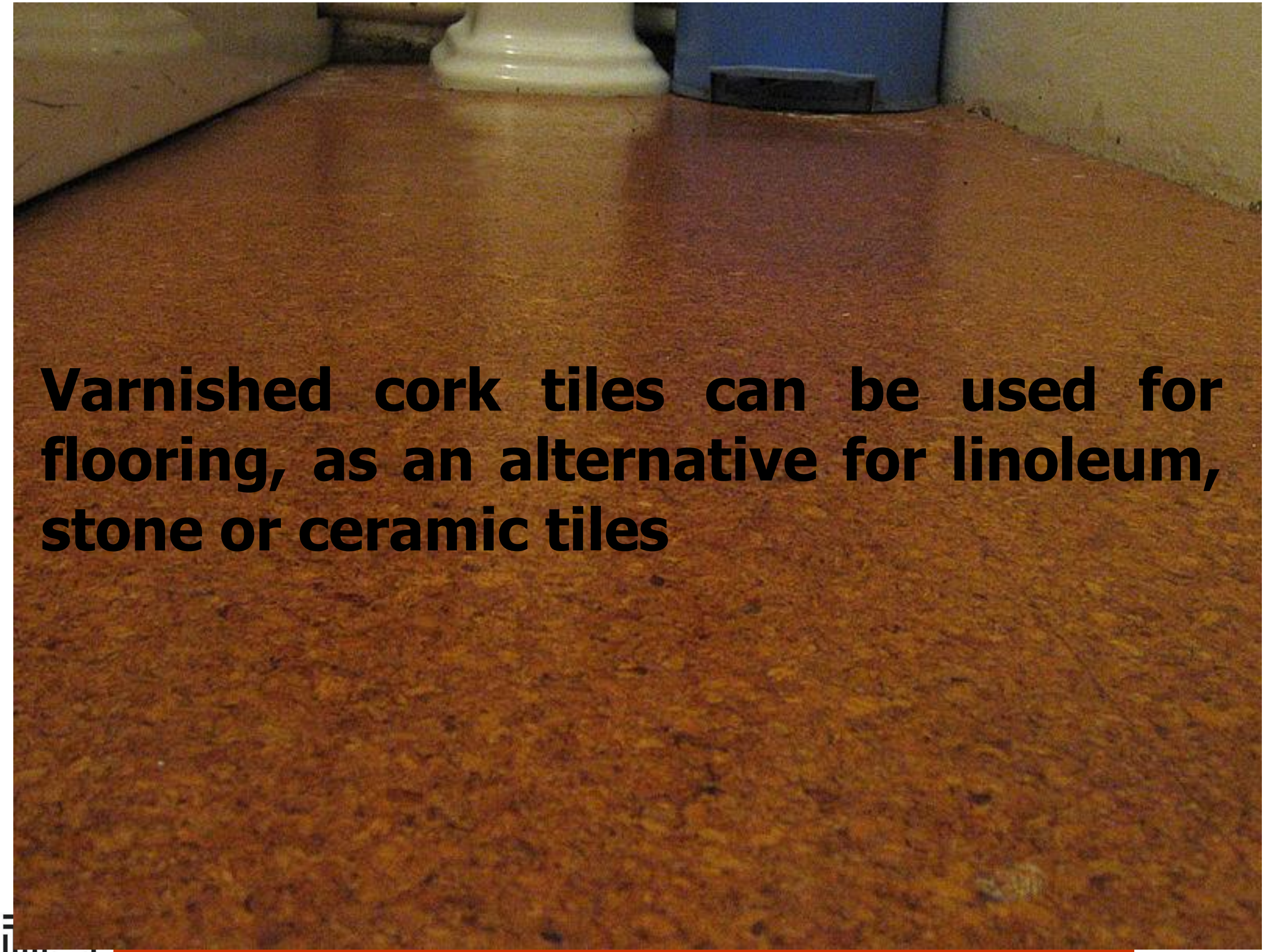
Examples of cellular materials



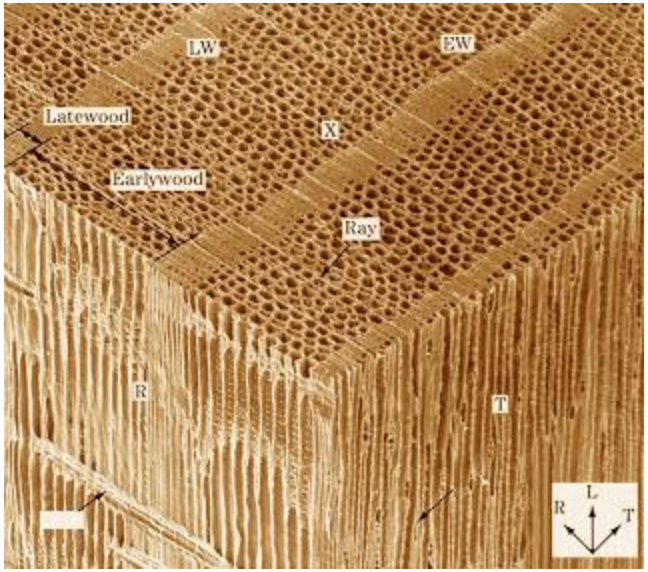
Examples of cellular materials

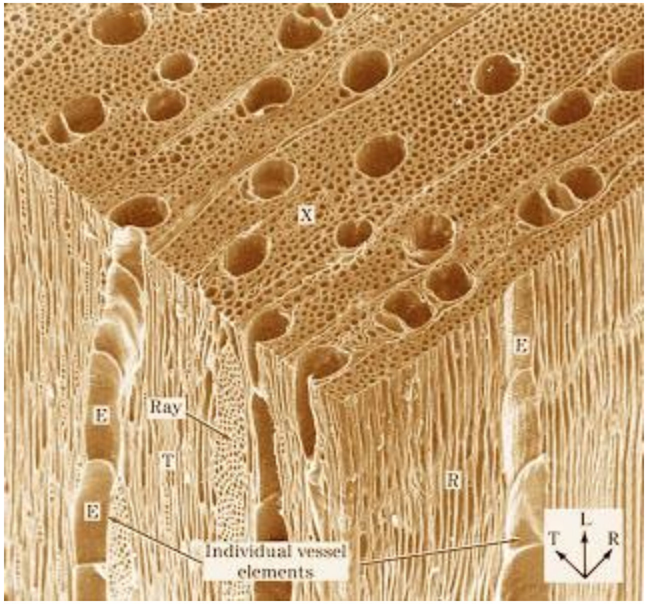
- Cork

Examples of cellular materials



Examples of cellular materials



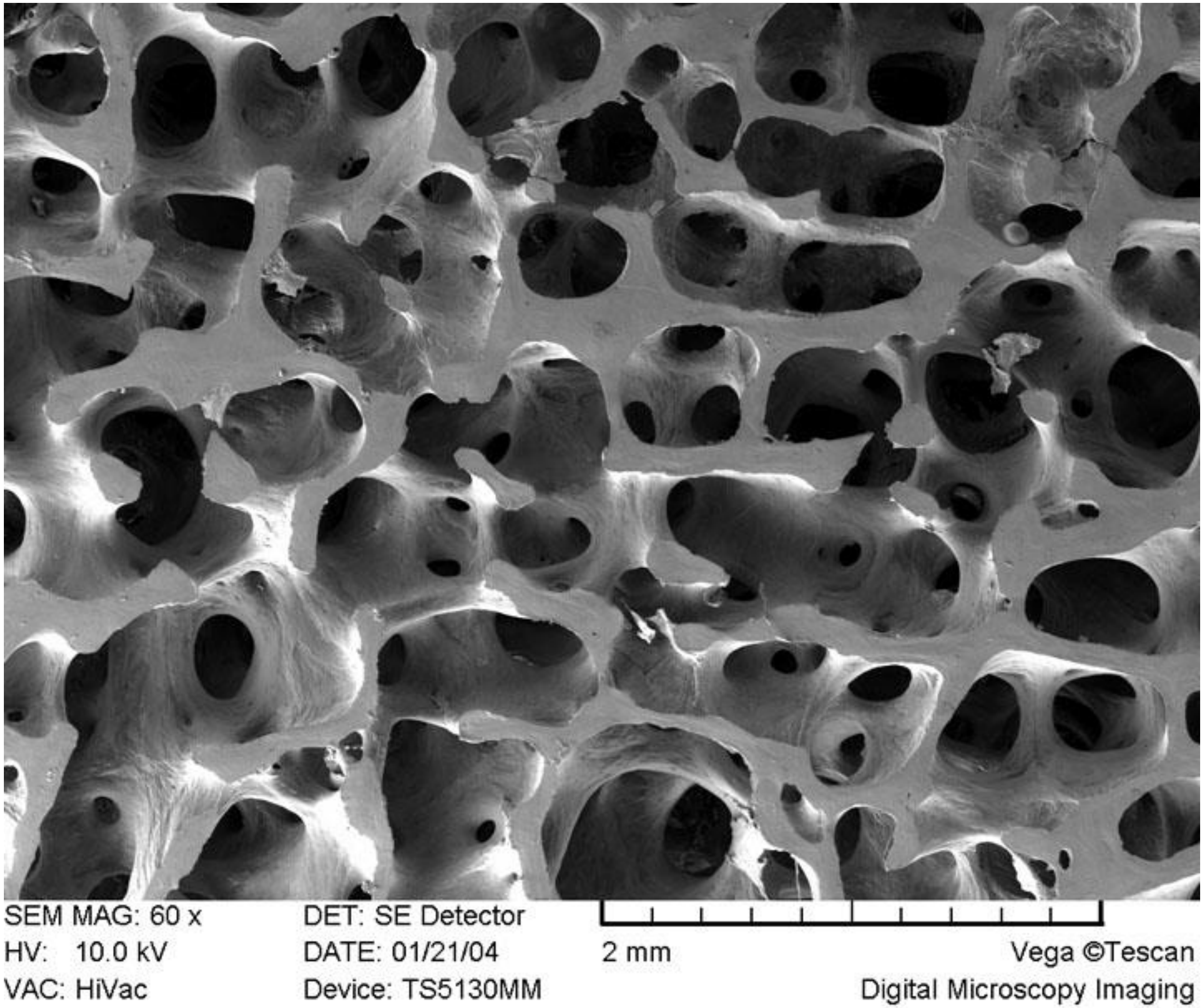


Wood under microscope

Examples of cellular materials

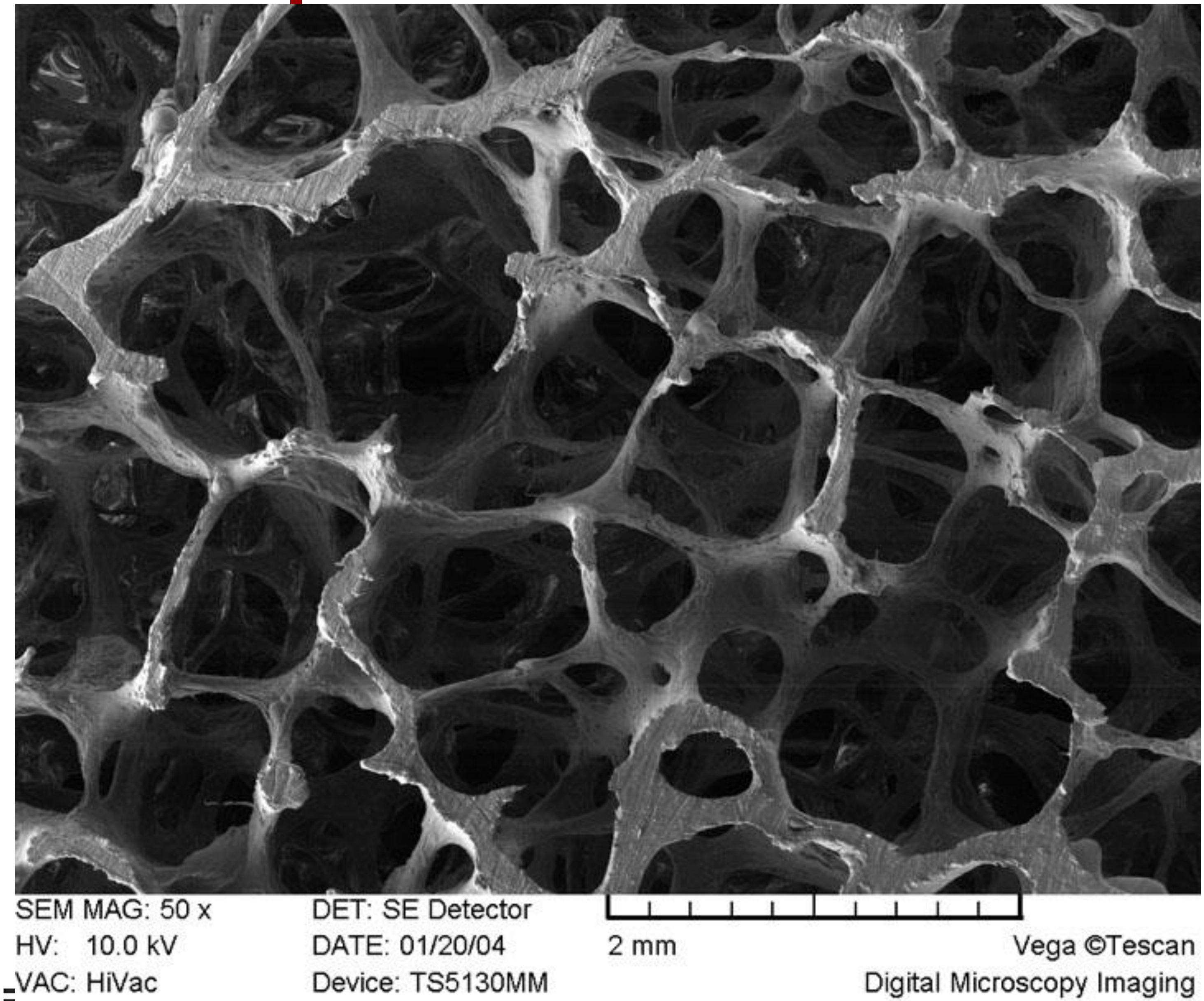
Human bones under microscope

Examples of cellular materials



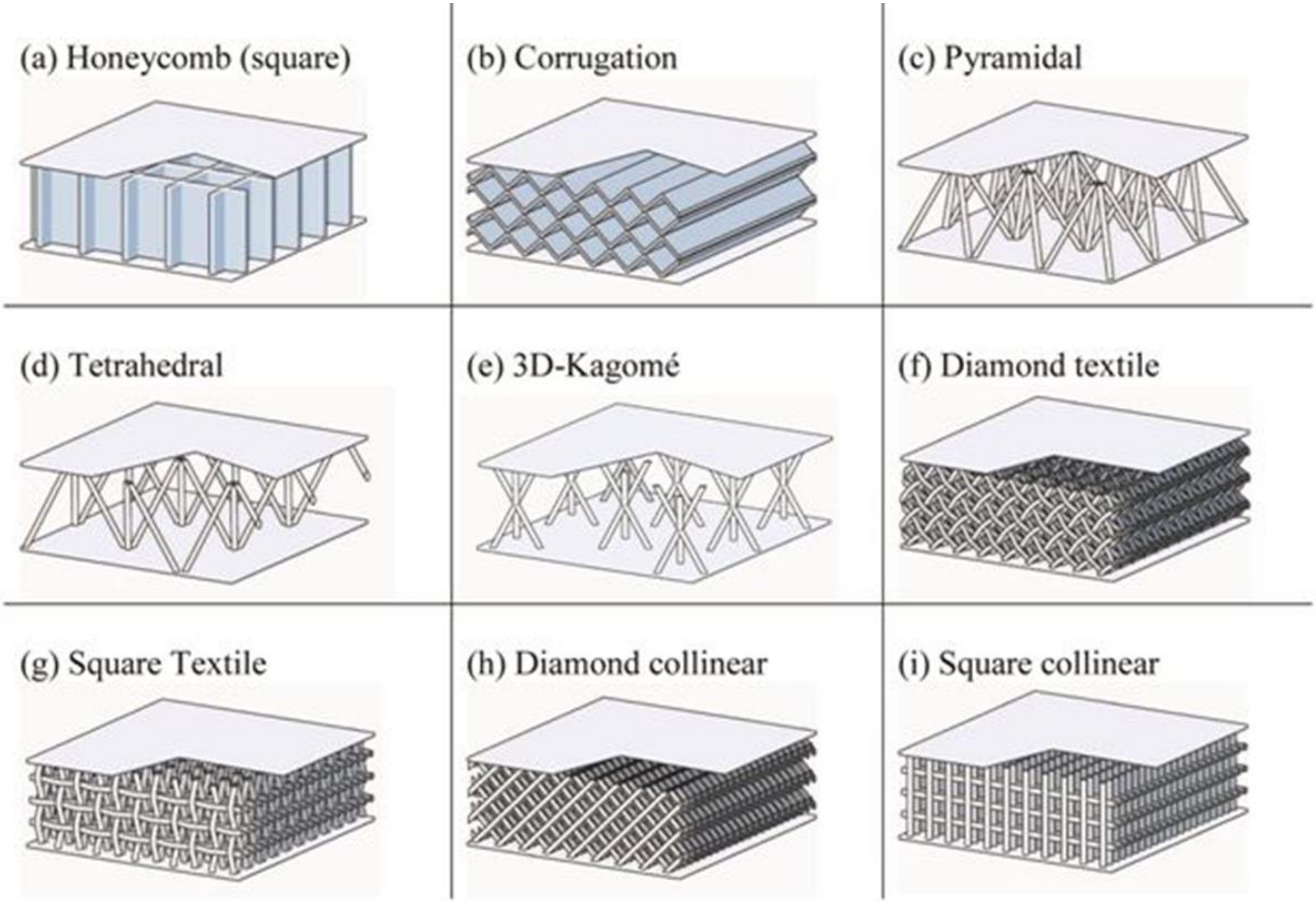
SEM of young (22-year old), male human bone

Examples of cellular materials



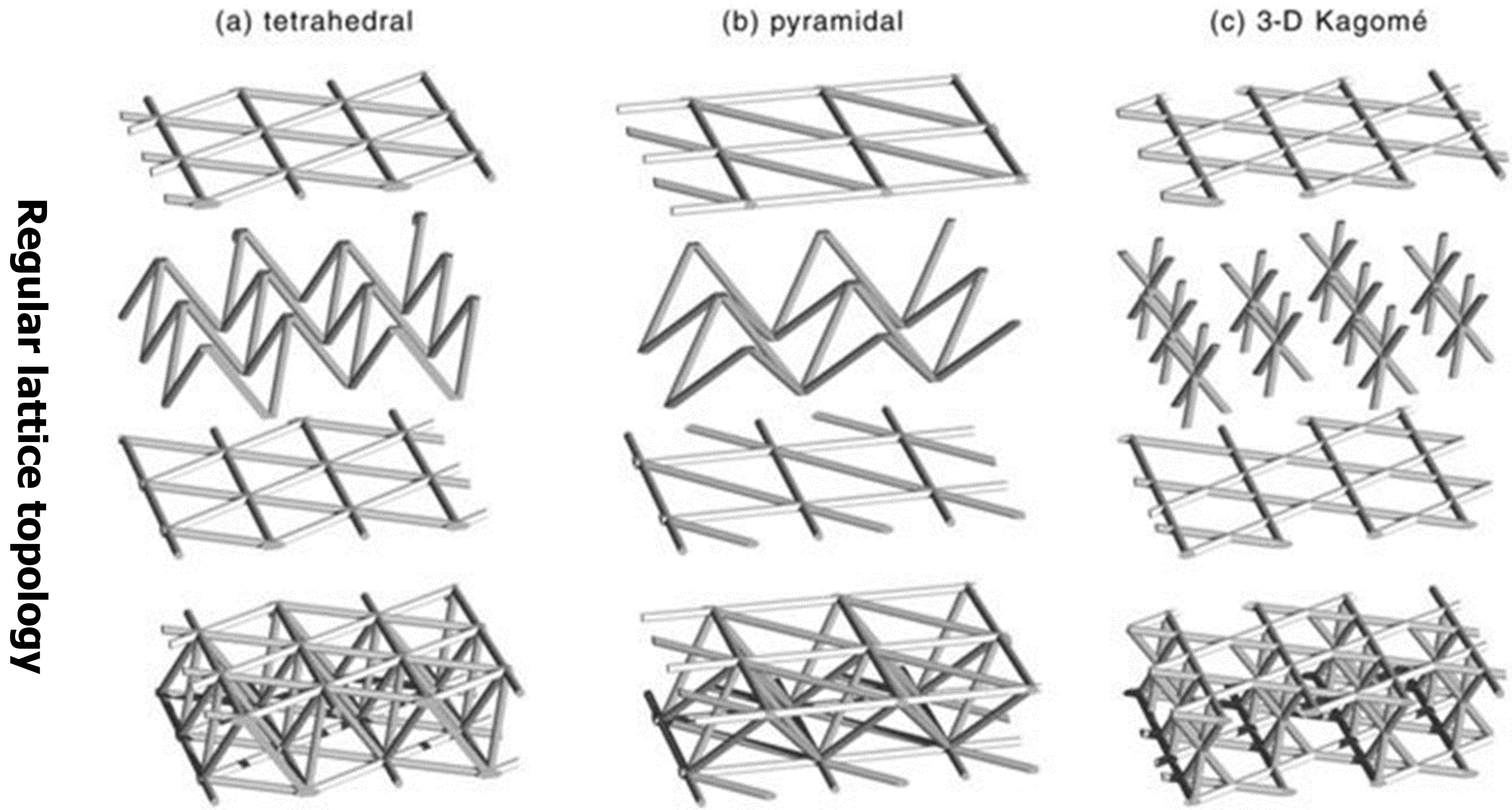
SEM of elderly bone (osteoporotic woman in her '80s)

Topologies of Cellular Lattices



Regular lattice topology

Topologies of Cellular Lattices



These structures pick-up applied stresses and efficiently resolve them onto the trusses whose in-plane displacement is restrained by interlayers of planar trusses.

http://www.fernandofraternaliresearch.com/research.asp?pg=3

Home activity

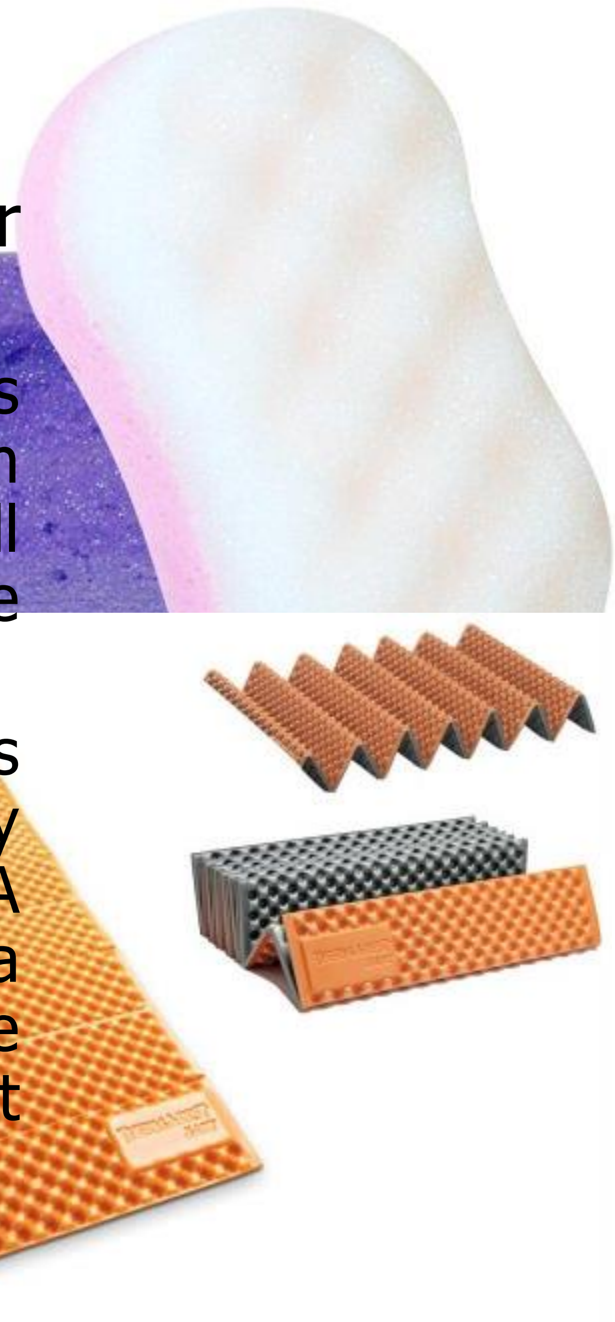
Solid foams

- A foam is a substance formed by trapping pockets of gas in a liquid or solid. A bath sponge and the head on a glass of beer are examples of foams. In most foams, the volume of gas is large, with thin films of liquid or solid separating the regions of gas.

Iregular foam structure

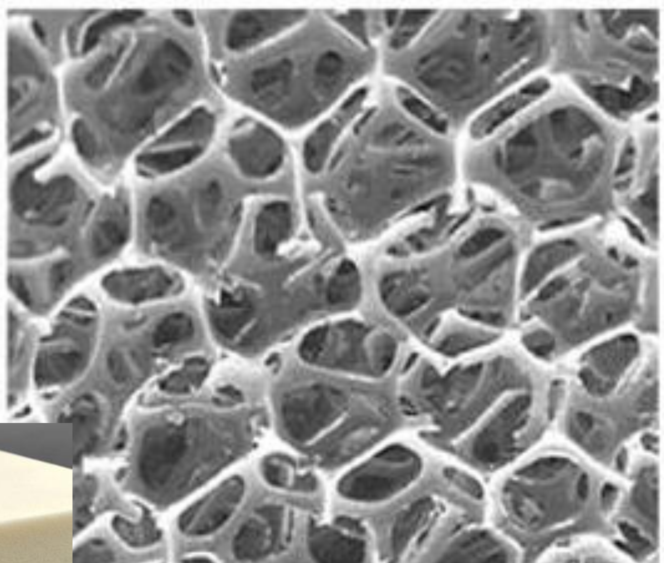
Solid foams

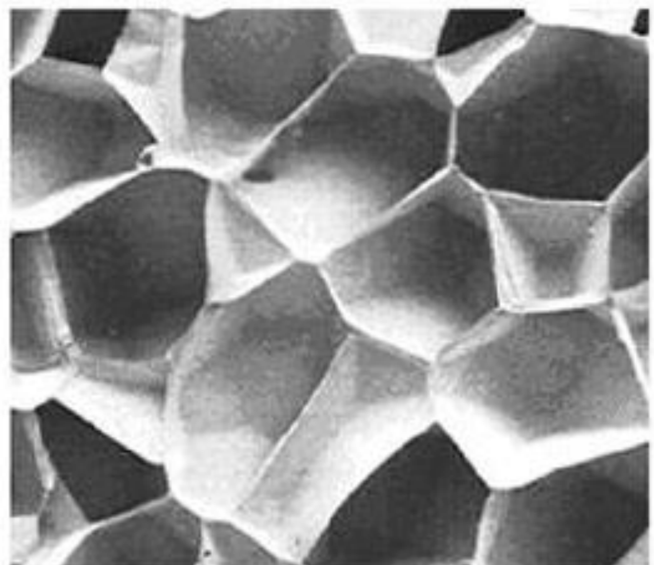
- **Solid foams** can be open-cell or closed-cell.
  - In open-cell foam, gas pockets connect to each other (A bath sponge is an example of an open-cell foam: water easily flows through the entire structure, displacing the air).
  - In closed-cell foam, the gas forms discrete pockets, each completely surrounded by the solid material (A sleeping mat is an example of a closed-cell foam: gas pockets are sealed from each other so the mat cannot soak up water).



Solid Foams

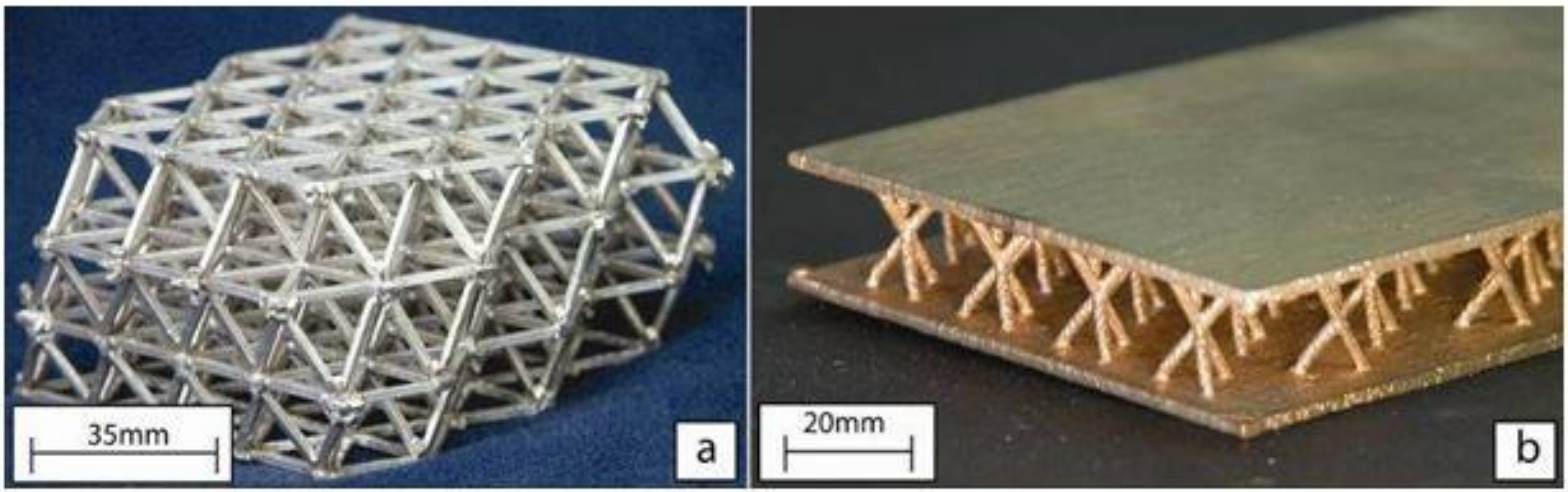
- Open-cell solid foams
  - Lighter, softer
- Closed-cell solid foams
  - Heavier, harder





Metallic Cellular Materials

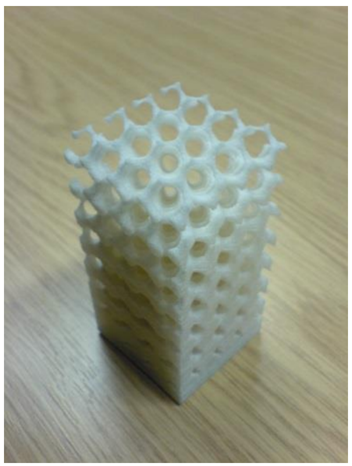
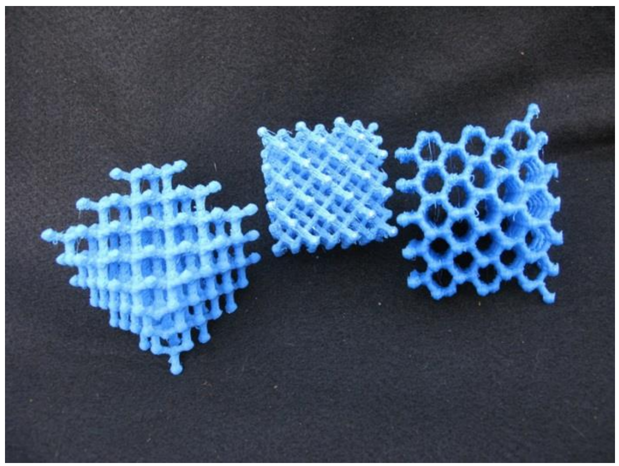
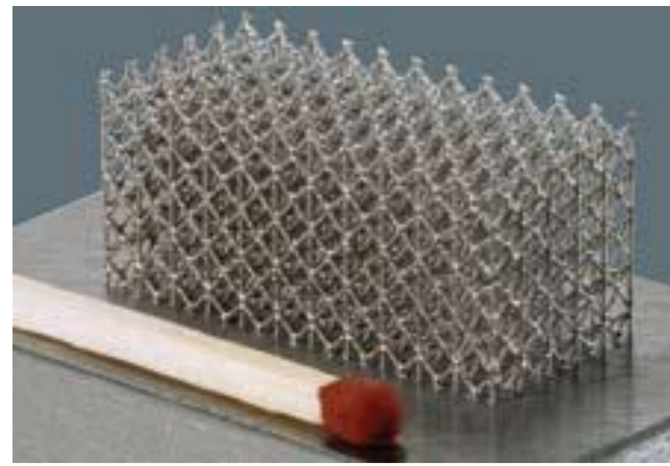
Aluminum octet truss structure and a high thermal conductivity copper 3D kagome structure (configured as the core of a sandwich panel)



http://www.virginia.edu/ms/research/wadley/celluar-materials.html

3D Printing Cellular Materials

- Many structures can be printed using FDM (Fused Deposition Modeling)
- Closed-cell foams are difficult to print

https://www.youtube.com/watch?v=2w-9KvBHago

https://www.youtube.com/watch?v=UhkIgFSELeU

Home activity

Mechanical properties

- One of the main advantages of cellular materials is that they are light, since most of the space is not filled with any material.
- The properties of cellular materials are governed by the topology (shape, size and orientation of the unit cell).

https://www.youtube.com/watch?v=T_ibOR2owQc

Microstructures to Control Elasticity in 3D Printing

https://www.youtube.com/watch?v=rMIDiyigYl4

3D-printed material can carry 160,000 times its own weight. And, Diffraction limit disproved

https://www.youtube.com/watch?v=qJt7zoJi7gQ

Metallic Microlattice - How It's Made

Home activity

Mechanical properties

- Also watch
  - Football Helmet Safety Improved With Microlattice Materials - GE
  - Large Aluminum Phase Transforming Cellular Materials (PXCMs)
  - https://physics.aps.org/articles/v7/109

  (Focus: Holey Rubber Slab Has Controllable Stiffness)
  - https://www.youtube.com/watch?v=YaobcfAXdGE

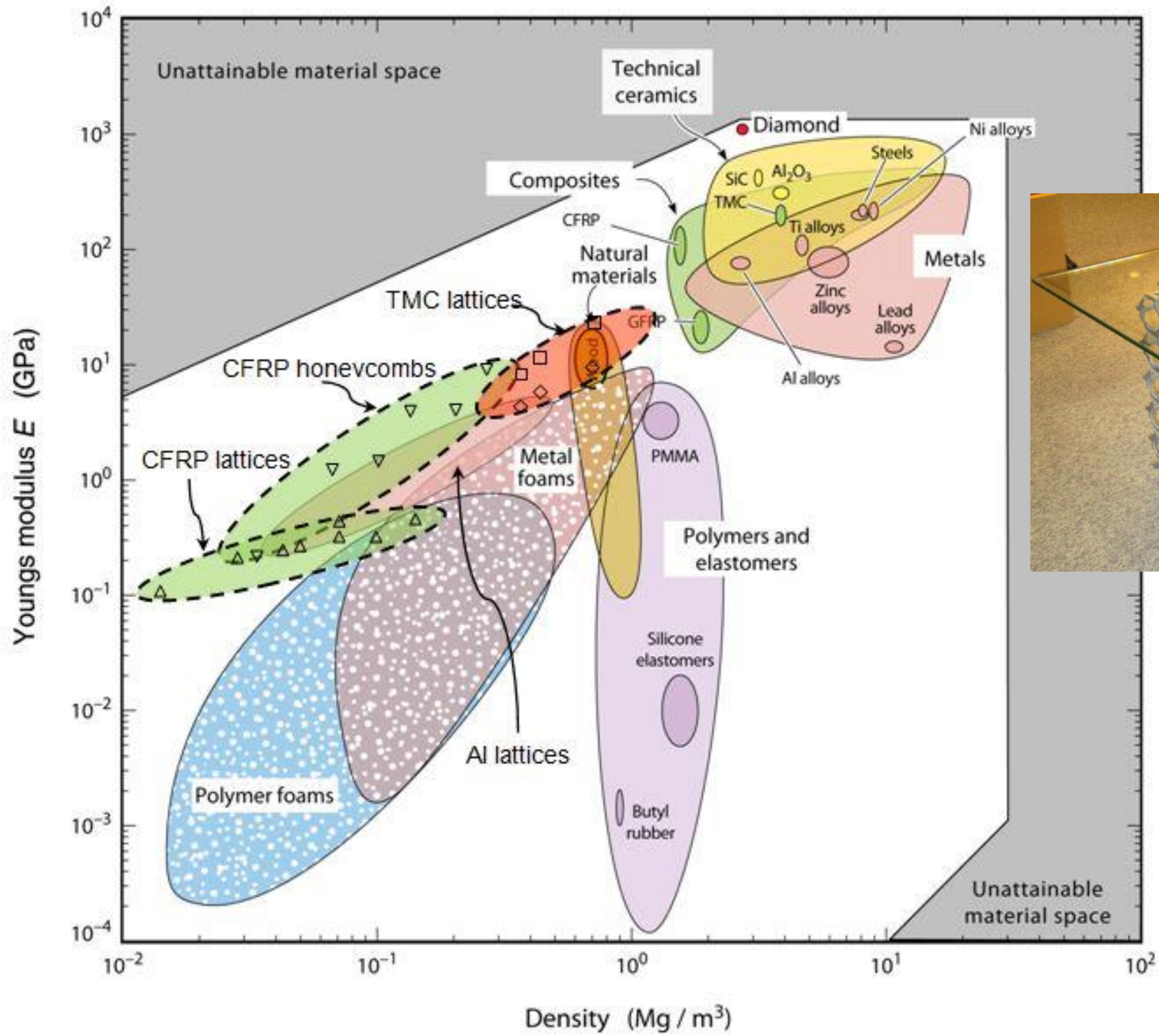
  (**Pentamode** Lattice Testing Immursed: Absorbing Mech. Energy)
  - https://www.youtube.com/watch?v=lsTiWYSfPck

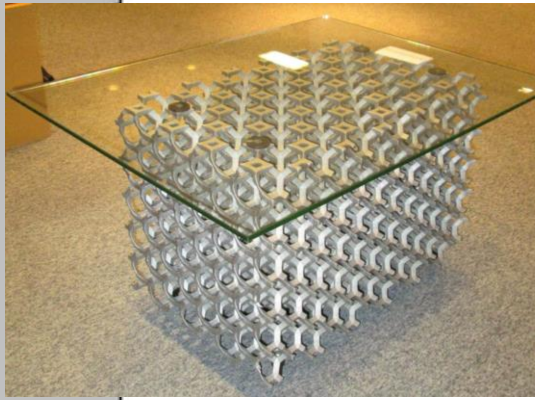
  (**Metamaterial** Mechanisms)
  - https://www.youtube.com/watch?v=vtFTZ_Dv8sc

  (Foam under shear, $\varphi = 1.25$)

Home activity

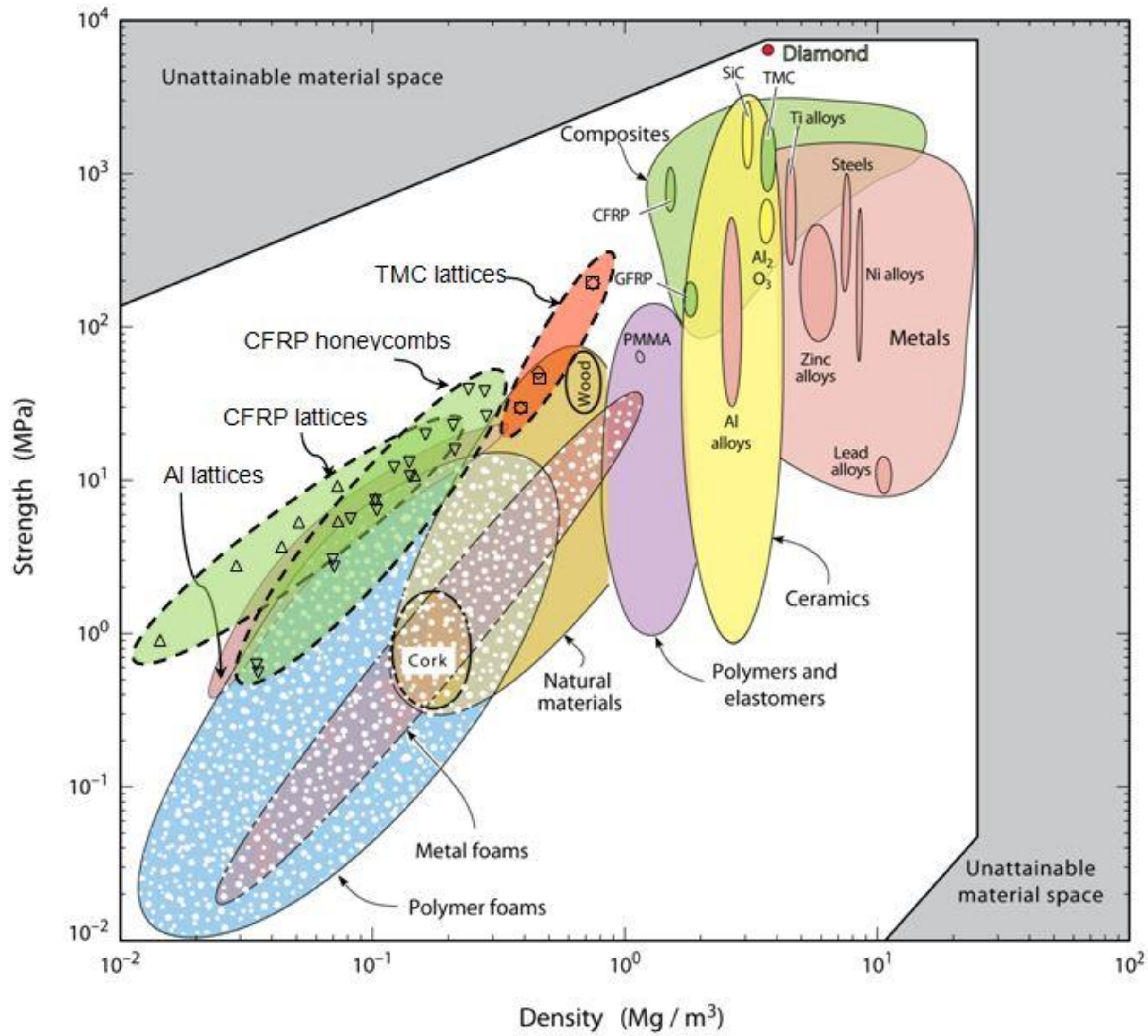
Mechanical Properties





http://www.virginia.edu/ms/research/wadley/celluar-materials.html

Mechanical Properties



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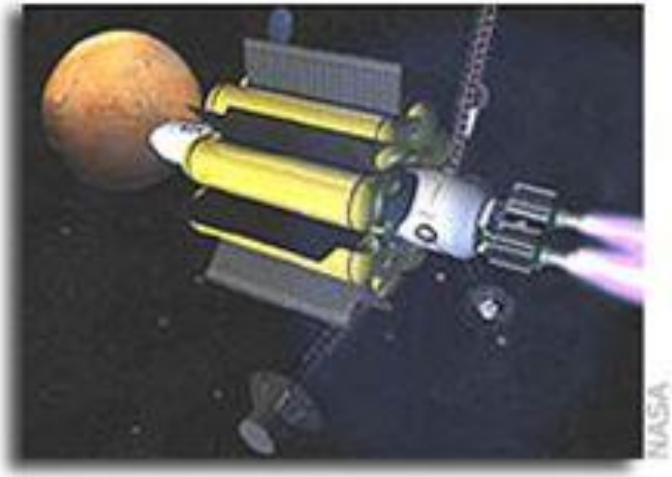
Applications



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Metamaterials

- Metamaterials
  - https://www.youtube.com/watch?v=AVeNgukCToE
- On The Quest To Invisibility - Metamaterials and Cloaking: Andrea Alu at TEDxAustin (from 10 min) https://www.youtube.com/watch?v=jseHPnqXlPY
- Now you see it ... UT develops 'cloak of invisibility`
  - https://www.youtube.com/watch?v=ScaxoyDIrqs

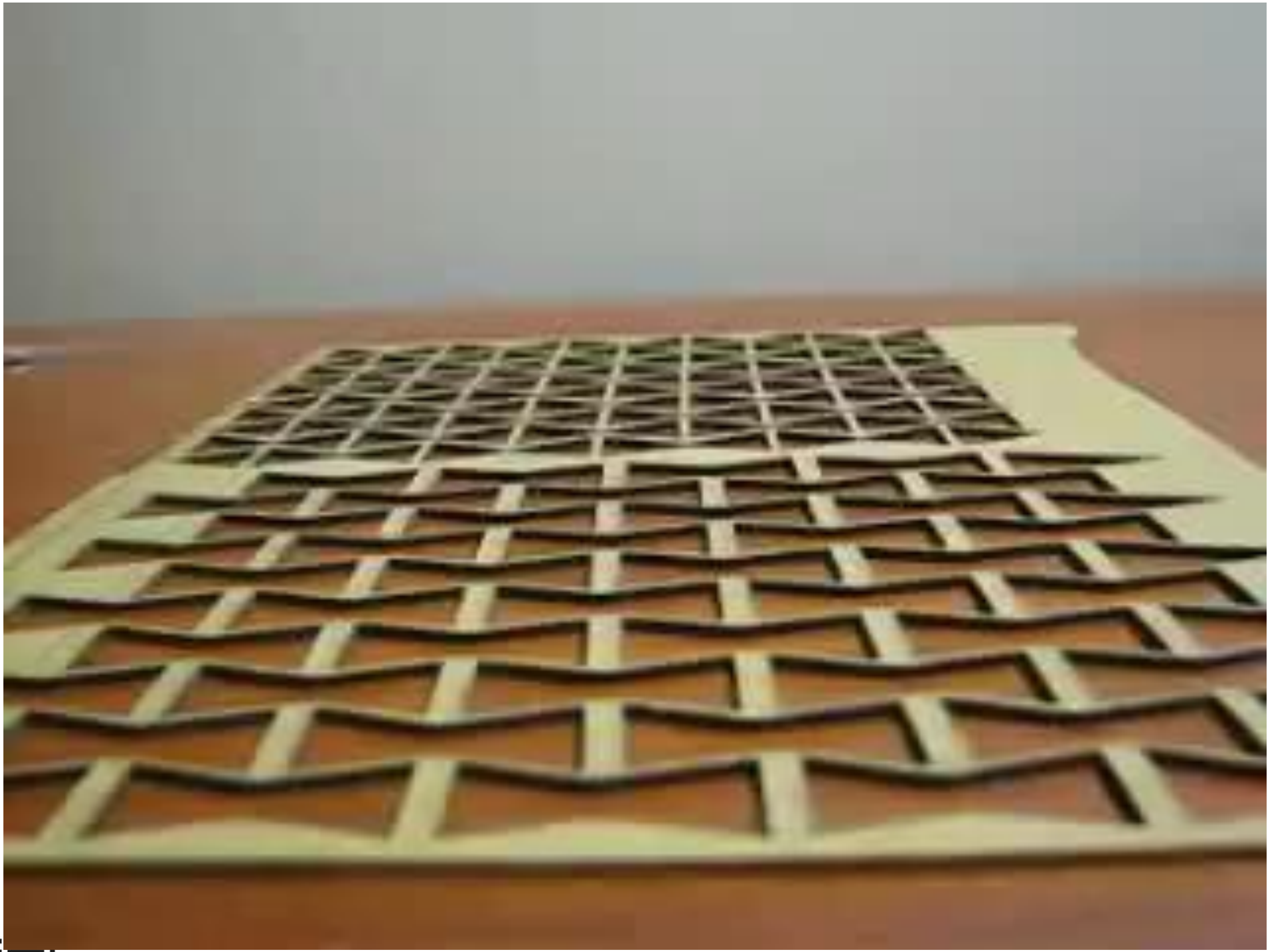
Metamaterials

- A **metamaterial** (from the Greek word μετά meta, meaning "beyond") is a material engineered to have a property that is not found in nature (wiki).
- The materials are usually arranged in repeating patterns (Periodic cellular structures), at scales that are smaller than the wavelengths of the phenomena they influence.
- Metamaterials exhibit mechanical, optical, acoustic, or electromagnetic properties that cannot be achieved in materials found in nature

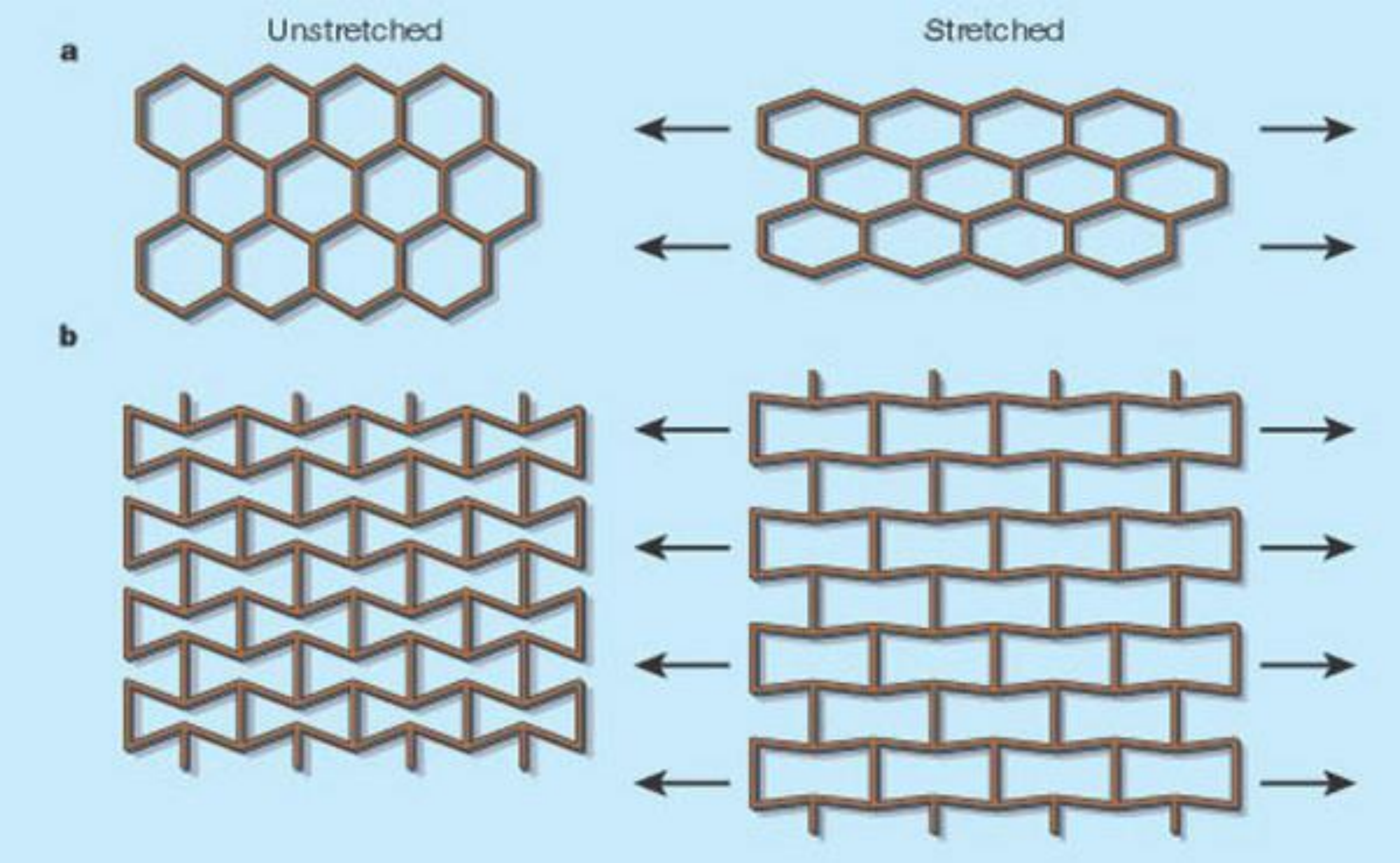
Metamaterials

- Their special properties arise due to the material structure rather than the constituent materials.
- Some examples include
  - materials with a negative Poisson's ratio (materials that expand when being stretched),
  - pentamode metamaterials/meta-fluids (solid materials behaving like fluids -- easy to deform but hard to compress[resist compression: absorbing Mech. energy]),
  - and negative refractive index materials.
- They can be used for a variety of applications: antennas, absorbers, superlenses, or even cloaking devices.

Negative Poisson's Ratio



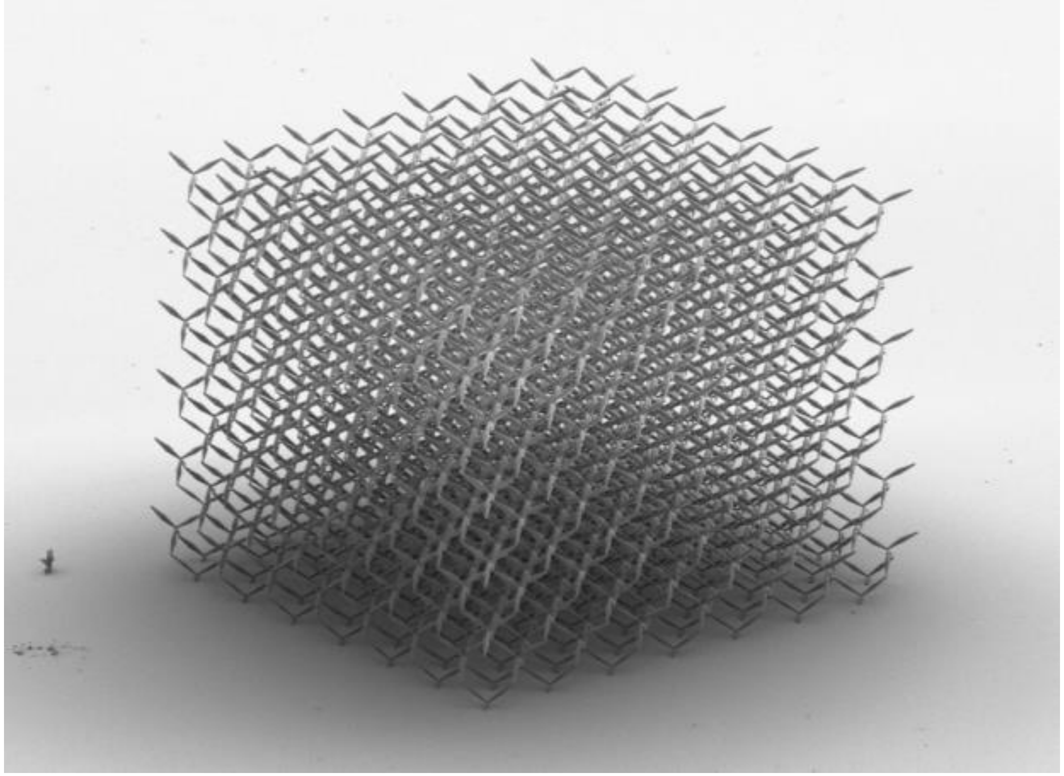
Negative Poisson's Ratio



Negative Poisson's Ratio

Pentamode Metamaterials (Meta-fluids)

- Solid that behaves like a fluid
- Hard to compress (resist to compression), easy to deform



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  - Cellular materials
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  - **Composite materials**
    - Piezoelectric composites
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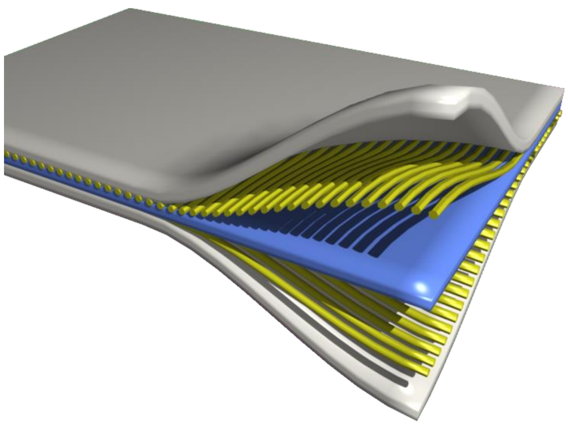
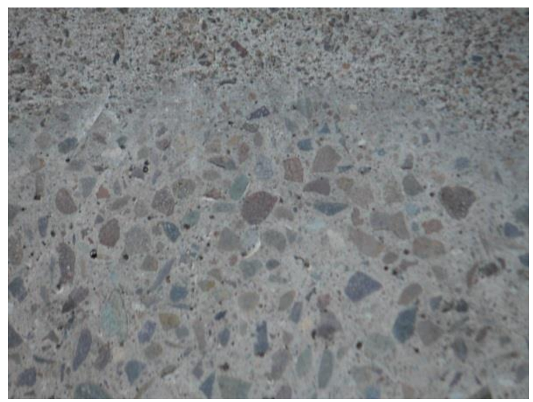
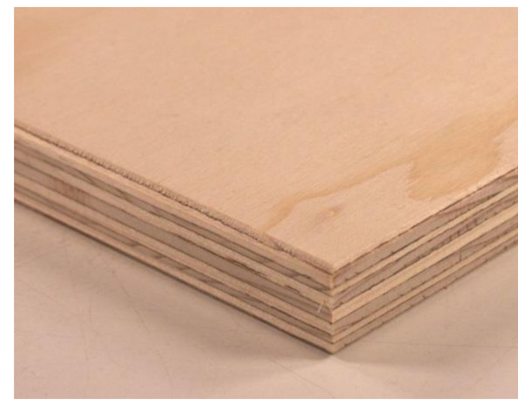
Composite Materials

- Made from two or more constituent materials
  - At least one **matrix** and one **reinforcement material** e.g., polymer + fiber







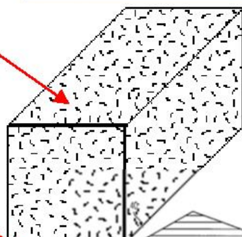
Classic examples: concrete (cement + loose stones)

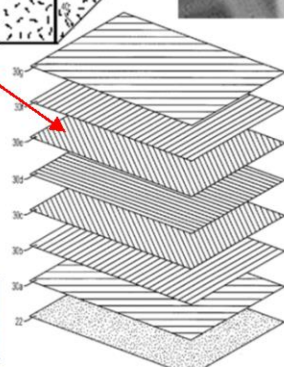
Matrices

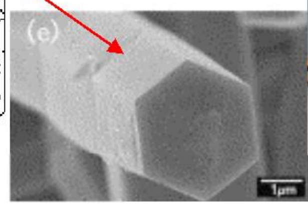
- **Matrices**
  - **Polymer**
    - Thermosets (Epoxy, Polyester)
    - Thermoplastics (Polystyrene, Nylons)
  - **Metal**
    - Alloys (Steels, Aluminiums)
  - **Ceramic**
    - Glass
    - Ceramics (Semi conductors, Cermets)
    - Cements
  - **Carbon and Graphite**

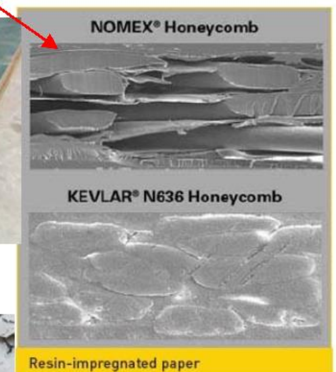
Reinforcements

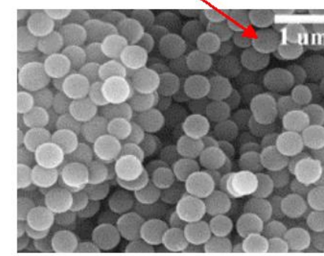
- **Reinforcements**
  - **Fibres**
    - Short
    - Long
    - Plies
    - Threads
    - Organic
    - Inorganic
  - **Whiskers**
    - Single crystals
  - **Laminar**
  - **Flakes**
  - **Filled**
  - **Particulates**
  - **Microspheres**





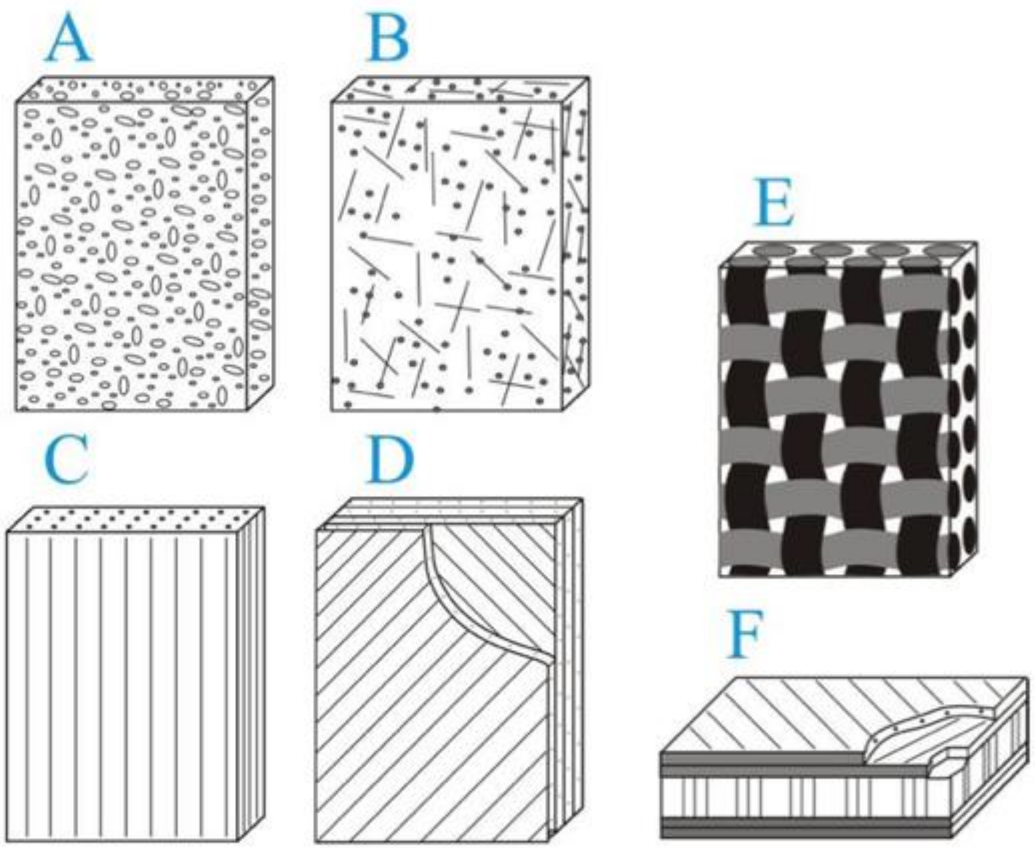






Reinforcements

A. composites reinforced by particles;
B. composites reinforced by chopped strands;
C. unidirectional composites;
D. laminates;
E. fabric reinforced plastics;
F. honeycomb composite structure;



Natural composites

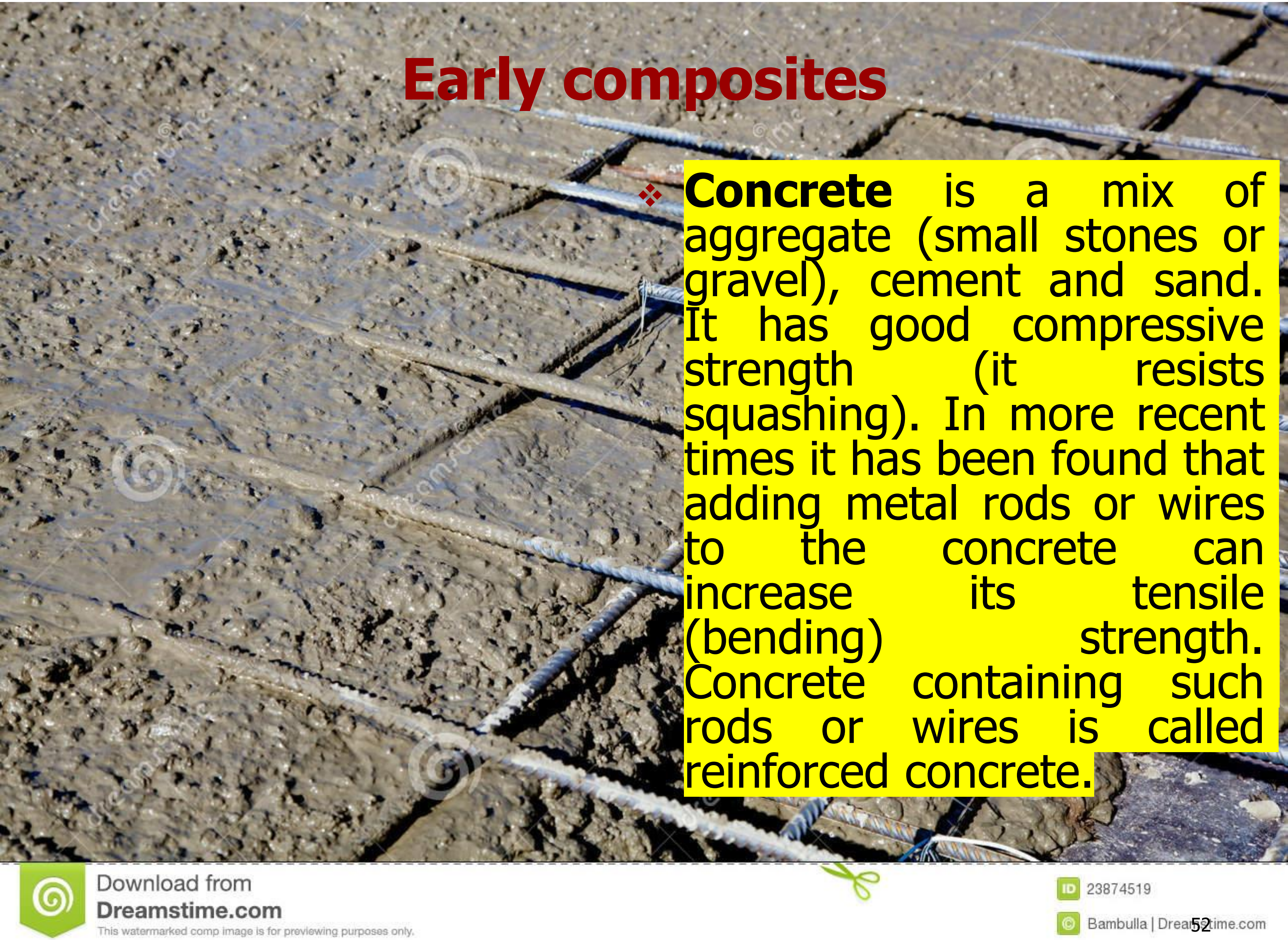
- **Wood** is a composite – it is made from long cellulose fibres (a polymer) held together by a much weaker substance called lignin. Cellulose is also found in cotton, but without the lignin to bind it together it is much weaker. The two weak substances – lignin and cellulose – together form a much stronger one
- The **bone** in your body is also a composite. It is made from a hard but brittle material called hydroxyapatite (which is mainly calcium phosphate) and a soft and flexible material called collagen (which is a protein). Collagen is also found in hair and finger nails. On its own it would not be much use in the skeleton but it can combine with hydroxyapatite to give bone the properties that are needed to support the body.

Early composites

- **Mudbricks**: **Mud** is strong if you try to squash it (it has good compressive strength) but it breaks quite easily if you try to bend it (it has poor tensile strength). **Straw** seems very strong if you try to stretch it, but you can crumple it up easily. By mixing mud and straw together it is possible to make bricks that are resistant to both squeezing and tearing and make excellent building blocks.

Early composites

- **Concrete** is a mix of aggregate (small stones or gravel), cement and sand. It has good compressive strength (it resists squashing). In more recent times it has been found that adding metal rods or wires to the concrete can increase its tensile (bending) strength. Concrete containing such rods or wires is called reinforced concrete.



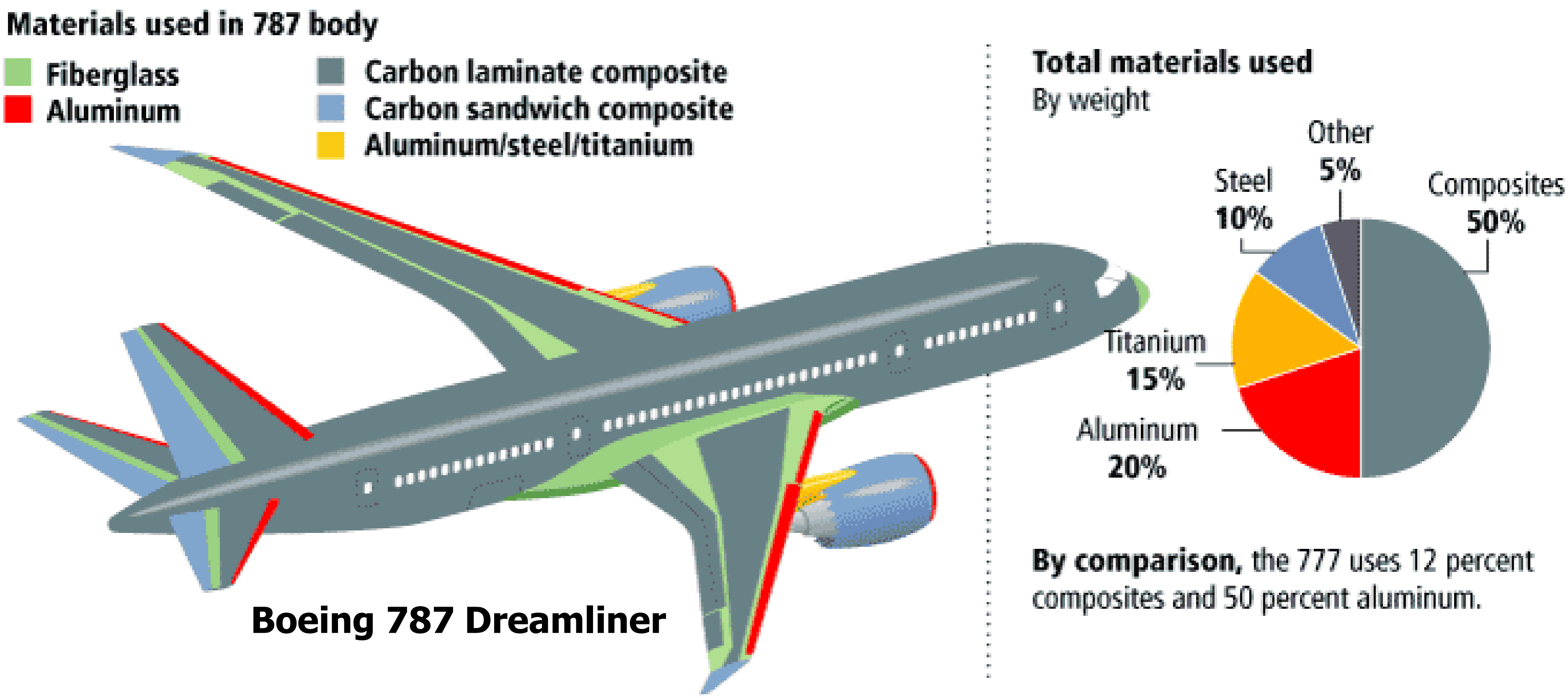
Modern composites

- **Fibreglass**: It is widely used today for boat hulls, sports equipment, building panels and many car bodies. The matrix is a plastic and the reinforcement is glass that has been made into fine threads and often woven into a sort of cloth.
- On its own the glass is very strong but brittle and it will break if bent sharply. The plastic matrix holds the glass fibres together and also protects them from damage by sharing out the forces acting on them.

Modern composites

- **Carbon Fibers**: These materials are lighter and stronger than fibreglass but more expensive to produce. They are used in aircraft structures and expensive sports equipment such as golf clubs.
- **Carbon nanotubes**: These are even lighter and stronger than composites made with ordinary carbon fibres but they are still extremely expensive. They do, however, offer possibilities for making lighter cars and aircraft (which will use less fuel than the heavier vehicles we have now).

Applications



Boeing 787 Dreamliner

Applications

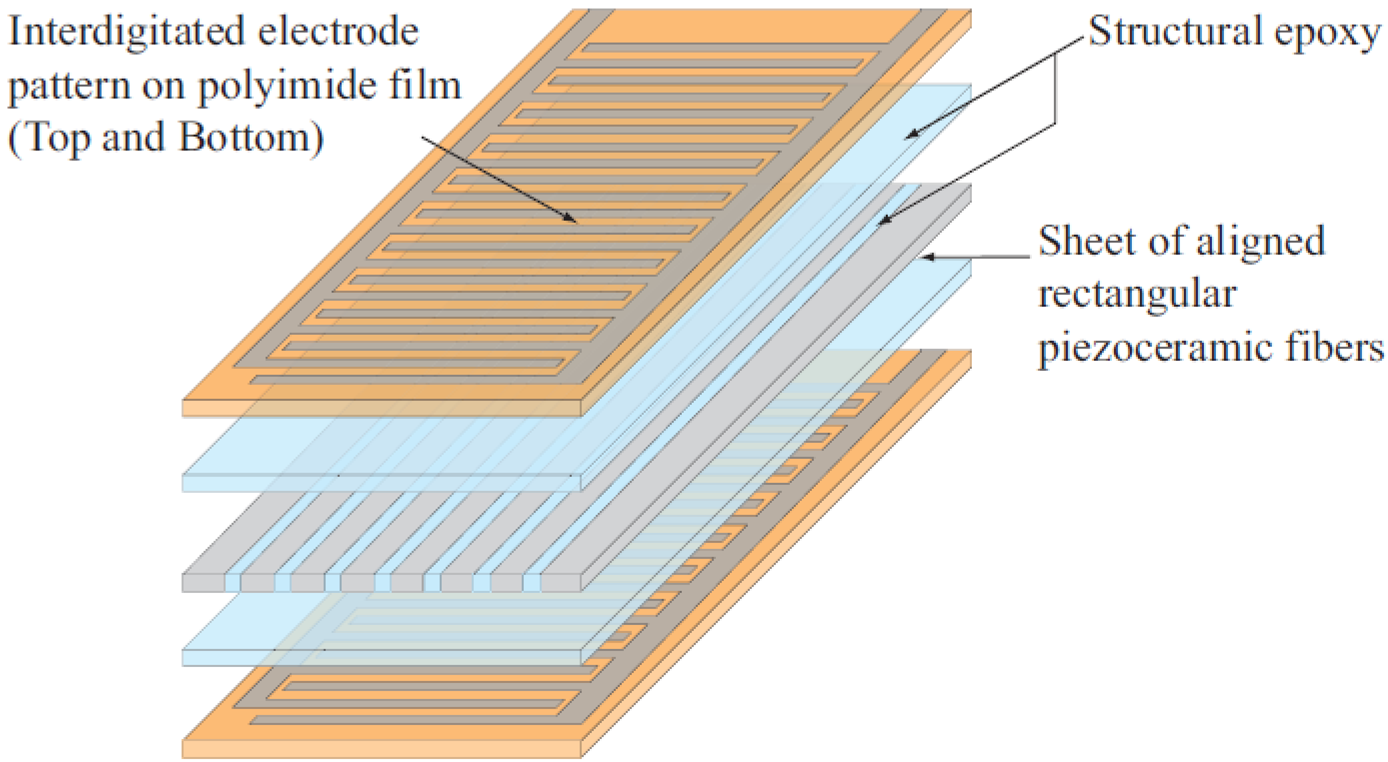
- Carbon fibre means wing tips can be near vertical, improving efficiency

Specific examples of Composites

- Piezoelectric composites: The structure and the actuation device are a one system

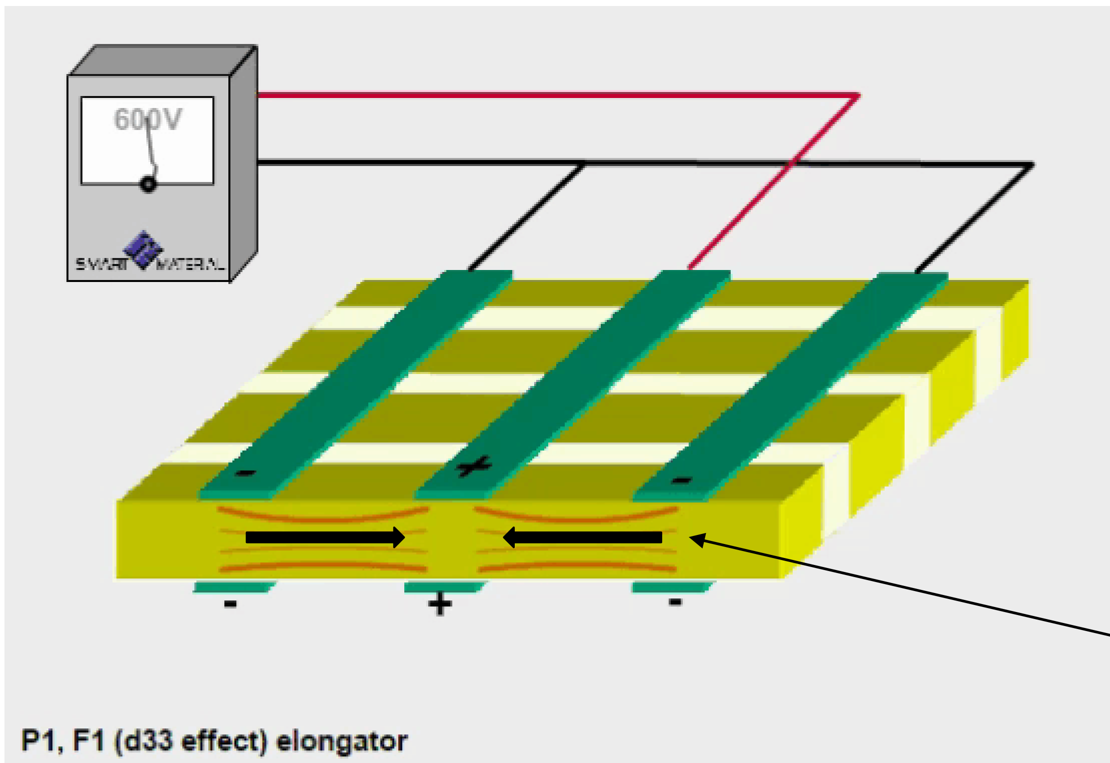
Specific examples of Composites

❖ Piezoelectric composites



Specific examples of Composites

- Piezoelectric composites



Poling direction

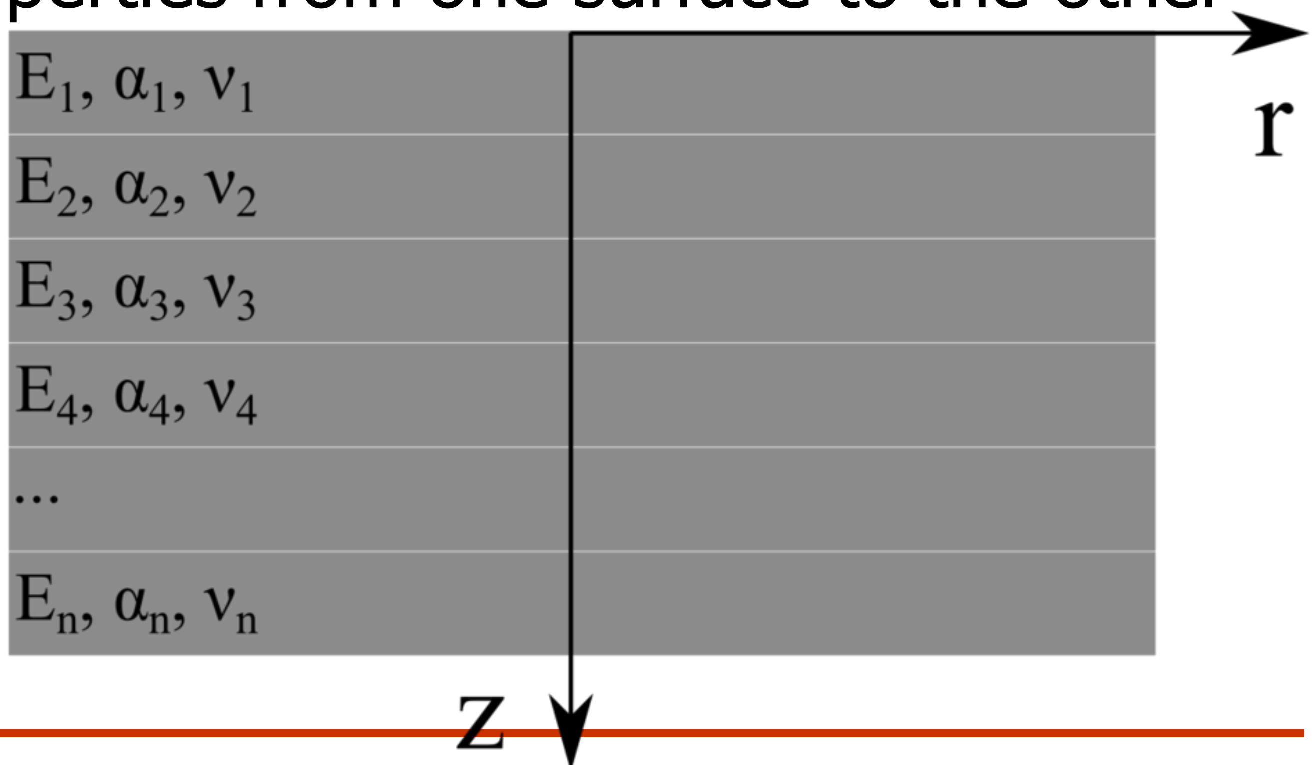
https://www.youtube.com/watch?v=Vc_3uZNaAIU

NASA Piezoelectric Autonomous Responsiveness (Plane Flapping Like a Bird)

http://www.smart-material.com/

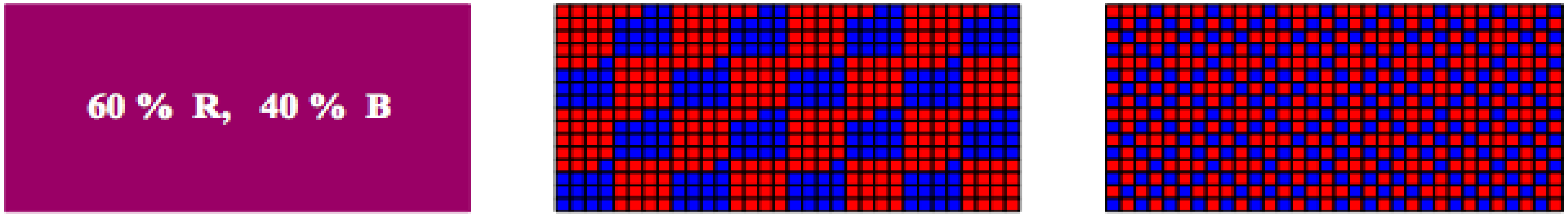
Specific examples of Composites

- **Functionally graded materials** (FGMs) are a new class of composite materials which are characterized by the smooth and continuous change of the mechanical and thermal properties from one surface to the other

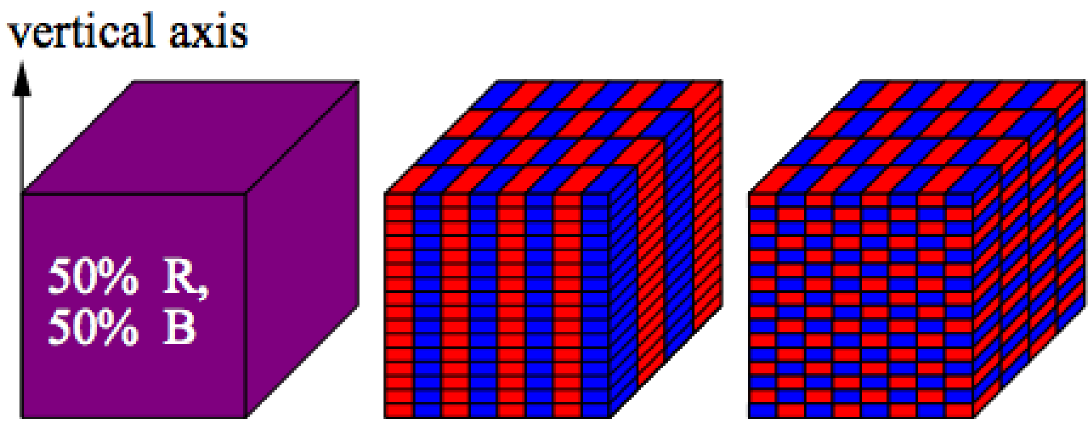


3D Printing FGMs

- The concept is to make a composite material by varying the microstructure from one material to another material with a specific gradient (FGMs are typically made from a mixture of ceramics



(a) Idealized model (b) Clustered–dot ordered dither (low frequency texture pattern) (c) Dispersed–dot ordered dither (high frequency fidelity)

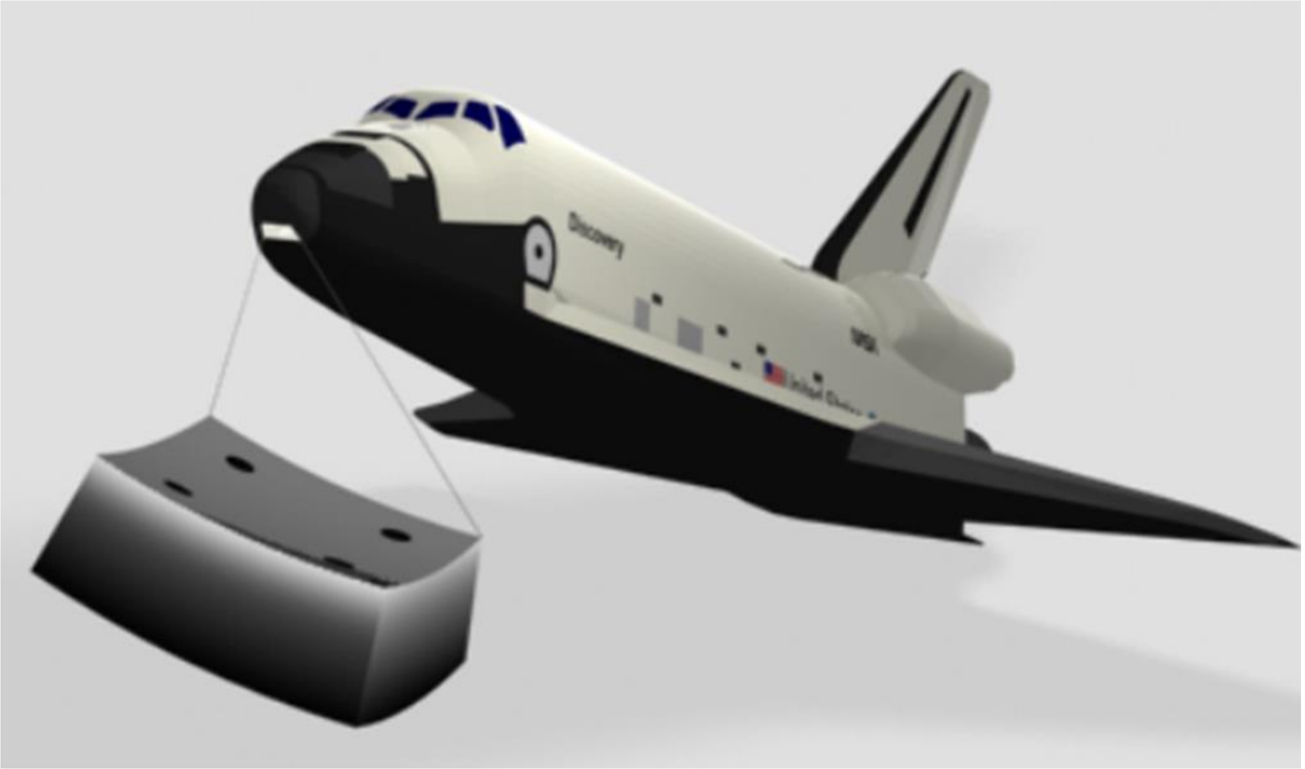


(a) Idealized model (b) Replication of each layer (c) Result by 3D halftoning

Specific examples of Composites

- **FGMs** are typically made from a ***mixture*** of ceramics and metal.
- Unlike fiber–matrix composites, in which cracking and debonding may occur at high temperatures due to the material property mismatch at the interface of two discrete materials, FGMs have the advantage of being capable of withstanding severe high temperature while maintaining structural integrity.

Applications



Ceramic-metal FGMs are particularly suited for thermal barriers in space vehicles

Specific examples of Composites

- **Robotic materials:** are composite materials that combine sensing, actuation, computation, and communication in a repeatable or amorphous pattern. They are changing with the world around them. They can enable smart composites that autonomously change their shape, stiffness, or physical appearance in a fully programmable way, extending the functionality of **classical "smart materials.**"
  - https://phys.org/news/2015-03-robotic-materials-world.html
- A three-dimensional actuated origami-inspired transformable metamaterial with multiple degrees
  - https://www.youtube.com/watch?v=xgl_mdzumZE

Why Composite Materials

- Advantages
  - Lower density (20 to 40%)
  - Higher directional mechanical properties
  - Strength (ratio of material strength to density)
    - 4 times greater than that of steel and aluminum
  - Higher fatigue endurance
  - Higher toughness than ceramics and glasses
  - Versatility and tailoring by design
  - Easy to machine
  - Can combine other properties (damping, corrosion)
  - Cost

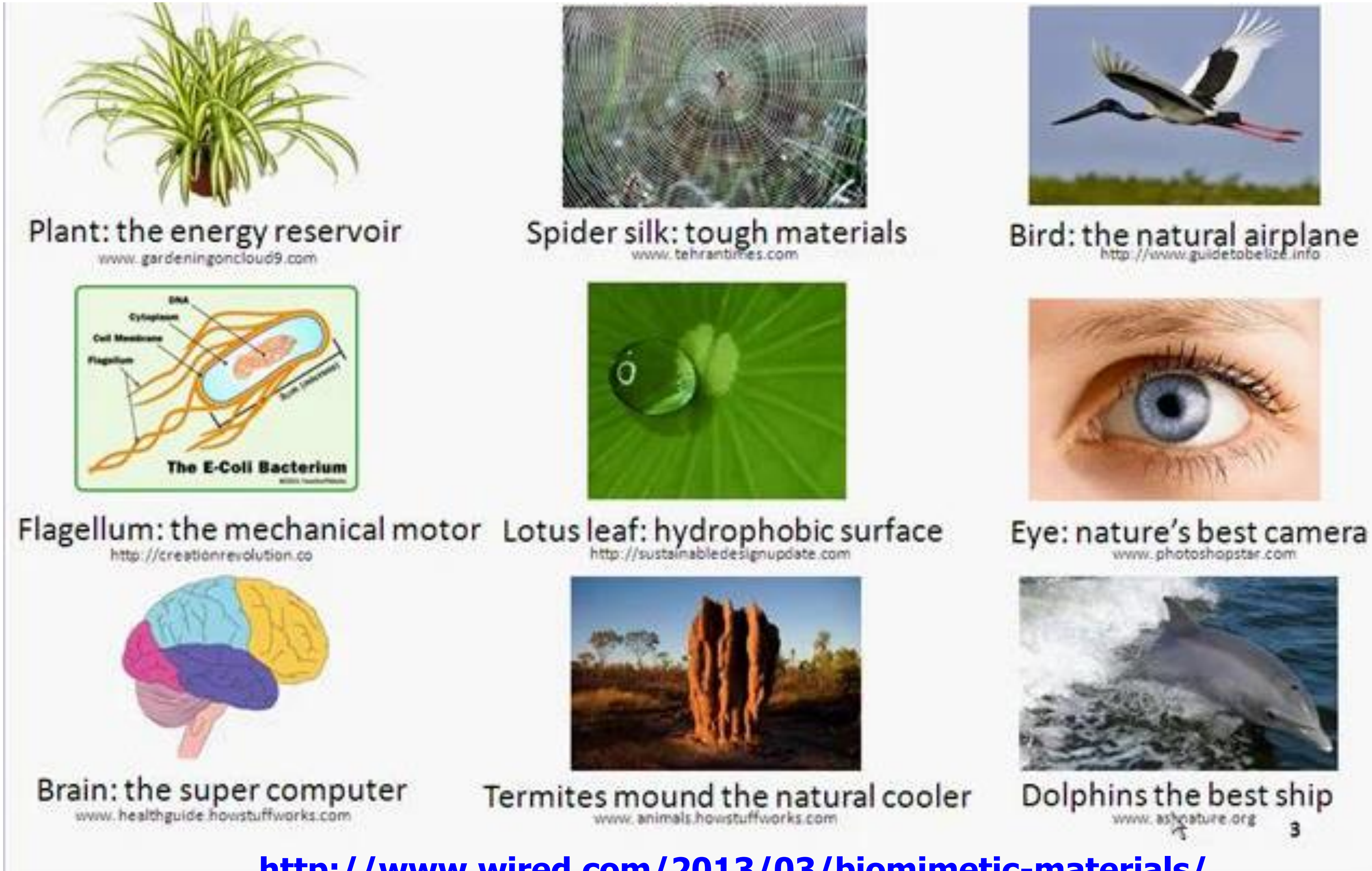
Why Not Composite Materials

- Disadvantages
  - Not often environmentally friendly ?
  - Low recyclability ?
  - Can be damaged
  - Anisotropic properties
  - Matrix degrades
  - Low reusability

Learning Objectives

- Smart materials
- Advanced materials
  - Cellular materials
    - Metamaterials
  - Composite materials
    - Piezoelectric composites
    - Functionally graded materials
    - Robotic materials
  - **Biomimetic/Bio-inspired materials**
  - Materials with structural hierarchy

Biomimetic/Bio-inspired Materials



http://www.wired.com/2013/03/biomimetic-materials/

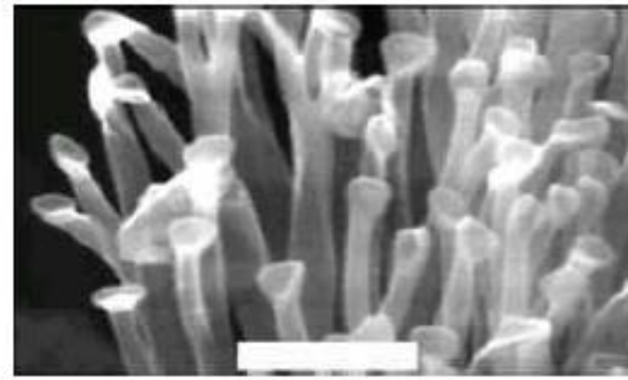
Biomimetic/Bio-inspired Materials

- These materials are developed drawing inspiration from nature.
- Typically, the spatial arrangements of the constituent materials are copied, while the constituent materials can be both copied or replaced.
- Examples of biomimetic materials include
  - honeycomb structures,
  - wood fibers, and
  - bone structures.
- Some interesting applications of biomimetic materials include
  - adhesive surfaces (found in mussels and geckos),
  - self-cleaning surfaces, water-repellent hydrophobic surfaces (found in lotus leaves),
  - extremely strong materials (found in marine mollusc teeth),
  - structurally iridescent materials (modeled based on butterfly wings),
  - and velcro (inspired by burrs).

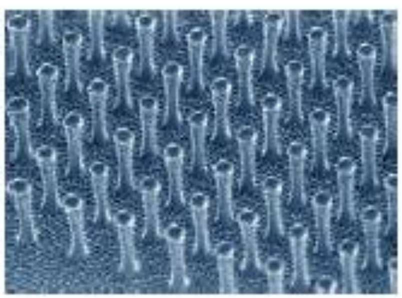
Biomimetic Materials: Gecko Tape

The example of Gecko

setae



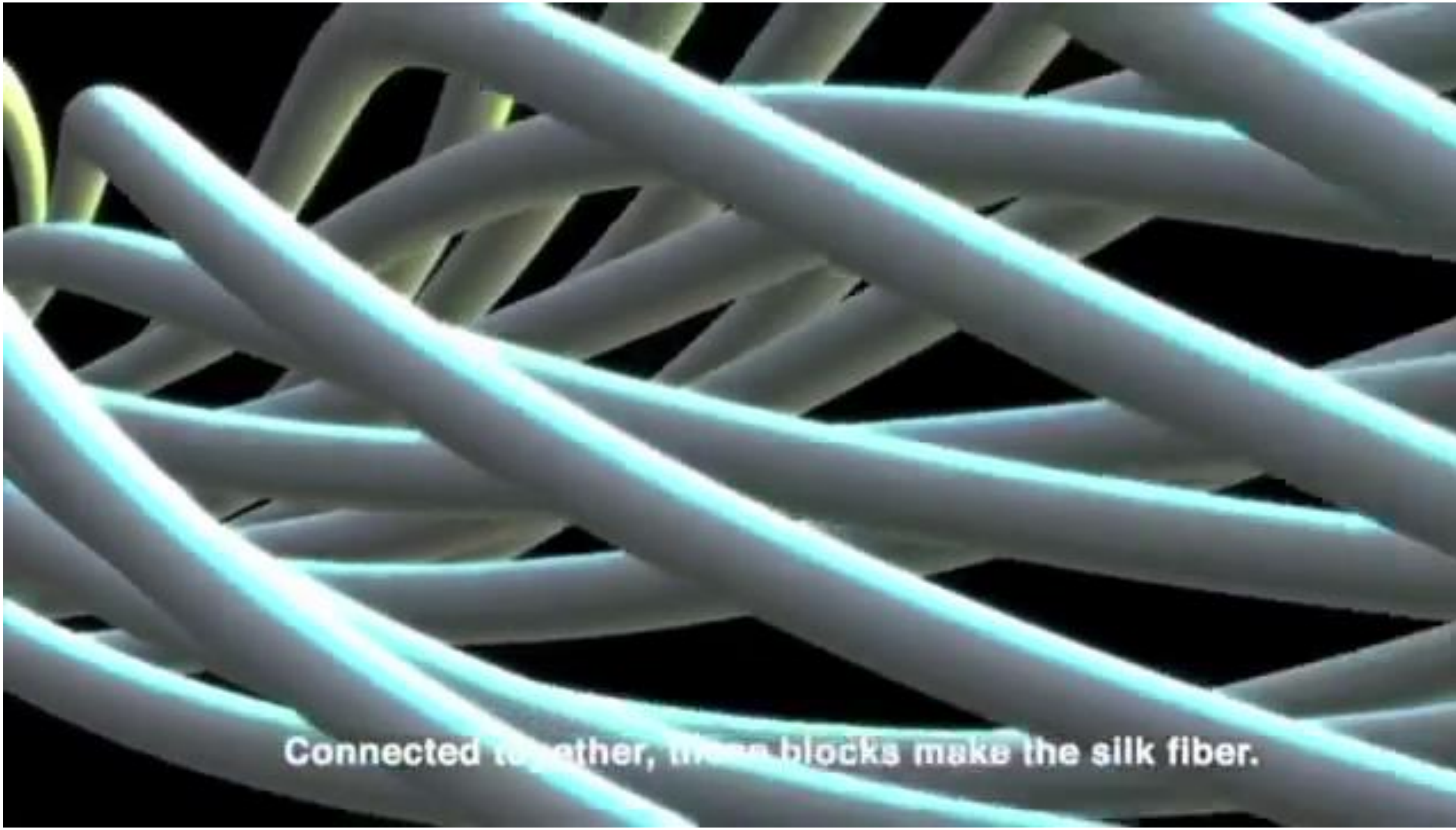
spatulae



Scanning electron microscope image of a 1cm^2 section of the Gecko-sticky tape made of polyimide fibers

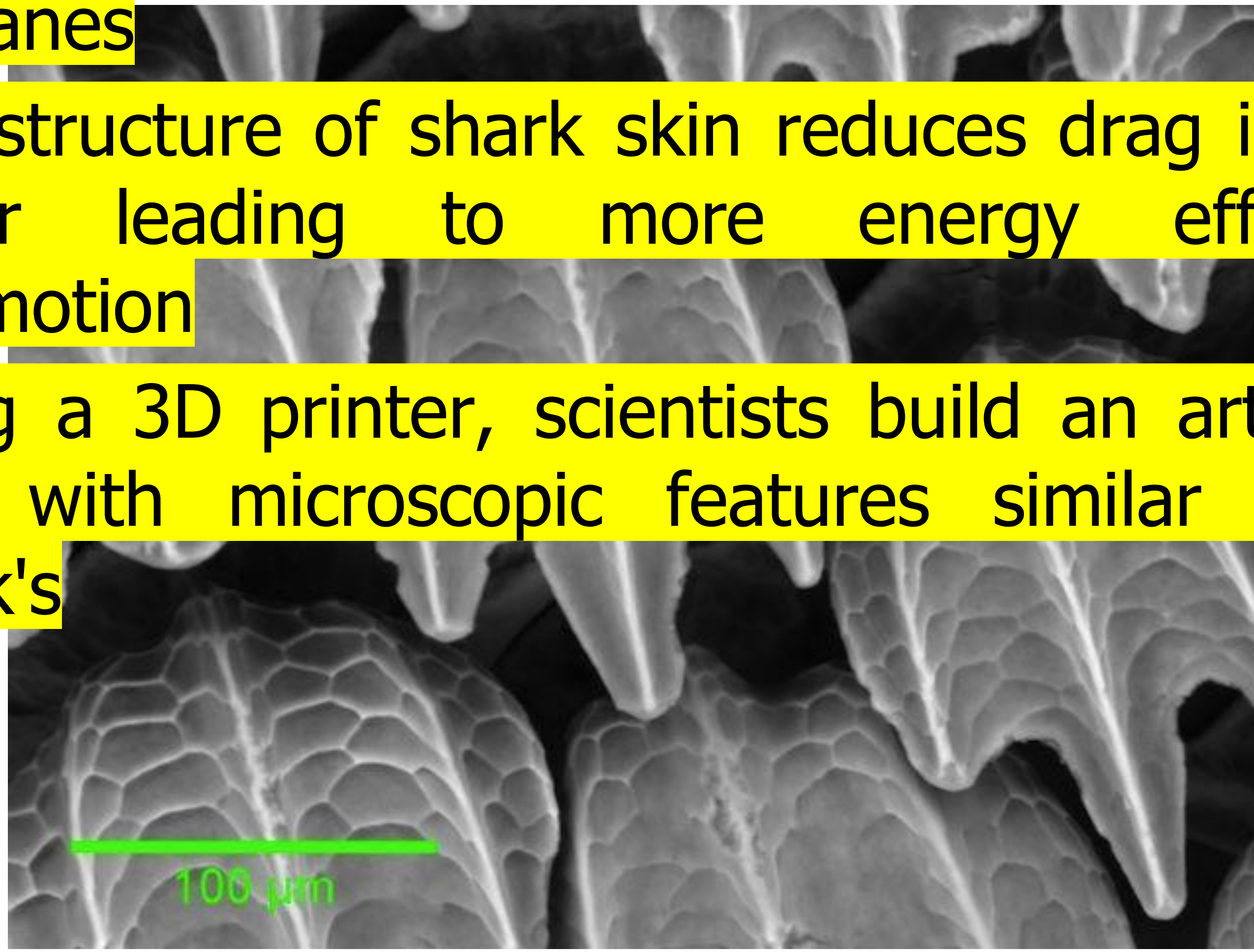
https://www.youtube.com/watch?v=odAifbpDbhs

Biomimetic Materials: Spider Silk



Biomimetic Materials: Swim Faster

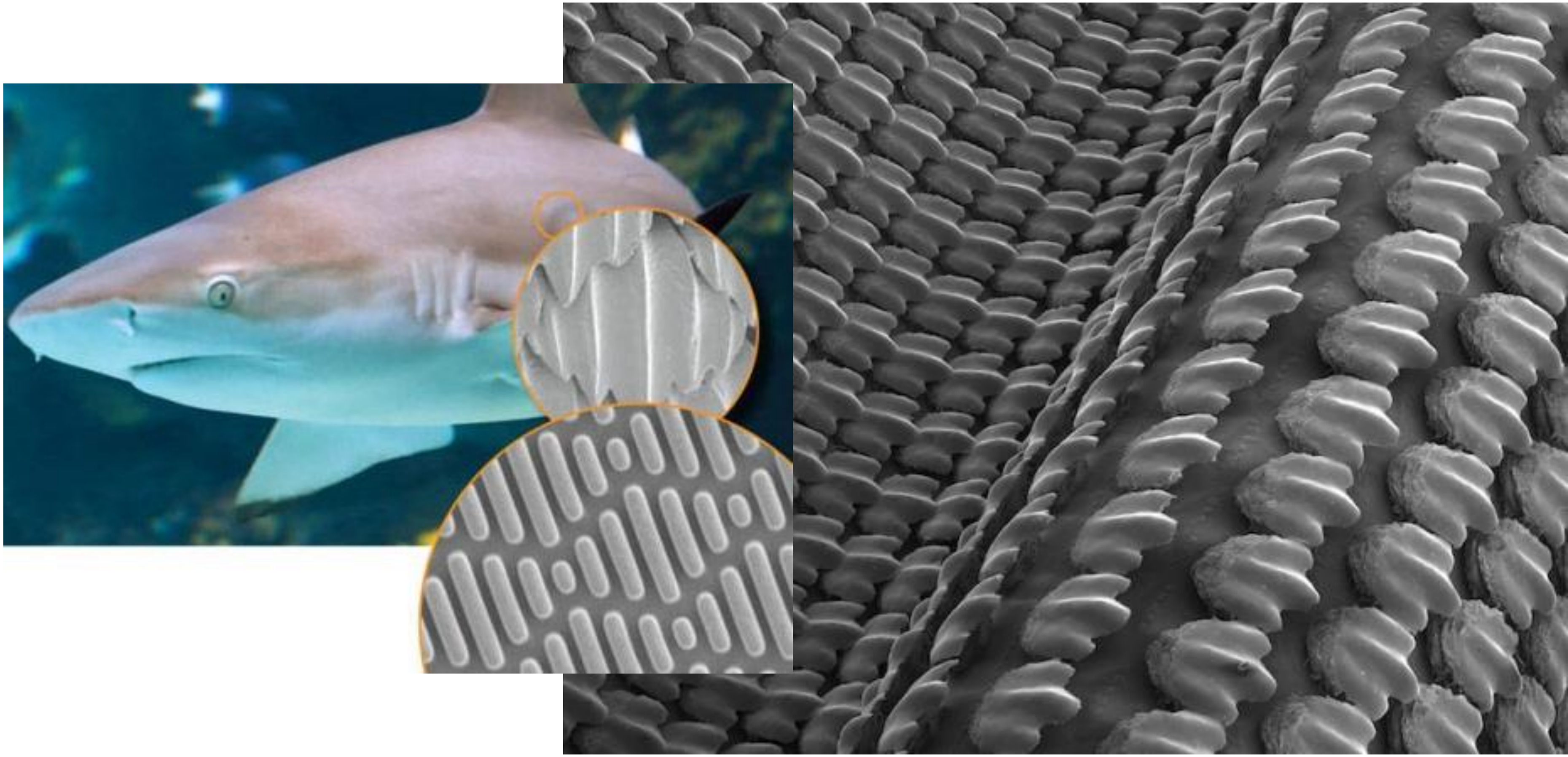
- Shark Skin Will Inspire Faster Swimsuits and Airplanes
- The structure of shark skin reduces drag in the water leading to more energy efficient locomotion
- Using a 3D printer, scientists build an artificial skin with microscopic features similar to a shark's



Denticles in shark skin

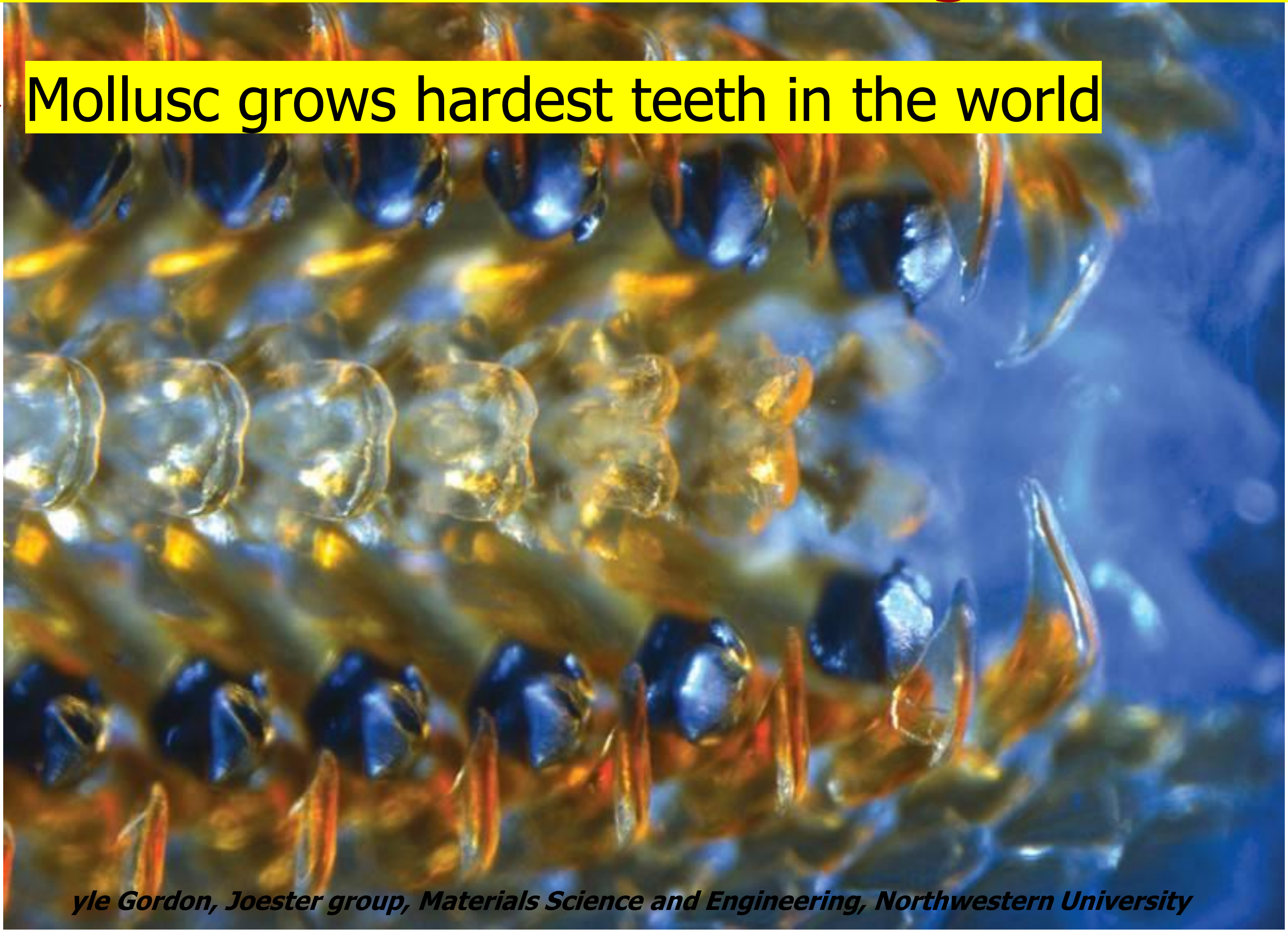
Biomimetic Materials: Swimming Faster

- A close-up of synthetic shark scales.



Biomimetic Materials: Strong Materials

- Mollusc grows hardest teeth in the world



yle Gordon, Joester group, Materials Science and Engineering, Northwestern University

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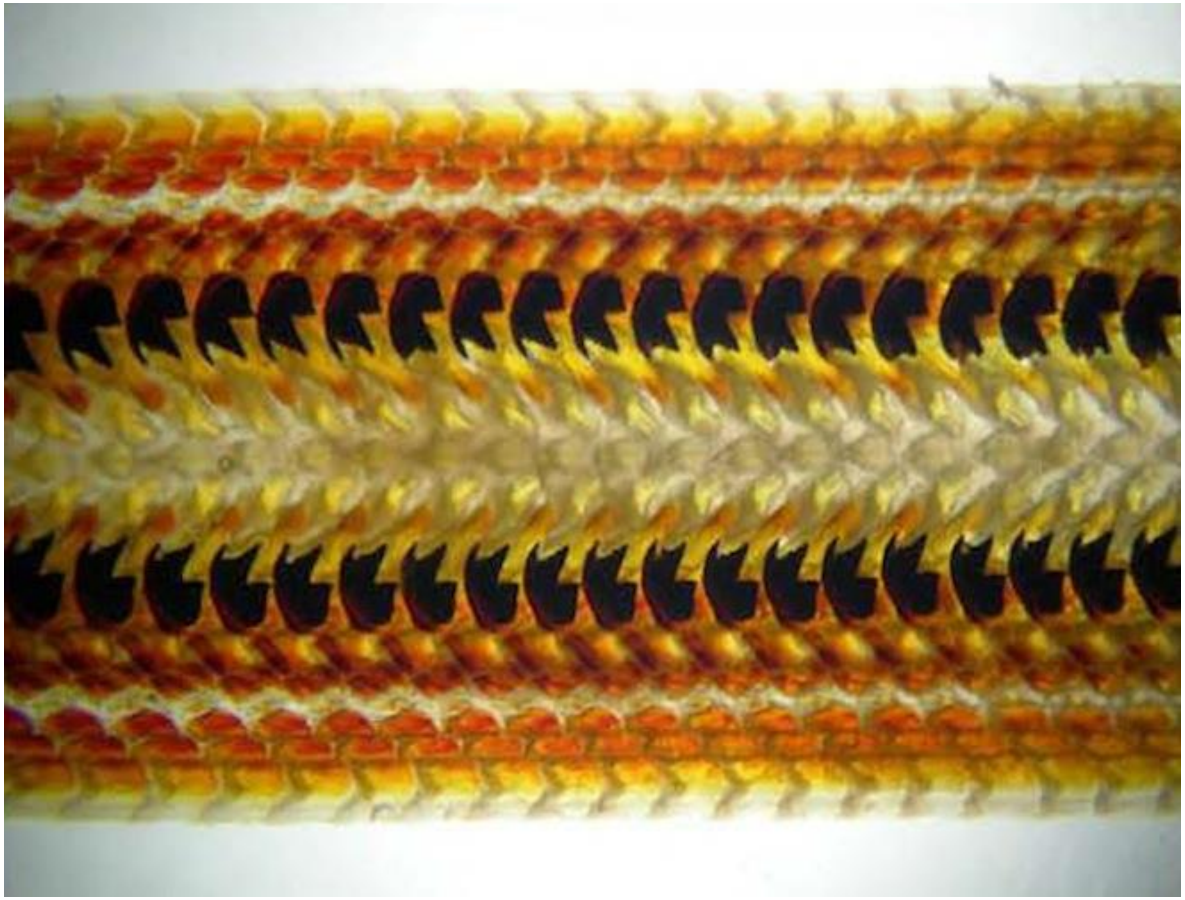


yle Gordon, Joester group, Materials Science and Engineering, Northwestern University

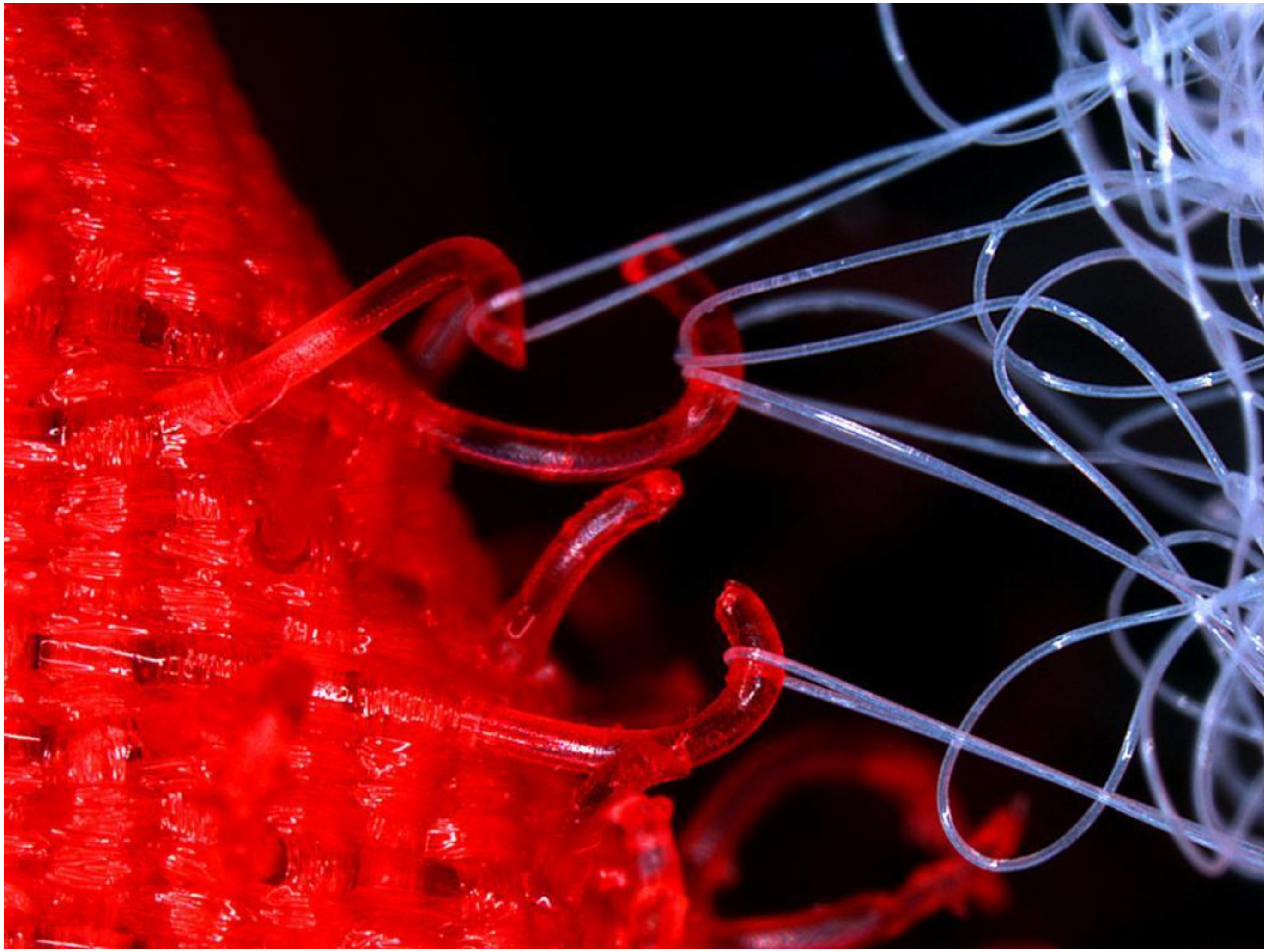
Biomimetic Materials: Velcro

- Inspired by Burrs

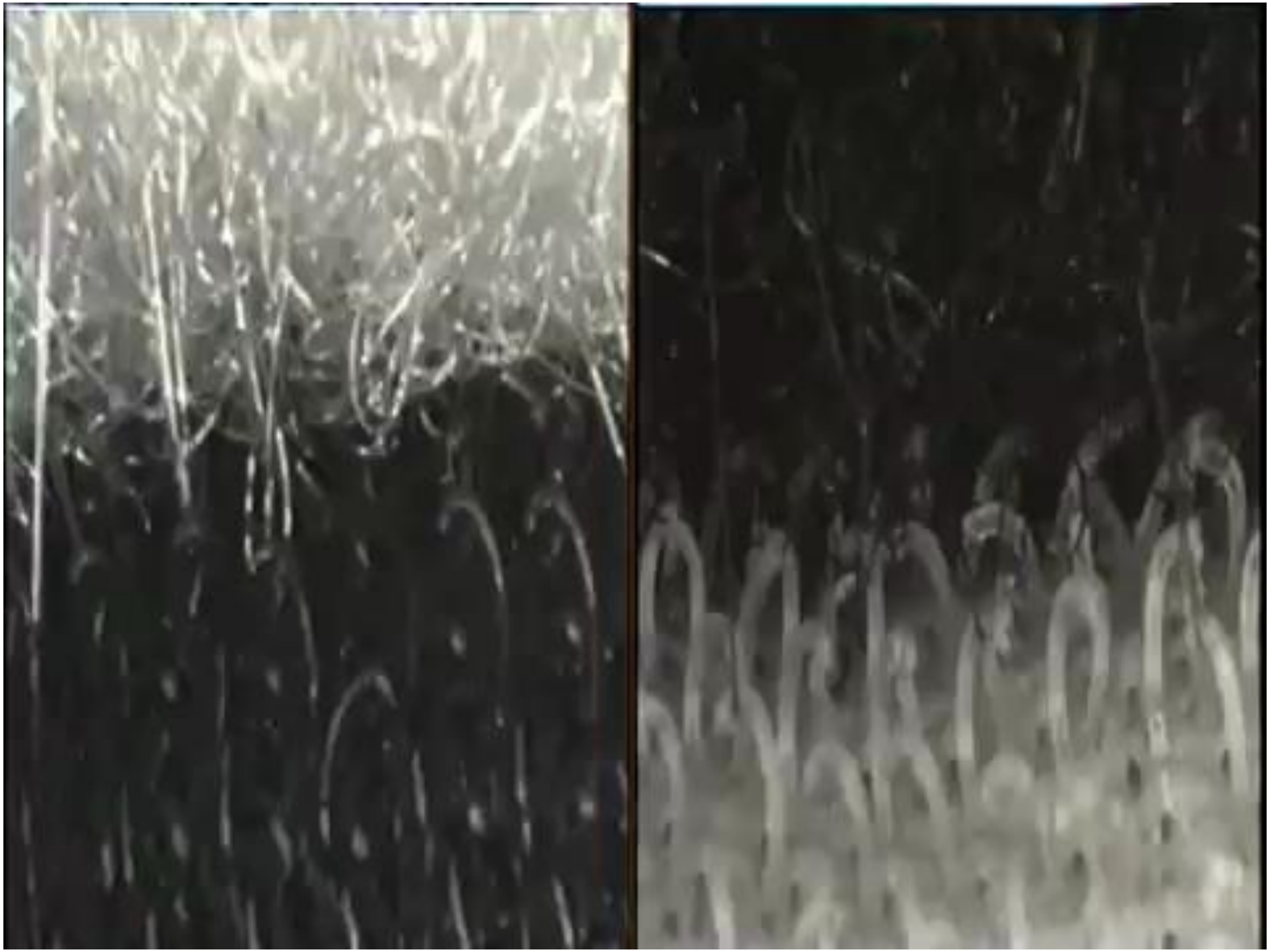
Biomimetic Materials: Velcro

- Detachable adhesive

Biomimetic Materials: Velcro



Biomimetic Materials: Velcro in Action



Biomimetic Materials: Velcro in Action

- Meet SCAMP: The Flying, Perching, Climbing Robot
  - https://www.youtube.com/watch?v=bAhLW1eq8eM

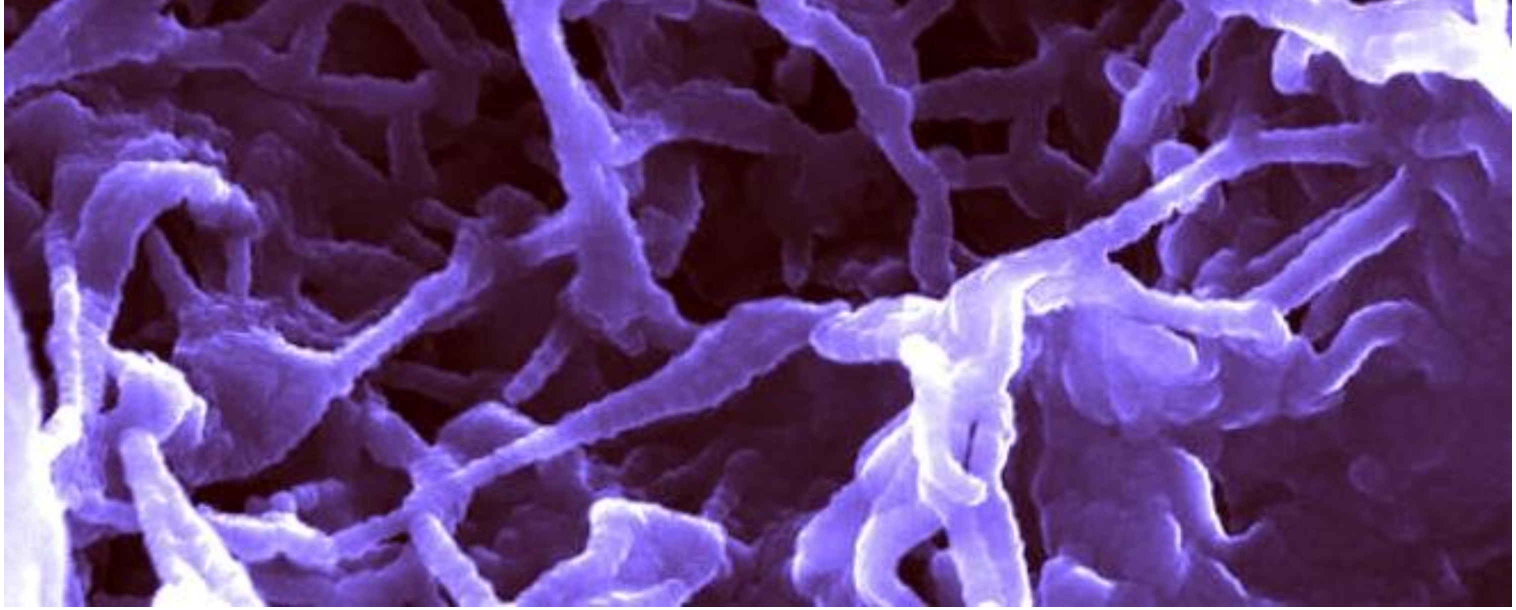
Materials with Varying Stiffness

- Inspired by sea cucumbers which can alter the stiffness of their dermis (outer skin layer)
- Change the structure of collagen fibers embedded in low stiffness matrix

https://www.youtube.com/watch?annotation_id=annotation_3978787121&feature=iv&src_vid=xjnvRKDdaWY&v=3g7nopQOJlU

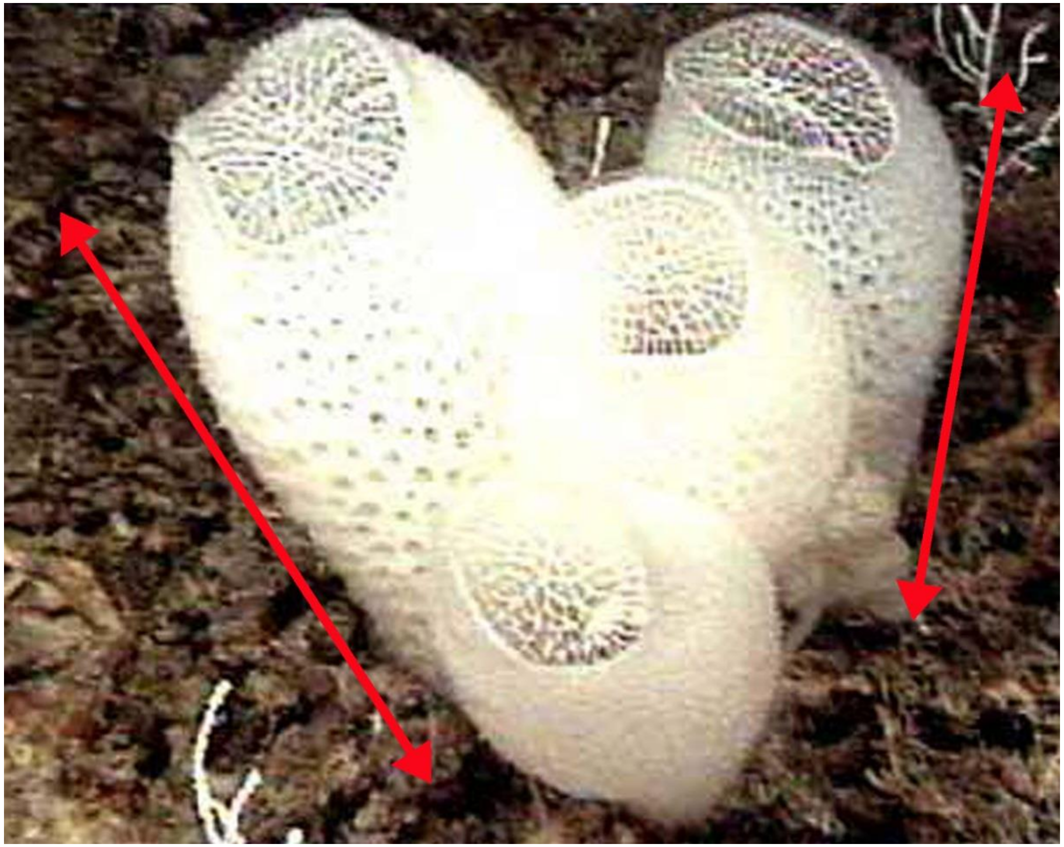
Materials with Varying Stiffness

- The artificial variant is made of cellulose fibers in a rubbery matrix. When water is added the hydrogen bonds between the fibers and matrix break causing the material to become softer.
- Imagine car tires that become softer for better grip/more contact area in the rain for example



Transparent Construction Materials

- Inspired by skeletons of undersea sponges made of glass and Venus Flower Basket



Transparent Construction Materials

- Glass sponge
  - Work done by Joanna Aizenberg at Harvard. The building blocks are arranged in a lattice like structure and layered so that they are ultra strong and can transmit light

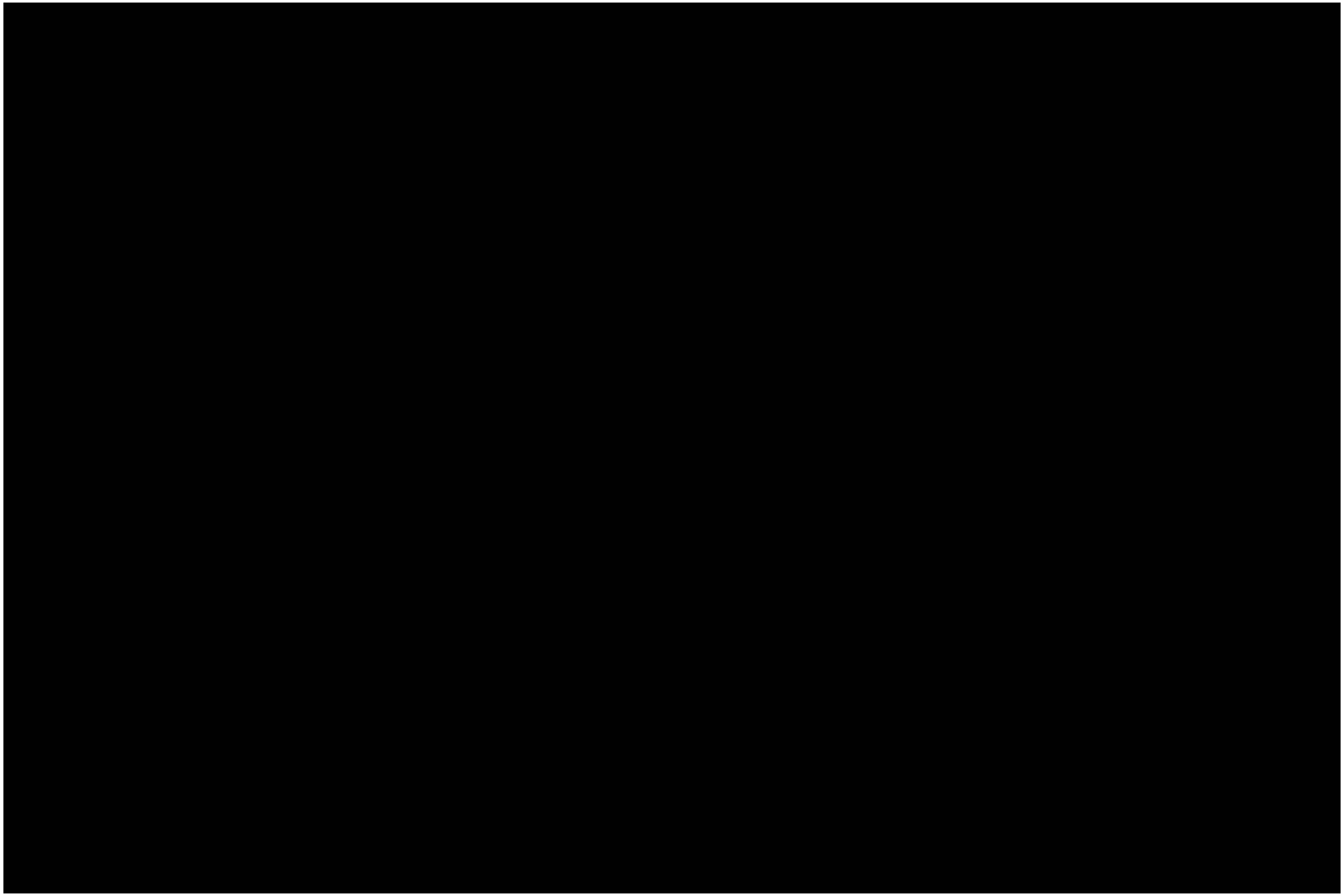
Mussel Superglue

- Mussels can stay attached to rocks in very strong tides
- They emit a slime that forms a thread-like, ultra-strong, water resistant adhesive on contact with water
- It's their ability to attach to surfaces underwater that makes the chemistry of mussels a possible breakthrough for use for bio-medical applications,

Mussel Superglue

- Scientists are jut incorporating the protein responsible for mussel glue into biomimetic adhesives.
- Also trying to figure out how to weaken it so that mussels can be more easily removed from ship hulls etc ..
- Mussel Power - New Self-Healing Sticky Gel
  - https://www.youtube.com/watch?v=4Xjm23u84LY

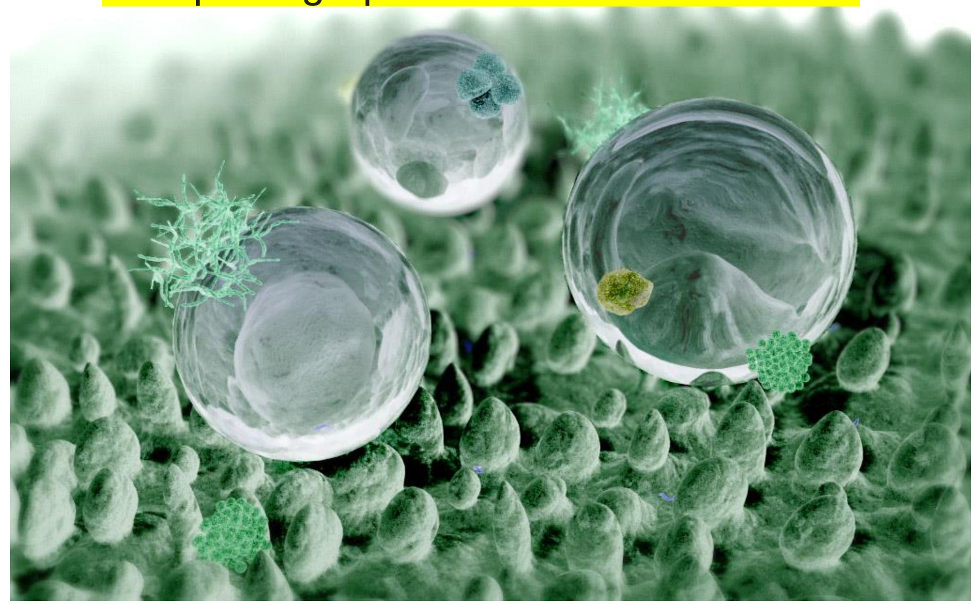
Mussel Adhesive in Action



Hydrophobic Materials: Lotus Leaf/self cleaning material

- Lotus leaves have a bumpy structure that causes water to bead and roll off

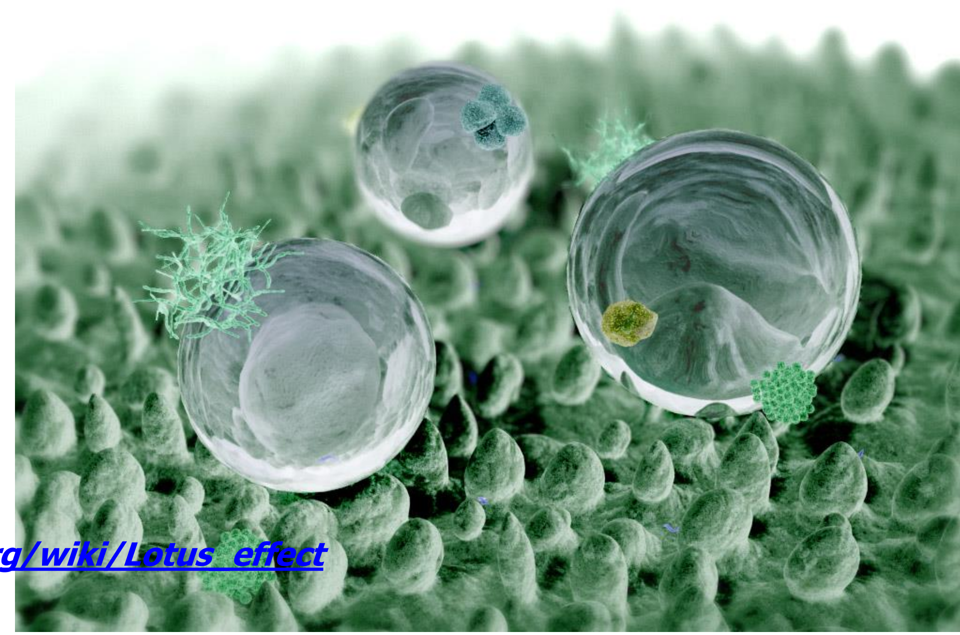
Computer graphic of a lotus leaf surface.



http://en.wikipedia.org/wiki/Lotus_effect

Hydrophobic Materials: Lotus Leaf/self cleaning material

- Instead of being absorbed, water droplets on a lotus leaf contract into balls
- Water-repellent surface: is the result of water's high surface tension and the leaf's bumpy (the leaf’s bumpy reduces contact area between droplet and leaf)



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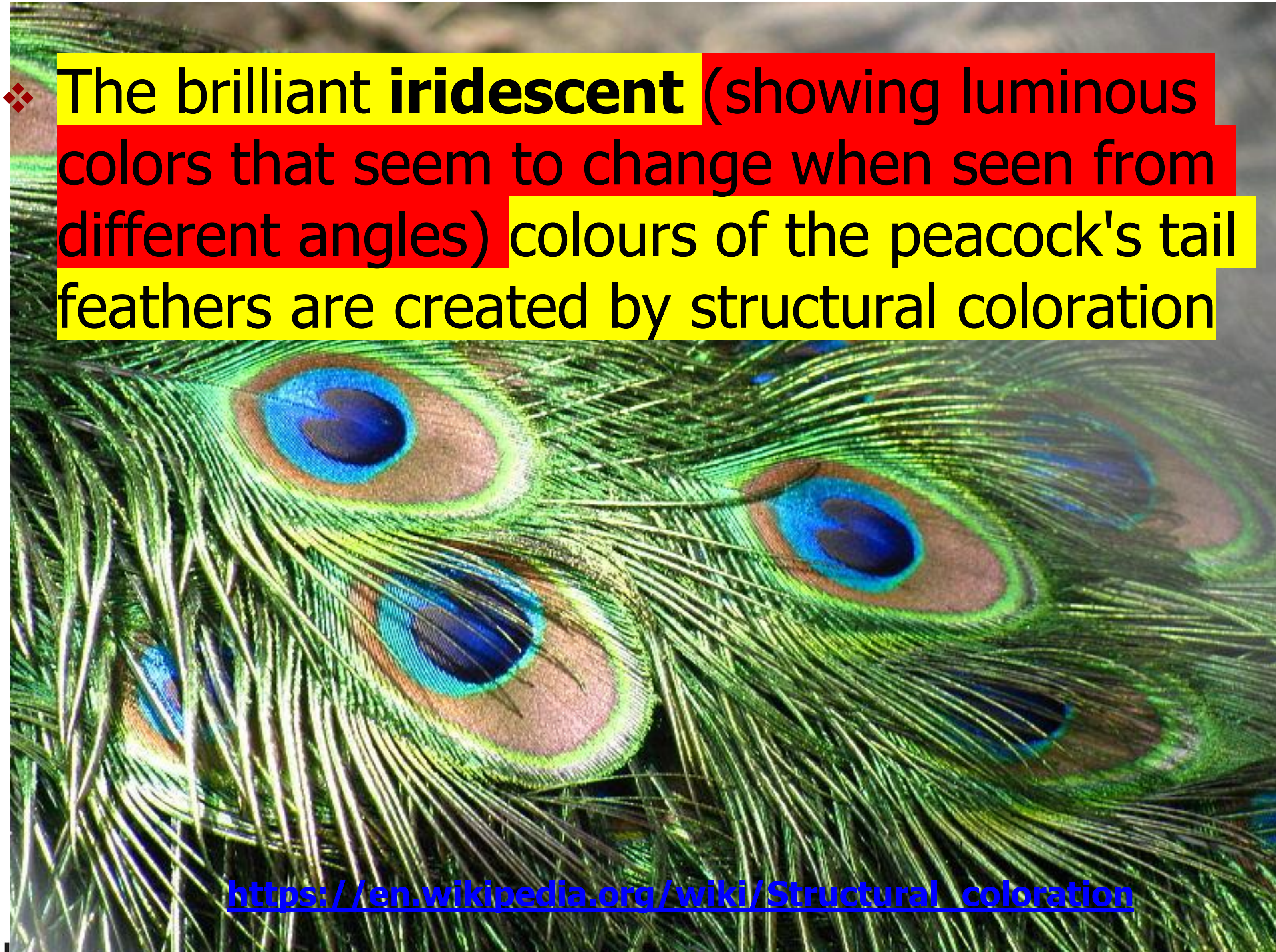
Hydrophobic Materials: self cleaning material

Structural coloration



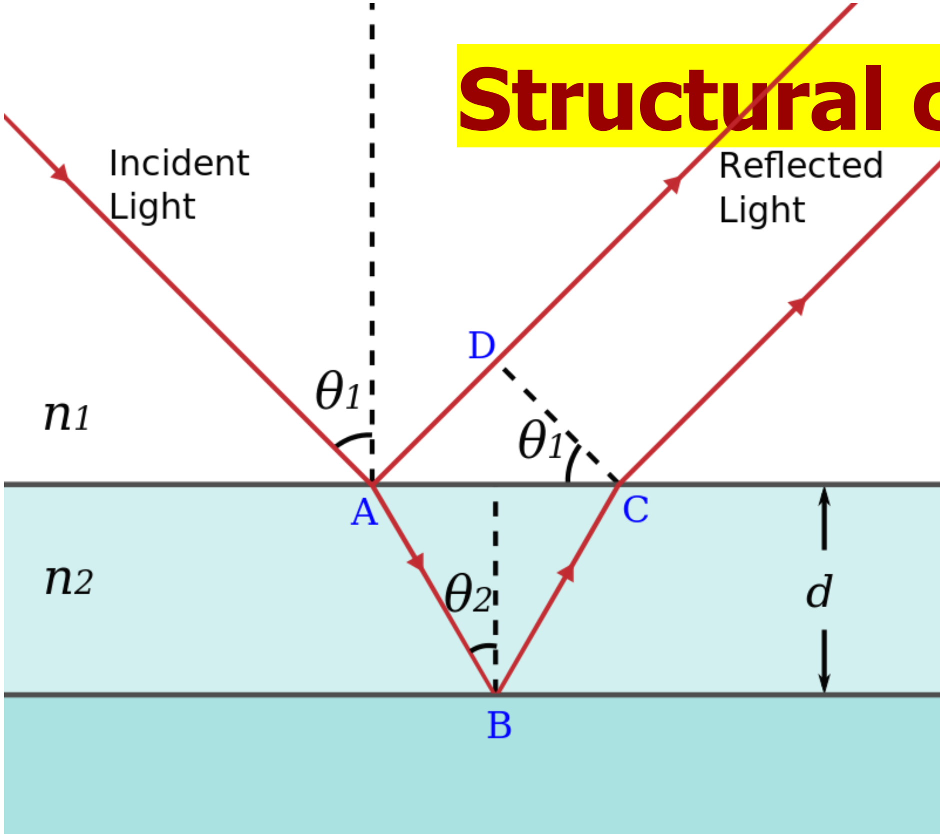
- The brilliant **iridescent** (showing luminous colors that seem to change when seen from different angles) colours of the peacock's tail feathers are created by structural coloration

https://en.wikipedia.org/wiki/Structural_coloration

Structural coloration

- **Structural coloration or schemochromes** is the production of colour by microscopically structured surfaces fine enough to interfere with visible light, sometimes in combination with pigments.
- **Structural coloration** is caused by interference effects rather than by pigments. Colours are produced when a material is scored with fine parallel lines, formed of one or more parallel thin layers, or otherwise composed of microstructures on the scale of the colour's wavelength

Structural coloration



https://www.youtube.com/watch?v=iBzzW4wv4

- When light falls on a thin film, the waves reflected from the upper and lower surfaces travel different distances depending on the angle, so they interfere.

Materials with structural hierarchy

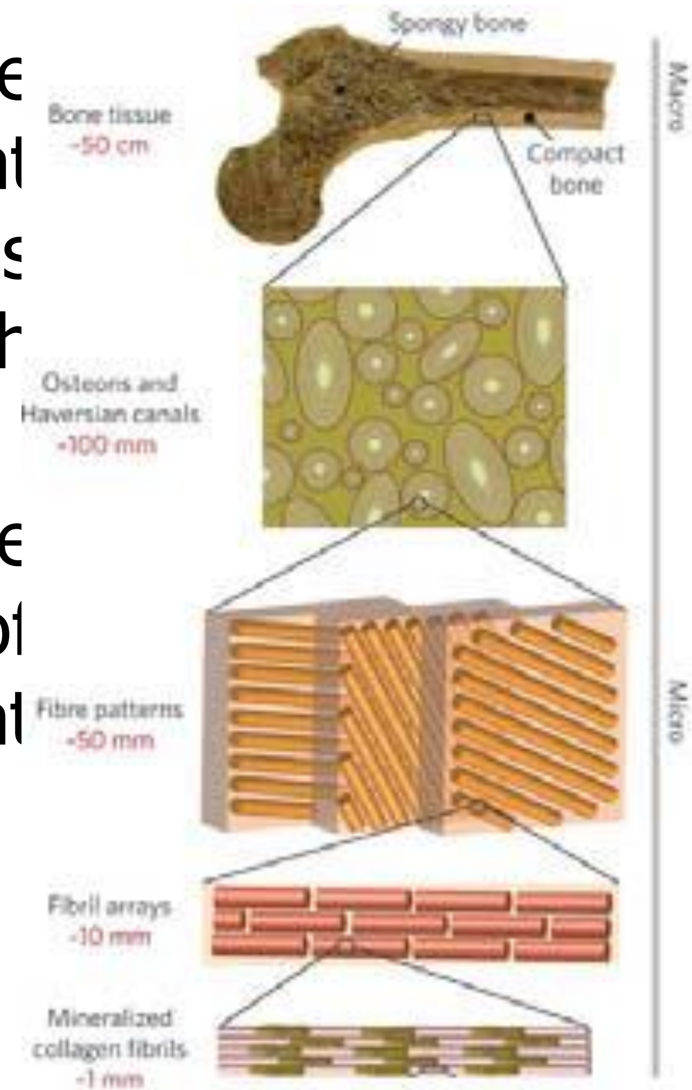
- There are many materials (both man-made and natural) that possess structure at more than one scale.
- The hierarchy of these structures plays a crucial role in defining the properties of the overall material.
- The structural hierarchy can result in improved mechanical properties of the overall material (e.g., strength, toughness).

Learning Objectives

- Smart materials
- Advanced materials
  - Cellular materials
    - Metamaterials
  - Composite materials
    - Piezoelectric composites
    - Functionally graded materials
    - Robotic materials
  - Biomimetic/Bio-inspired materials
  - **Materials with structural hierarchy**

Materials with structural hierarchy

- The structure of these materials has to be defined at multiple scales -- it involves identifying features at each scale.
- Human bones and livers are classical examples of materials with structure at different scales.



QUESTIONS?