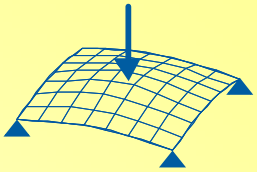
Cyklus prednášok pod záštitou rektora STU

Lecture series under the auspices of STU rector



Mechanics and applications of multifunctional materials and structures

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Arad
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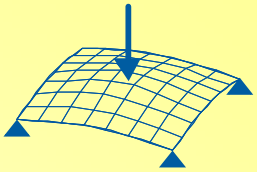
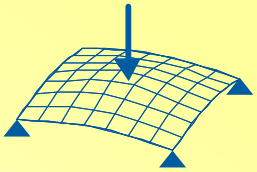
Where is Siegen?

Research subjects

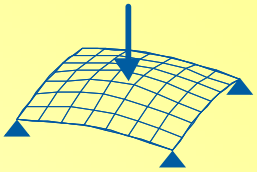


- Fracture analysis of FGMs
- Fracture analysis of smart materials
- Wave propagation in smart structures
- Wave propagation in phononic crystals
- Sensitivity analysis of damaged structures
- Computational mechanics

OUTLINE

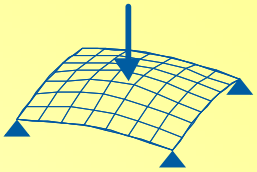


- Physical motivation
- Functionally graded materials (FGMs) and structures
- Phononic crystals (PCs) and structures
- Smart materials and structures
- Conclusions

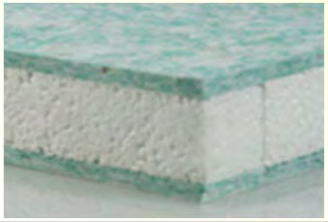


Physical motivation

Multifunctional materials



Mechanical loading



Super high temperature

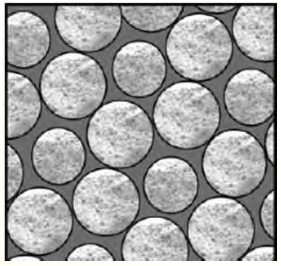
Wear

Corrosion

Noise protection

Oxidation

Light transmission and reflection



Chemical loading

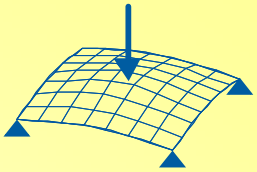
Radioactivity

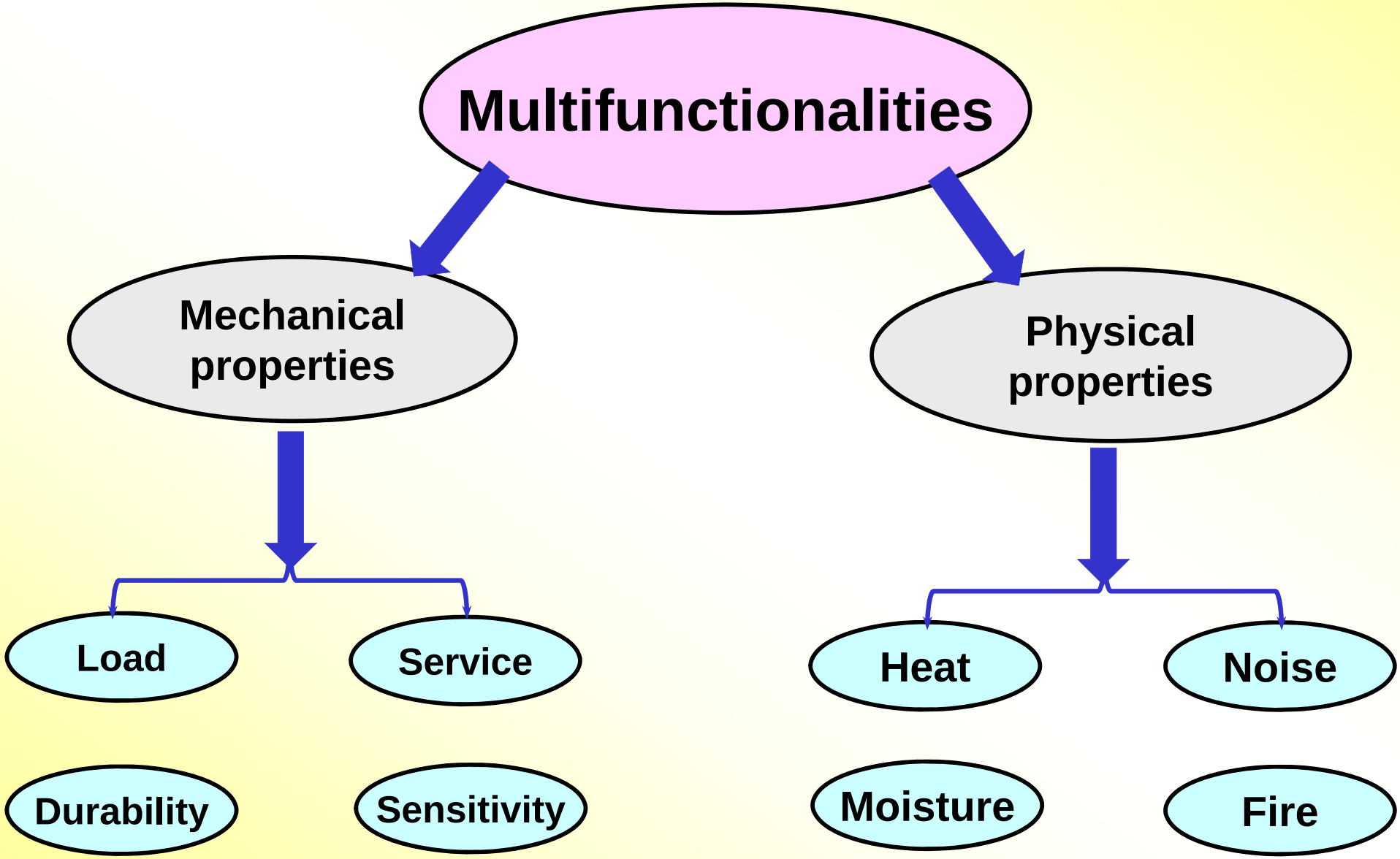
Electric and magnetic loading

Biological compatibility

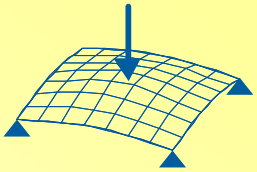
A single material phase cannot satisfy all these requirements!

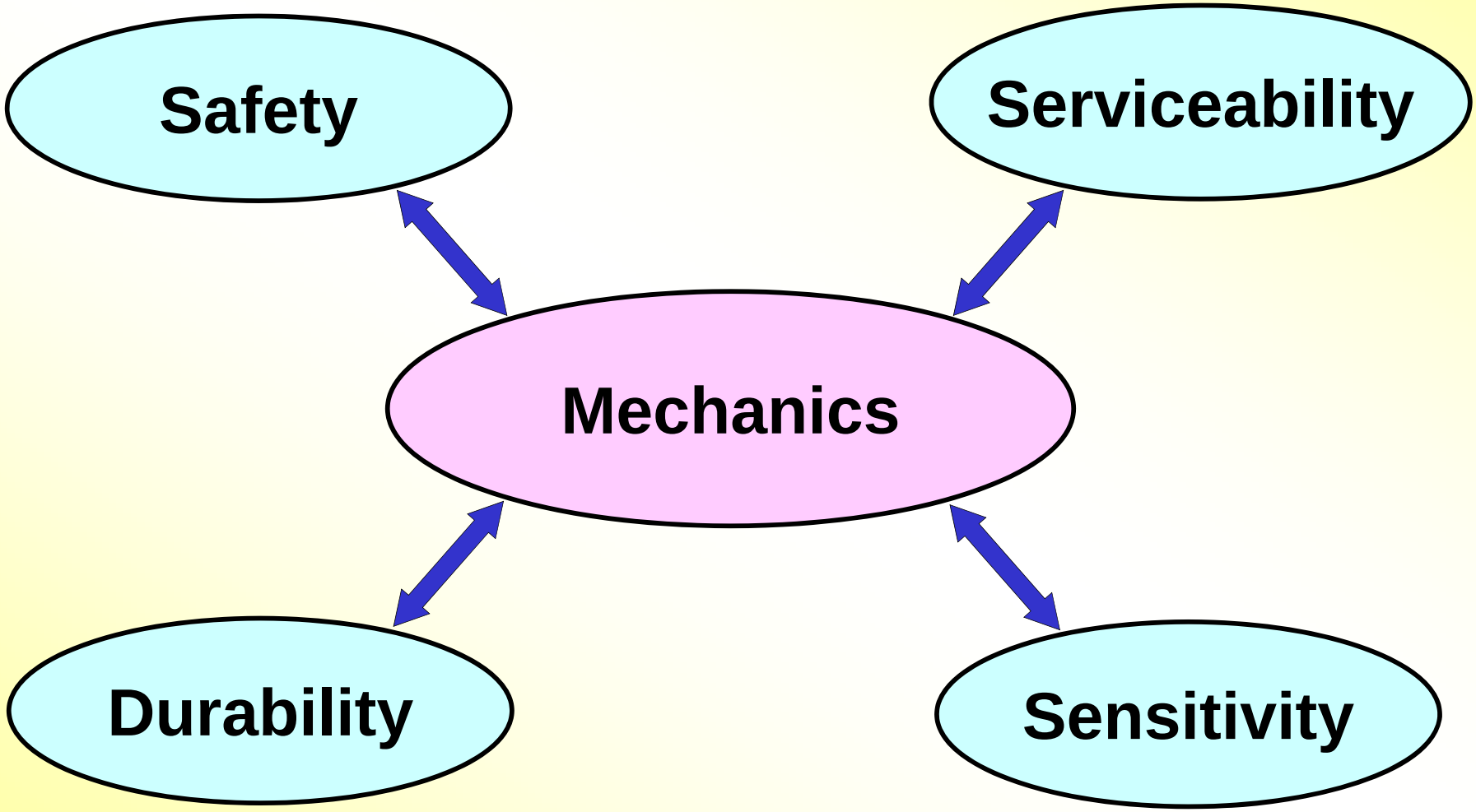
What does „multifunctional“ mean?



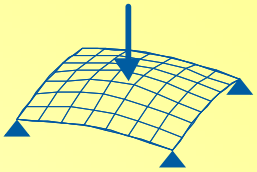


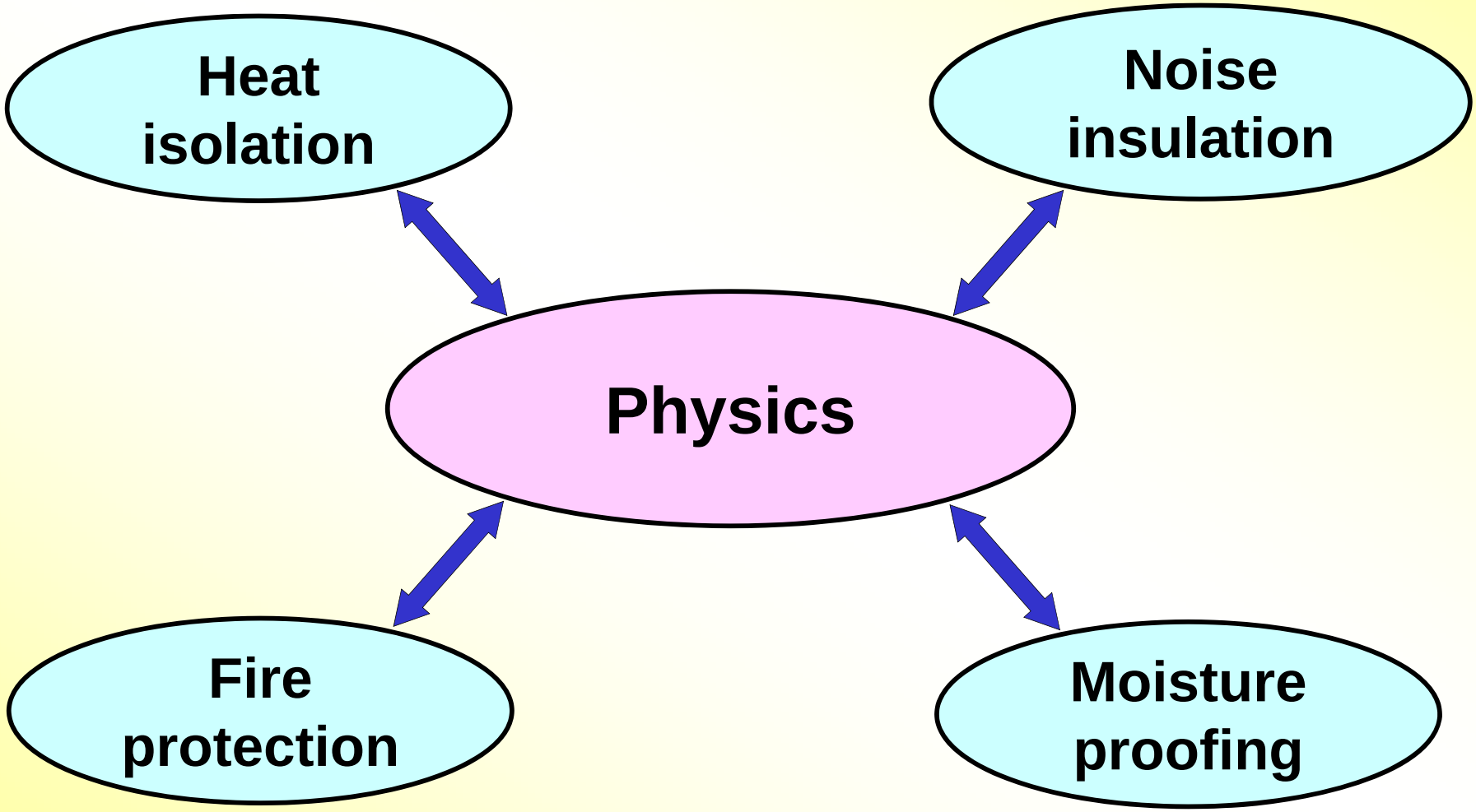
Multifunctionalities

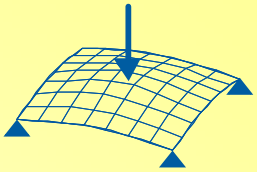




Multifunctionalities

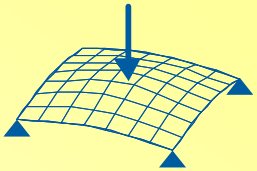






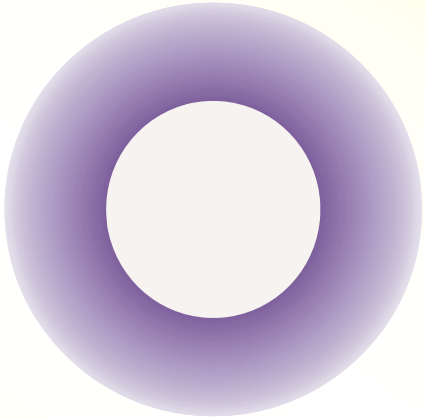
Fuctionally graded materials (FGMs) and structures

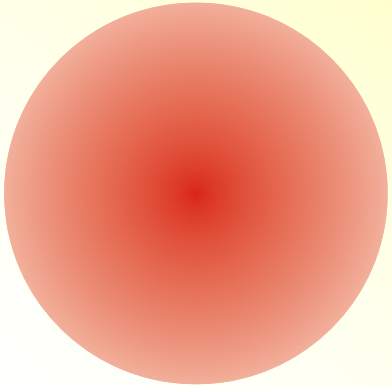
Why Functionally Graded Materials (FGMs)?



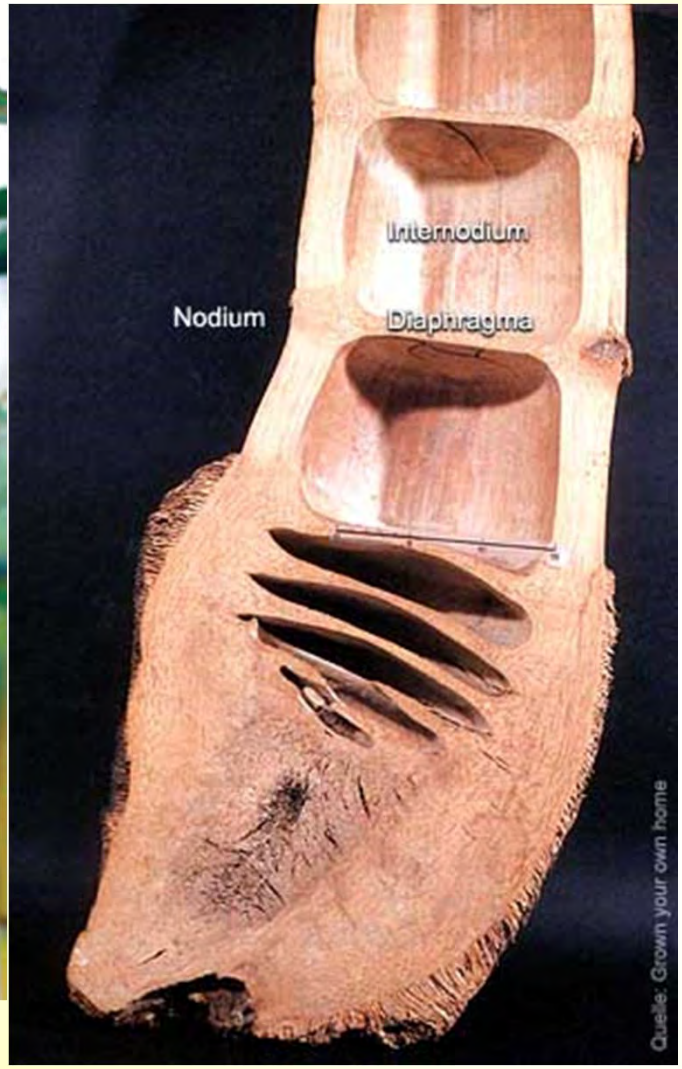
Functionally Graded Materials (FGMs):

- Advanced functional composites
- Continuous profile of materials constituents
- Material constants change continuously in space

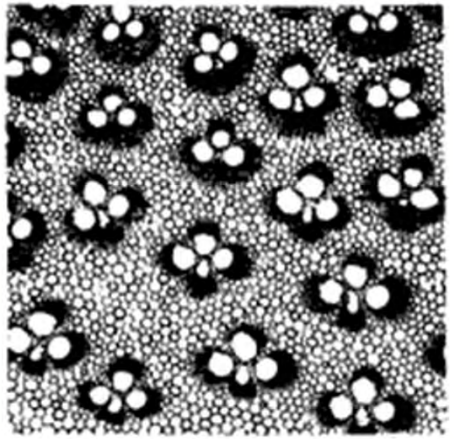




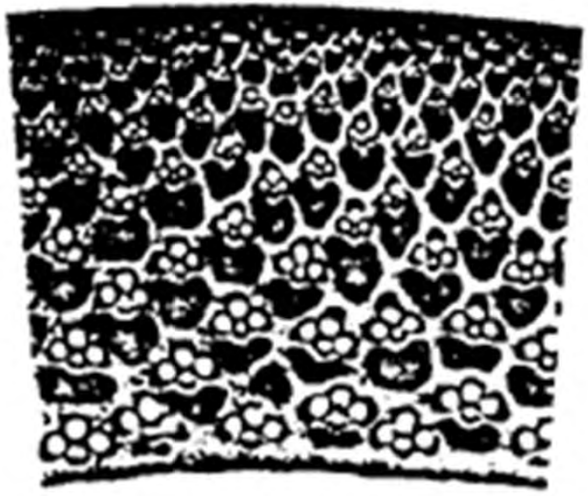
FGMs: Lesson from nature



Fiber

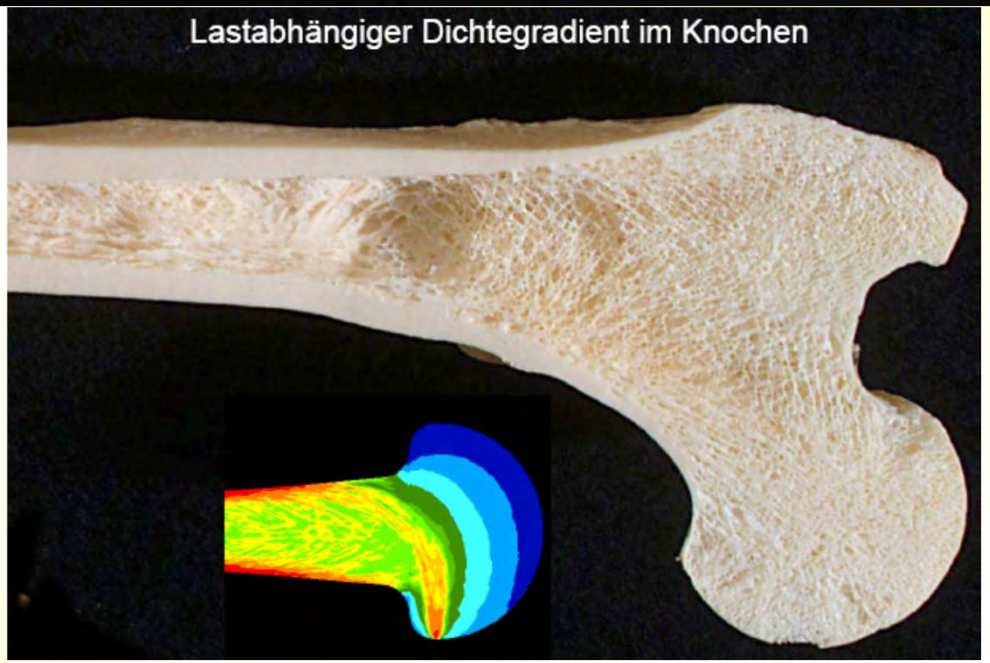


out side

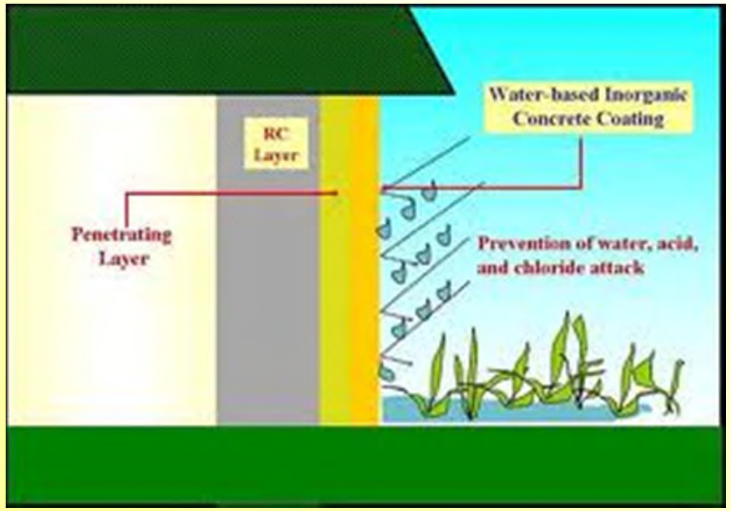


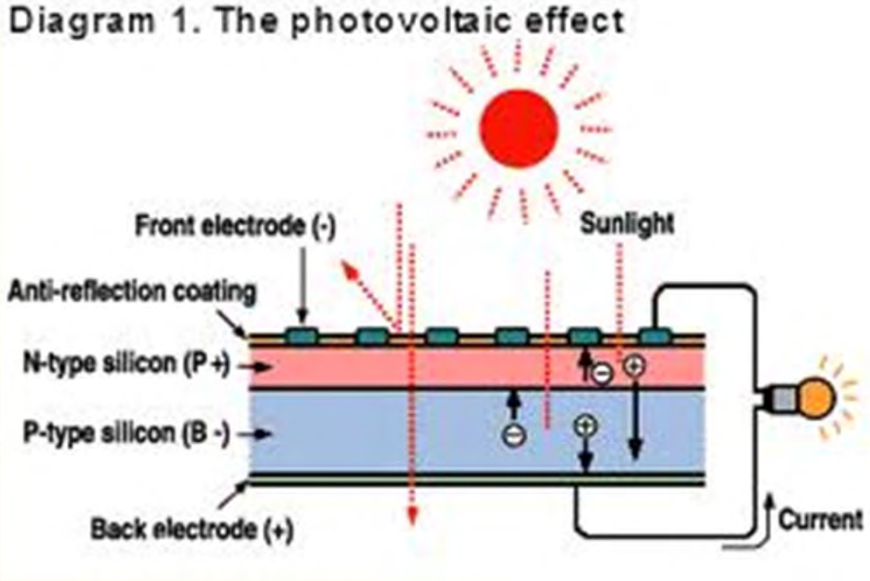
inner side

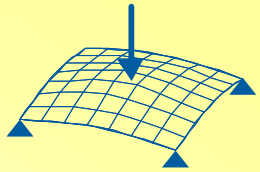
FGMs: Lesson from nature



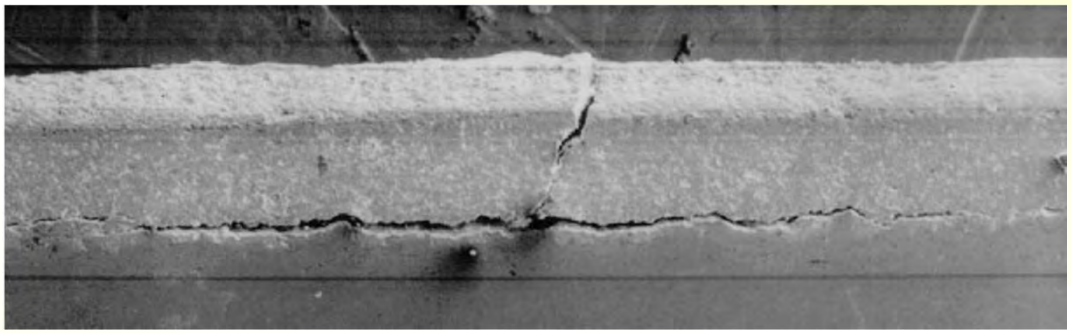
Innovative applications of FGMs and structures

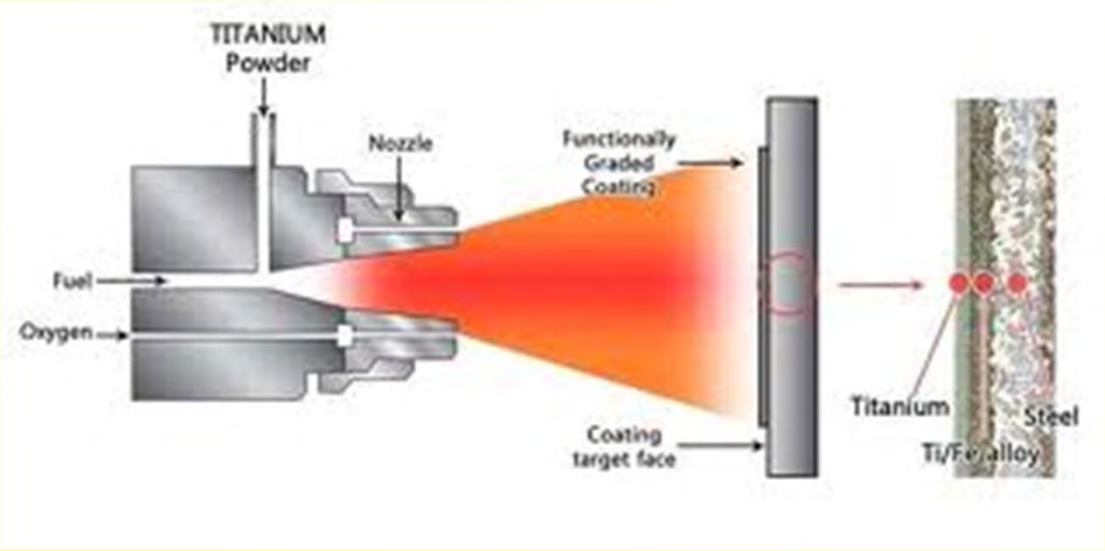


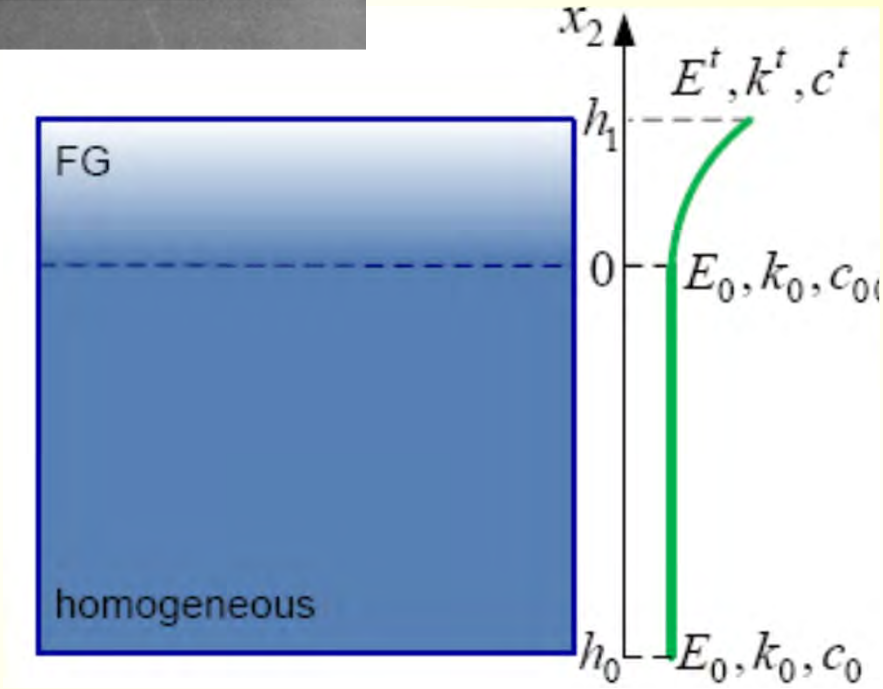




Problem: Interface cracking !







FG coating

Applications of FGMs and structures

Important applications:

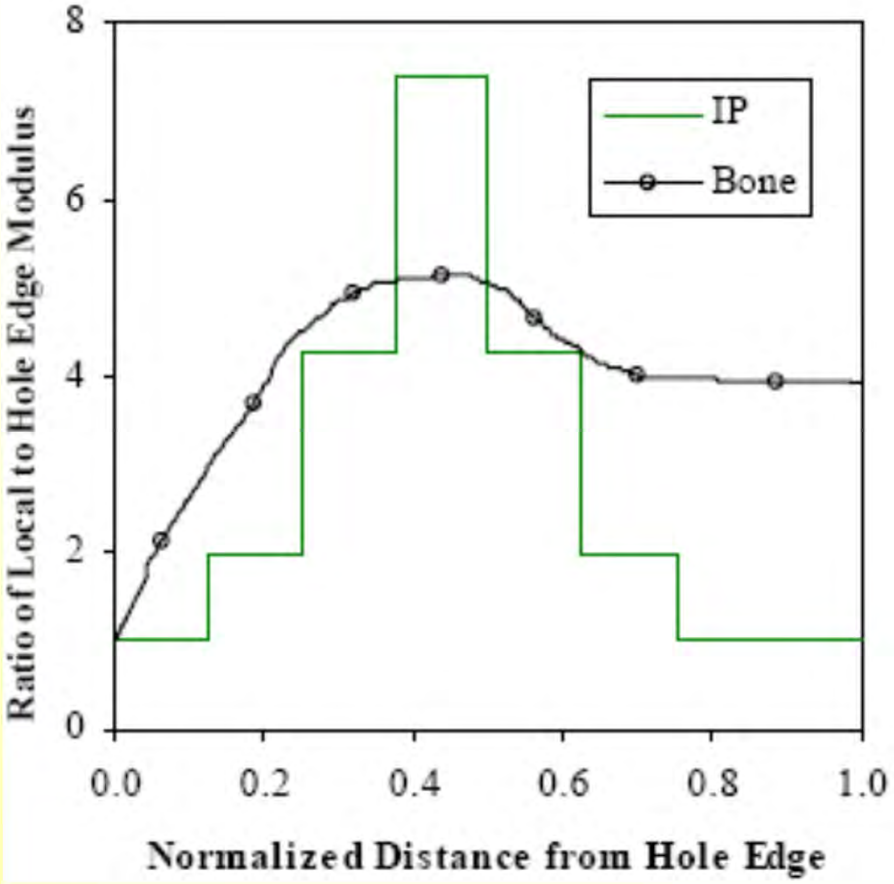
Thermal barrier coating for severe temperature conditions.

Objectives of our works:

Crack analysis for thermal shock loading and impact loading!

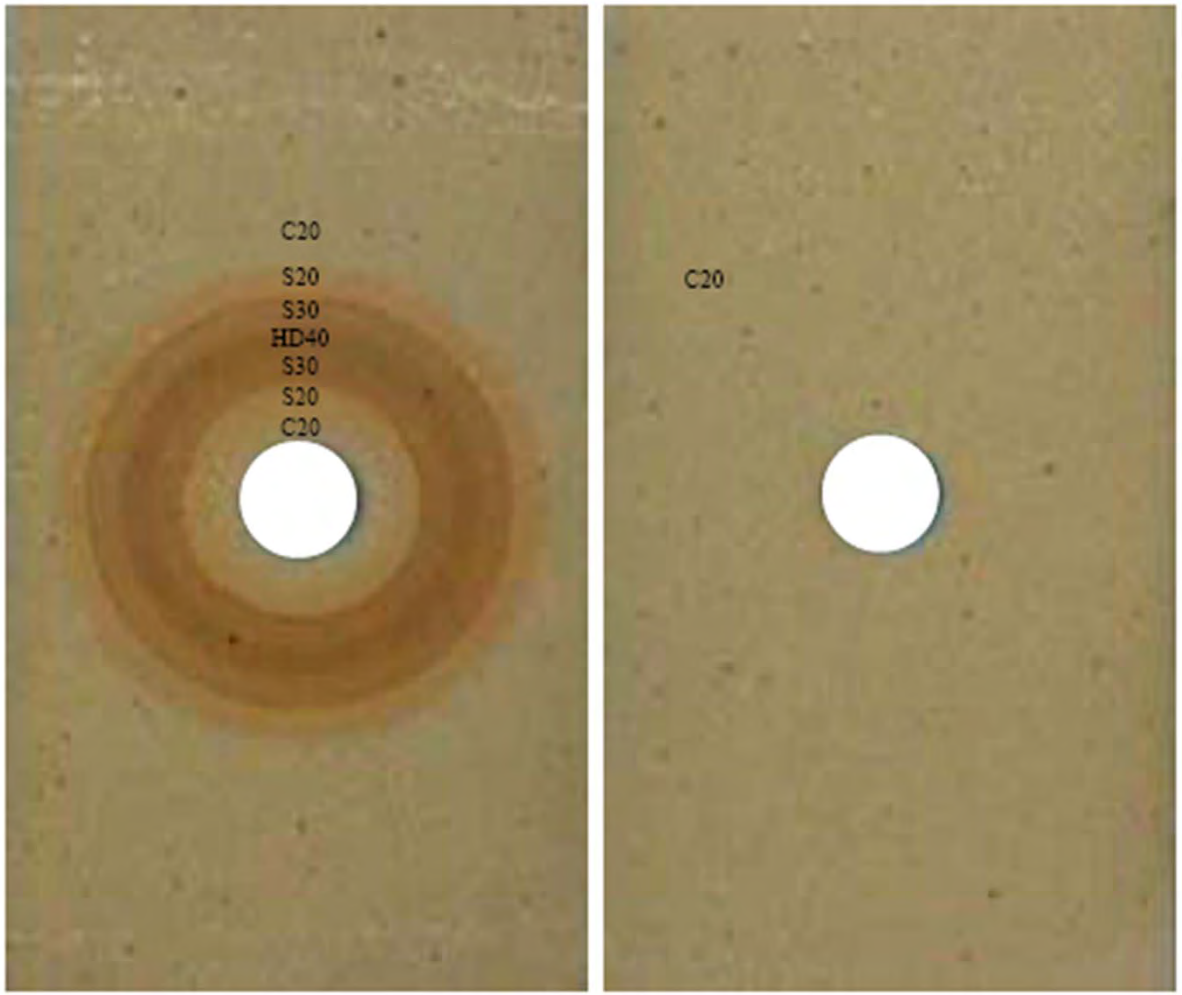
- **Natural holes (foramina) exist in all bones to allow blood vessels to pass through their hard outer shells.**
- **Foramina never appear as fracture sites clinically or in laboratory tests of hole bones.**

How bones design and adapt holes?



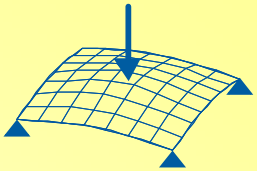
Local modulus distribution

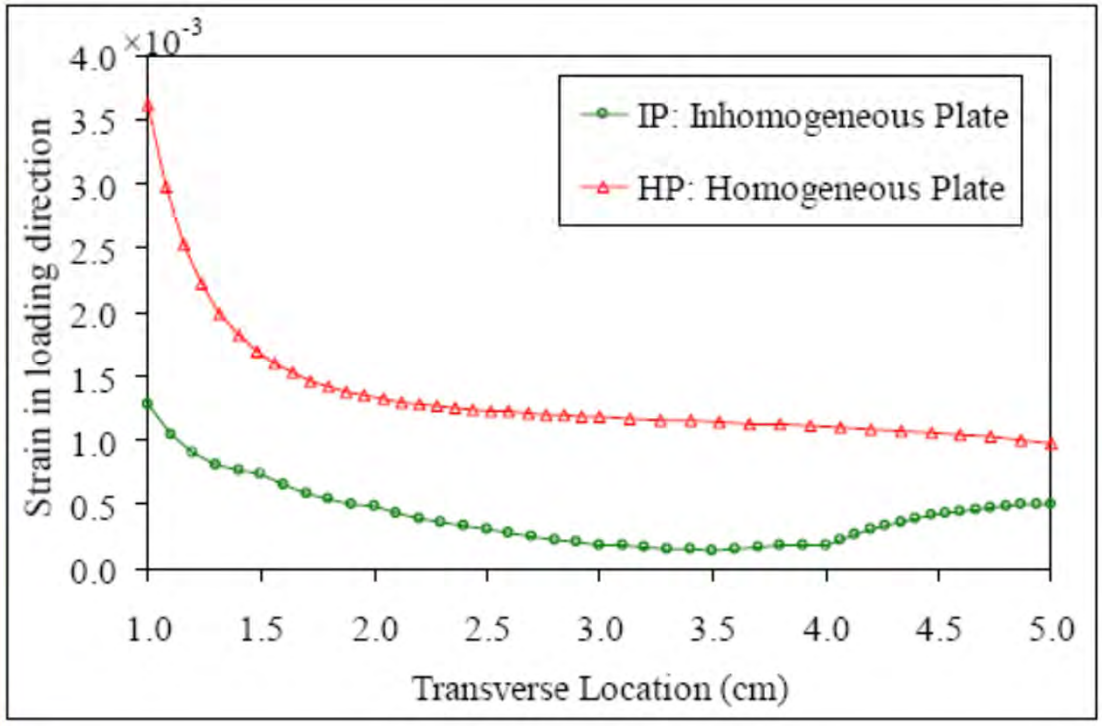
(Buskirk et al., 2002)

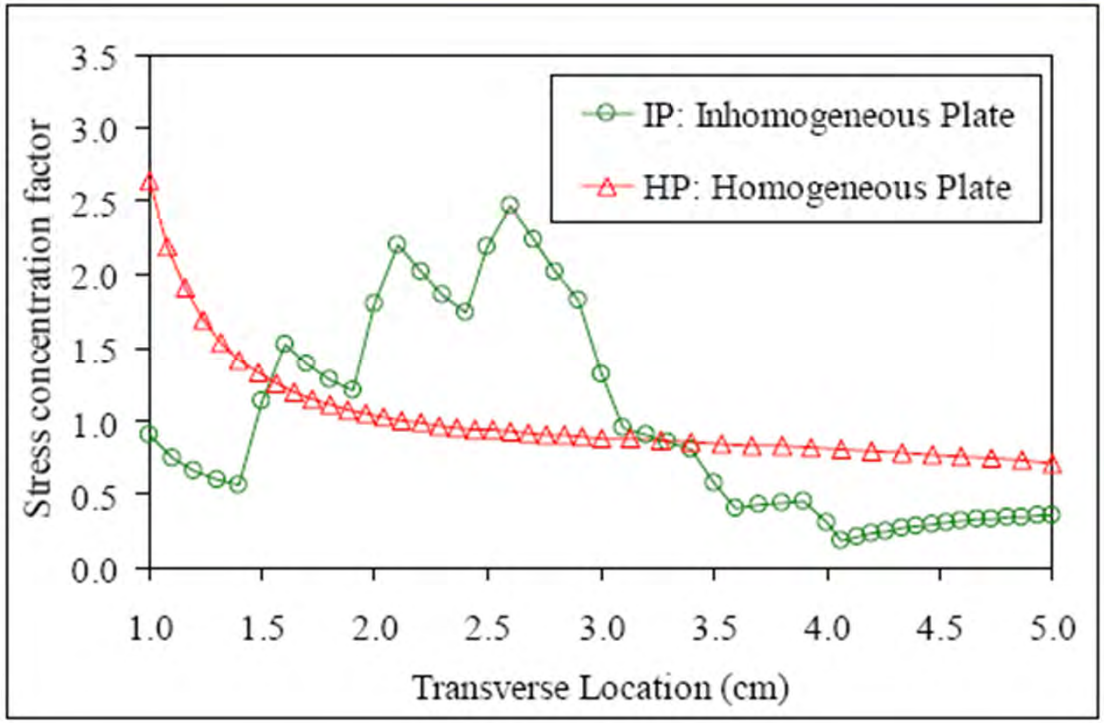


Biomimetic plate

Biological design of a hole



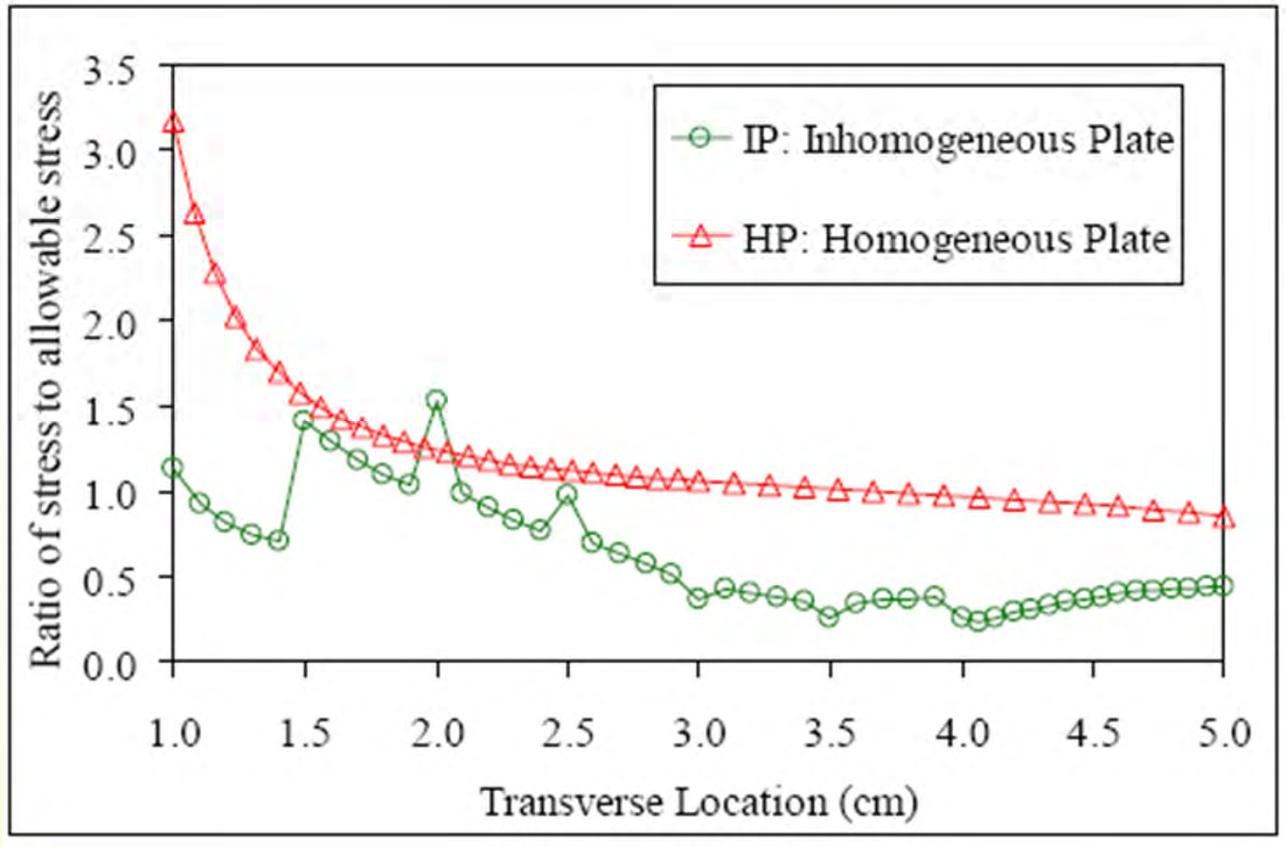




Strain distribution

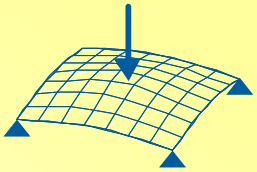
Stress distribution

Biological design of a hole

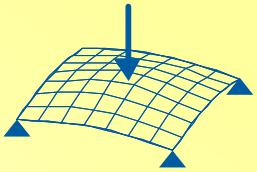


Stress failure index (load carrying capacity)

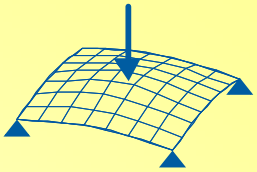
Key questions



- How to learn from nature materials?
- Can we design FGMs which allow holes but without stress concentration?
- Can we design FGMs which allow cracks but without or with reduced failure risk?

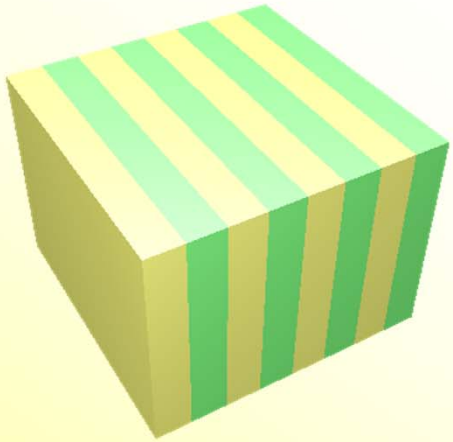


Phononic crystals (PNCs) and structures

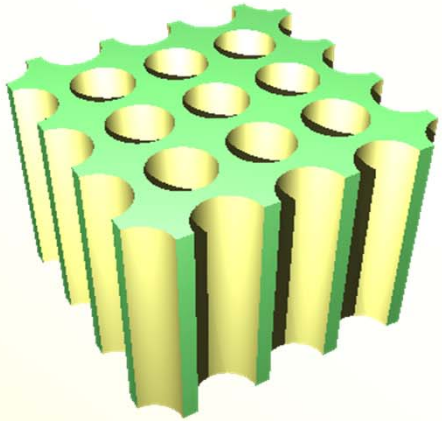


Phononic crystals

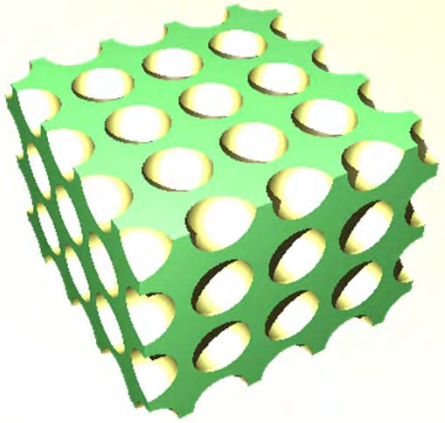
Composite materials composed of periodic arrangement of more than two materials with different elastic properties.



1-D



2-D



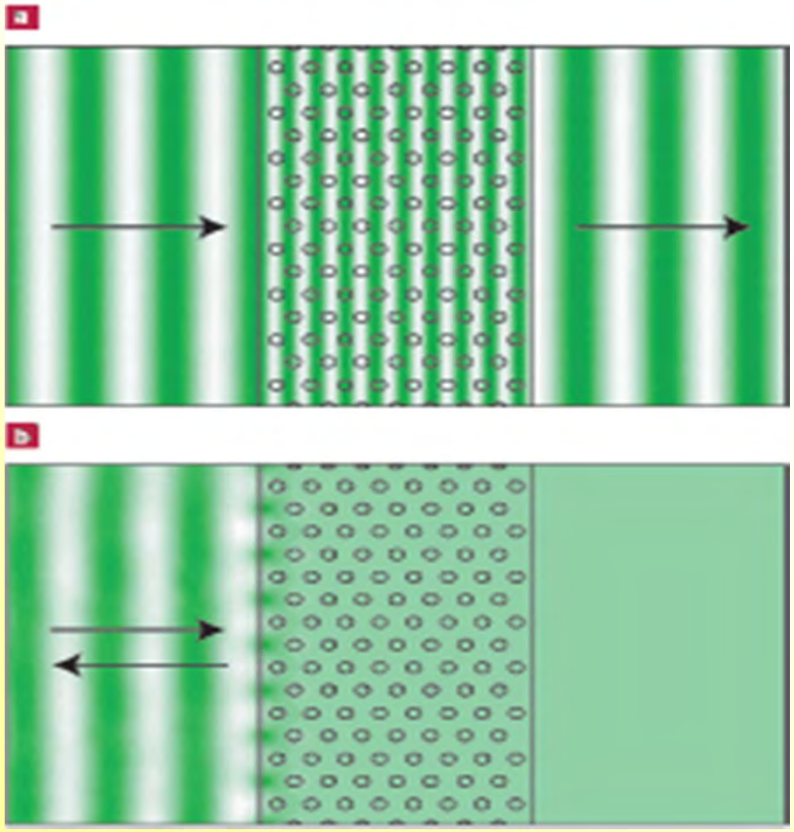
3-D

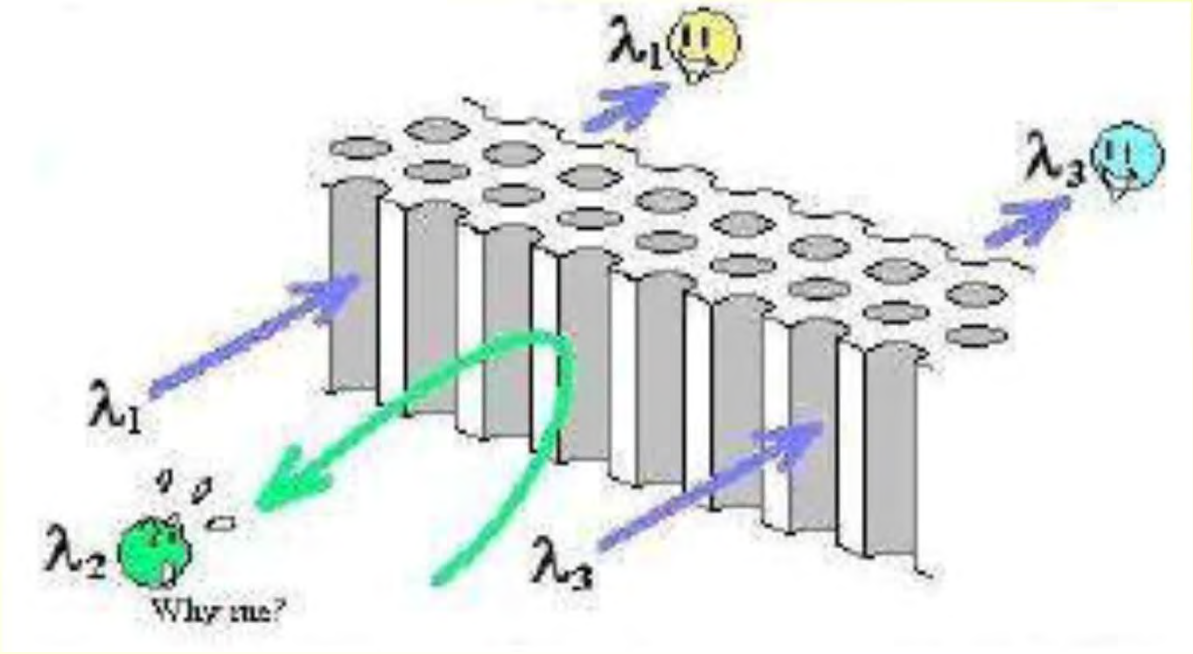
Phononic crystals may have frequency band gaps!

Wave propagation in phononic crystals

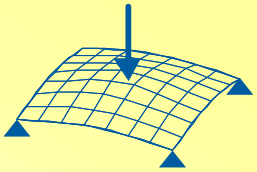
Band-gap: Frequency range, in which the propagation of elastic waves is prohibited.

Innovative applications: Acoustic filter, vibration isolation, noise reduction.

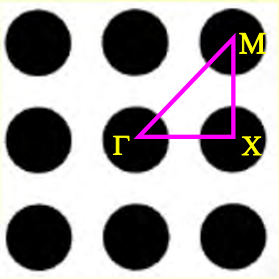




Band-gaps (stop bands)



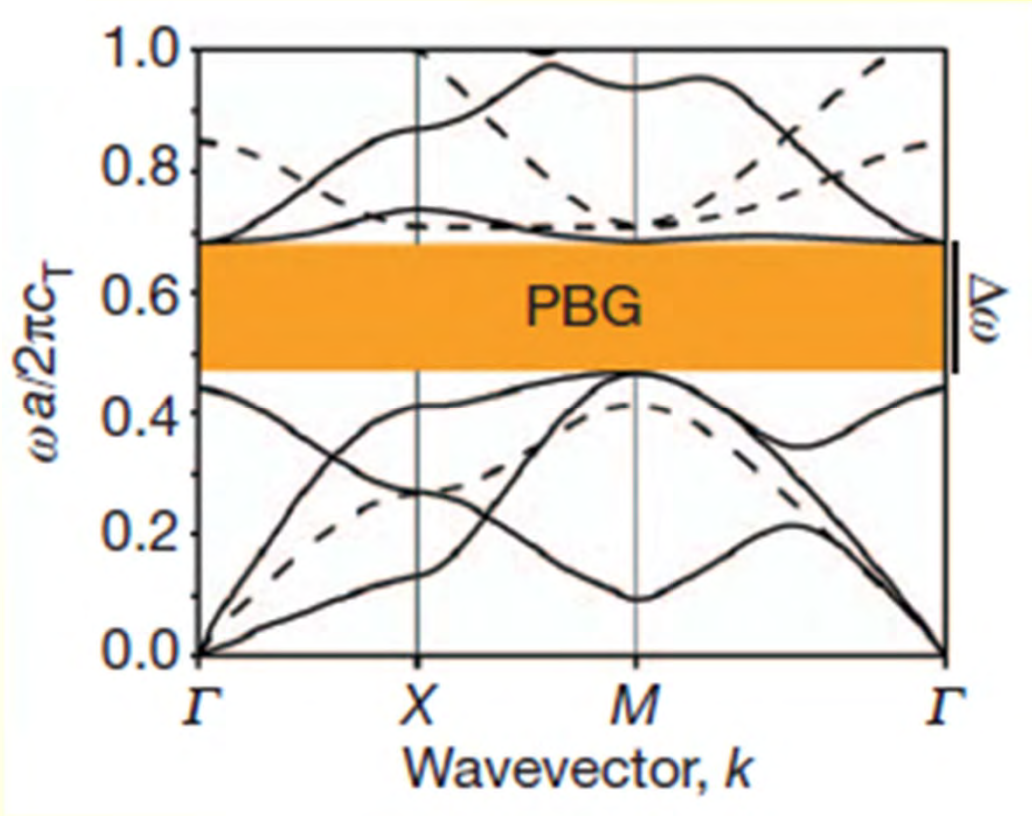
Elastic wave propagating in phononic crystals:



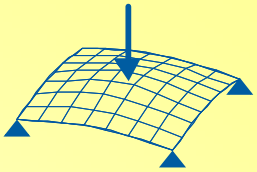
- Pass band
- Stop band: band-gap (PBG)

Mechanisms of band-gaps:

- Bragg scattering
- Local resonances



Wave propagation in phononic crystals



Applications:

- Noise reduction
- Vibration damping
- Design of new acoustic devices
- …

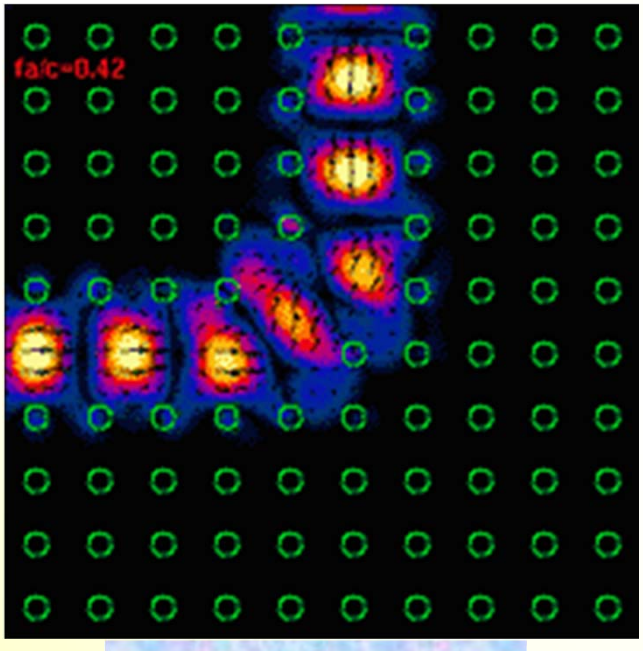
Nanoscale phononic crystals:

Hypersonic phononic crystals

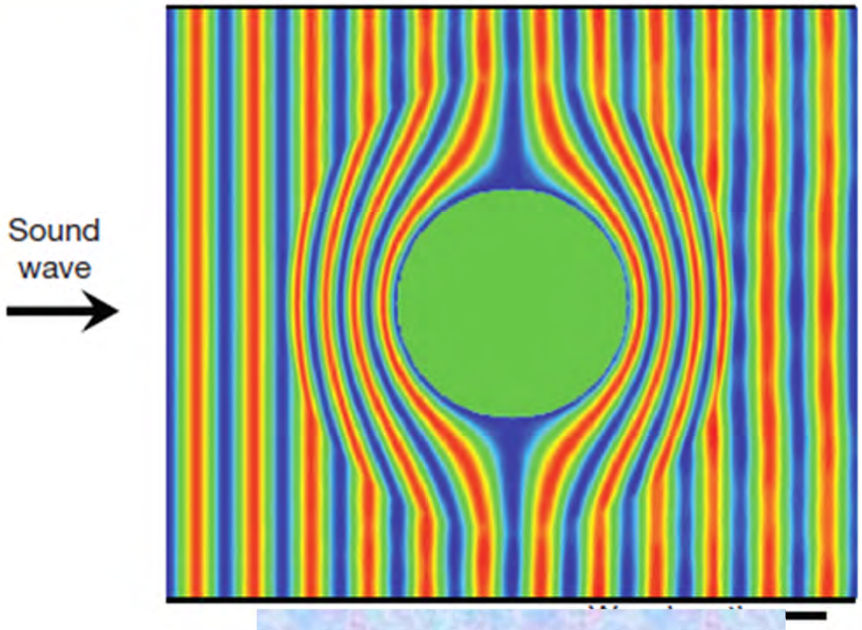
- Acousto-optical modulation
- Electron-phonon engineering
- Heat management
- …

Phys. Rev. Lett. 94, 115501, 2005
Phys. Rev. Lett. 101, 033902, 2008

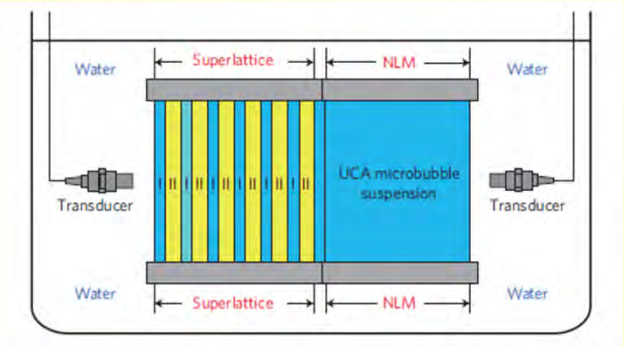
Innovative applications



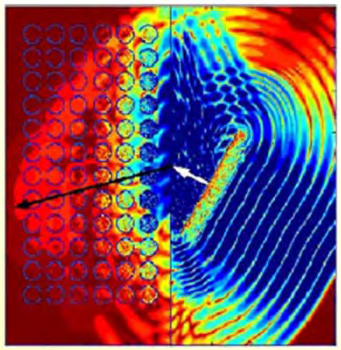
Wave bending



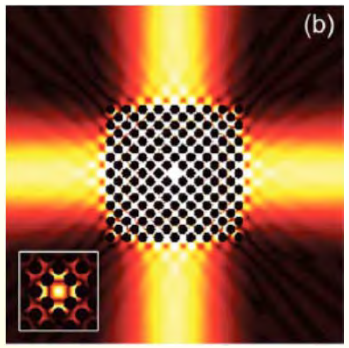
Acoustic cloaking



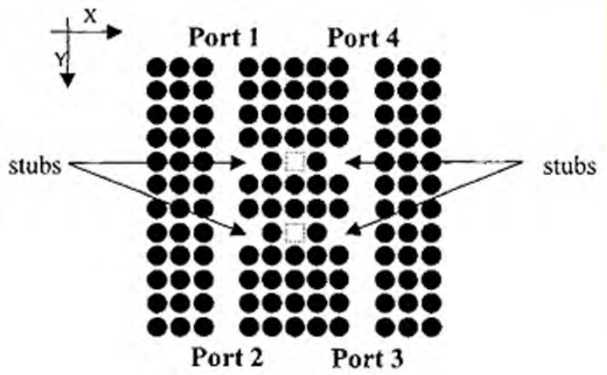
Acoustic diode



Negative refraction

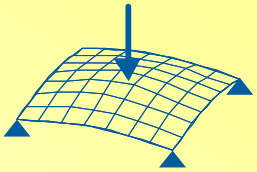


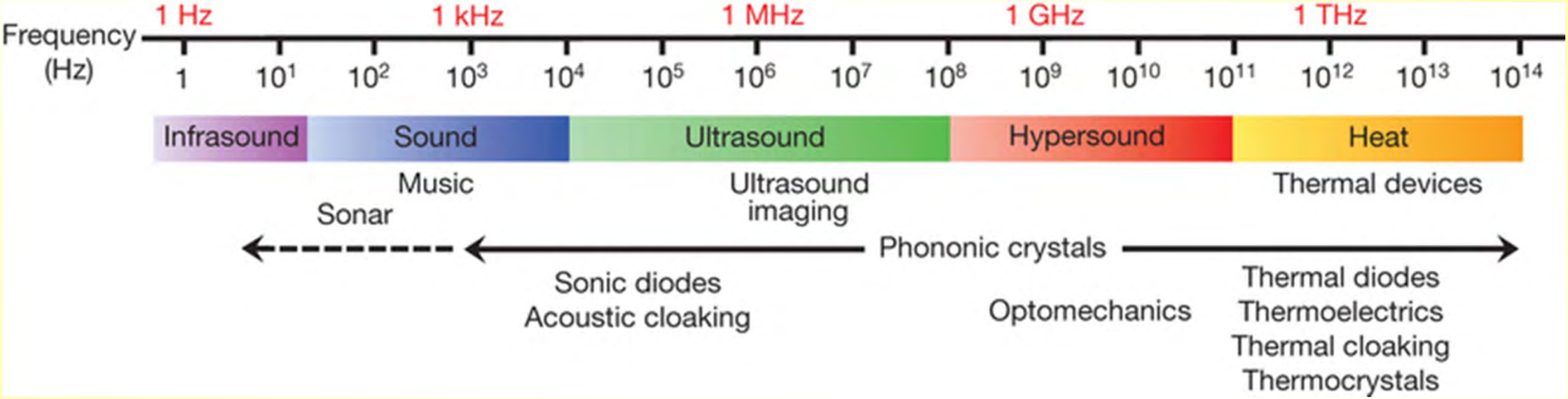
Wave guide



Phonic coupler

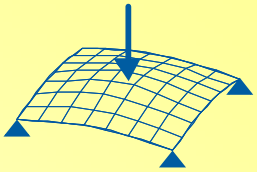
Phononic spectrum





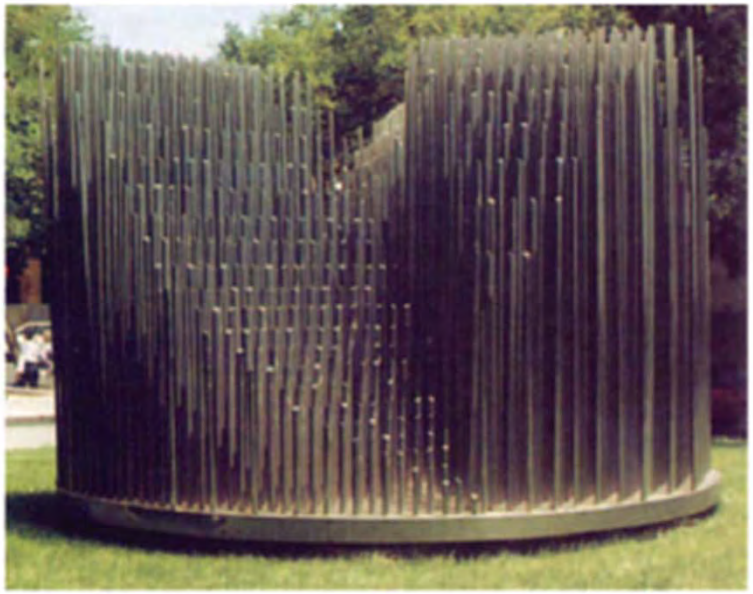
Martin Moldovan: *Nature* 2013, 503: 12608

From macroscale to nanoscale



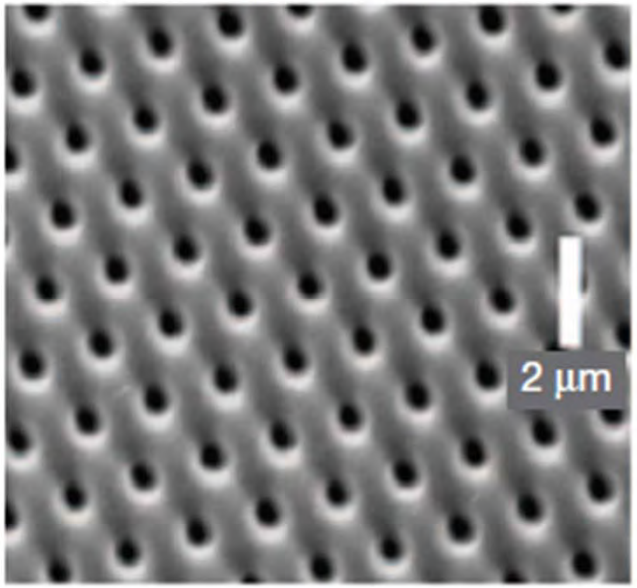
c

Sound



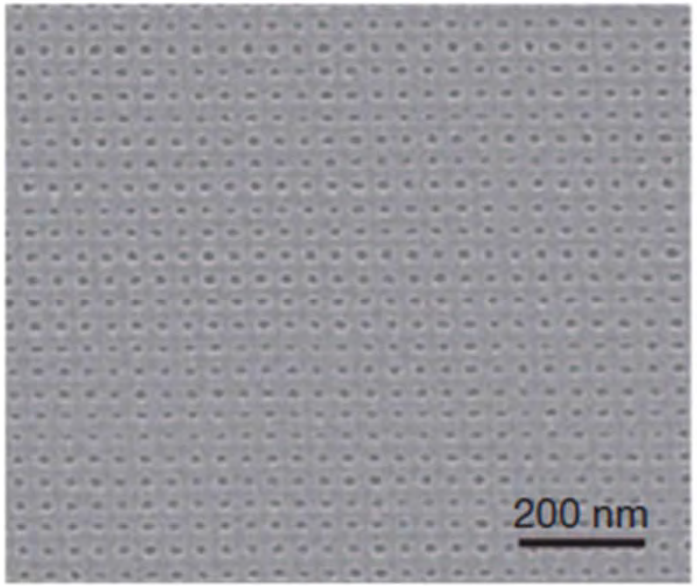
kHz

Hypersound



GHz

Heat



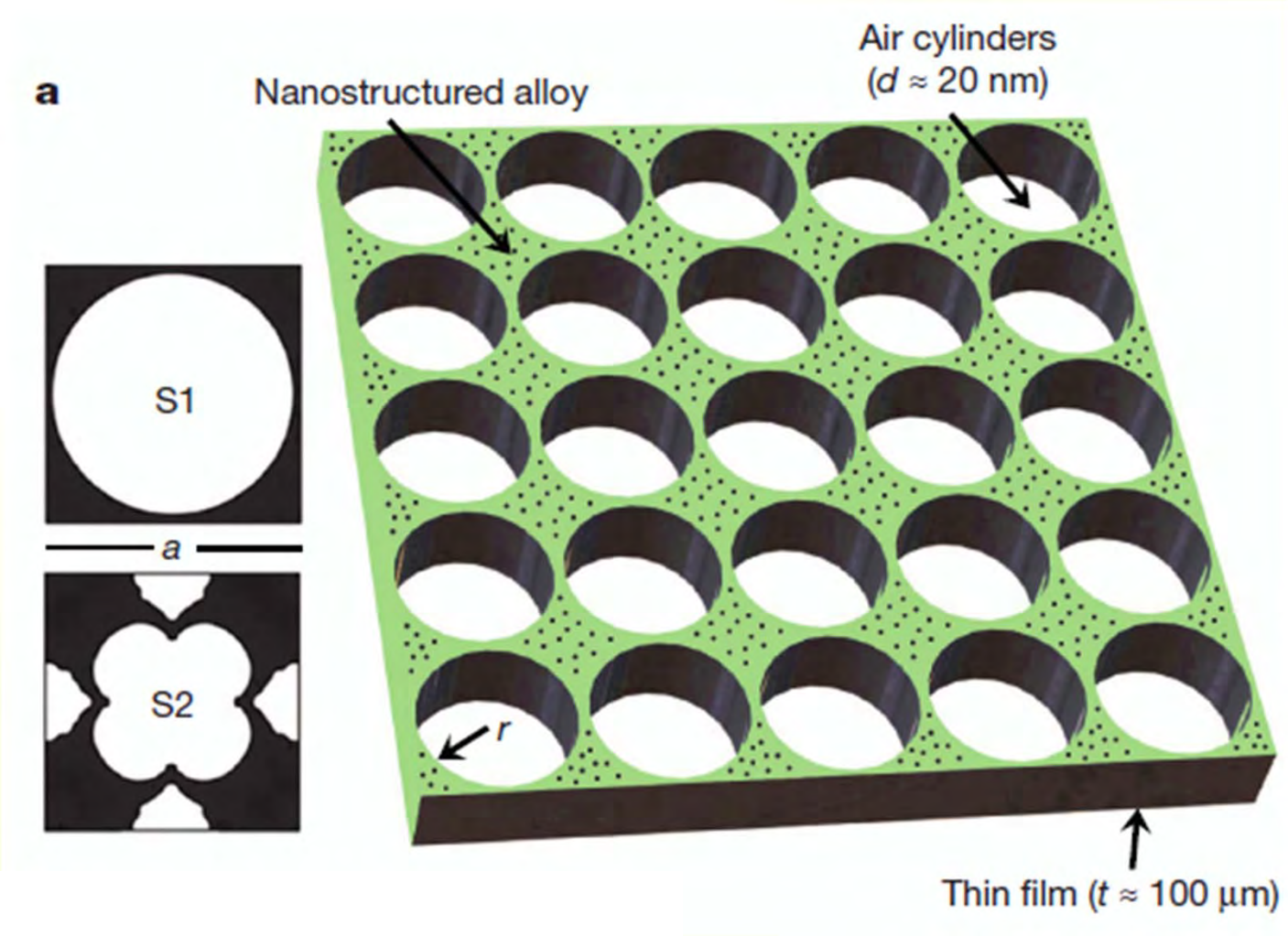
THz

Macroscale

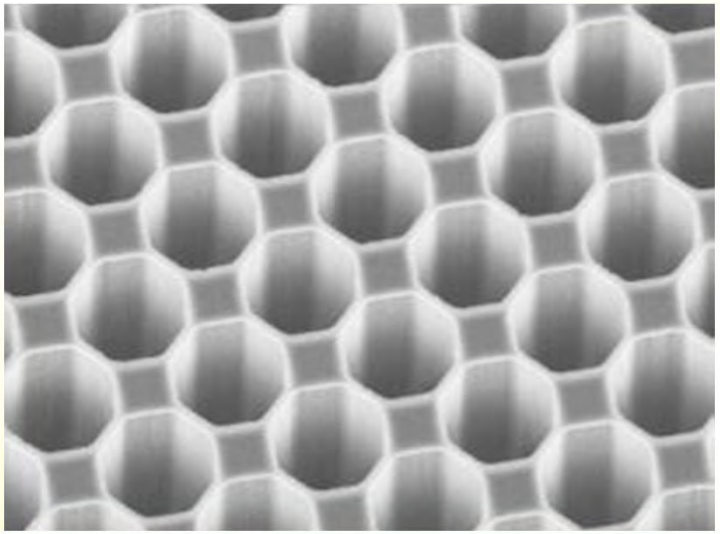
Microscale

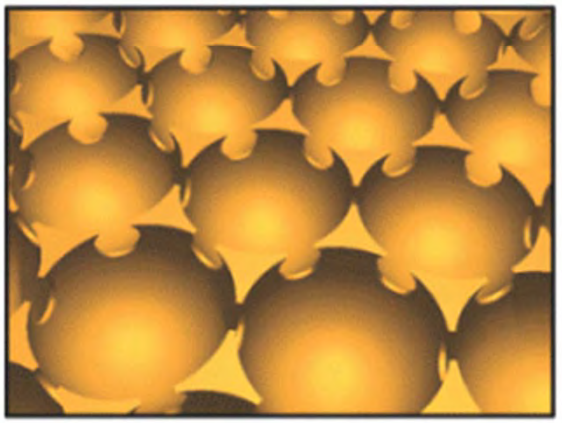
Nanoscale

Micro- and nanoscale PNCs

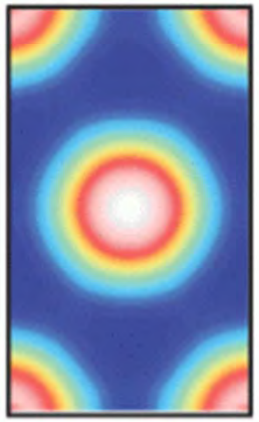


Micro- and nanoscale PNCs

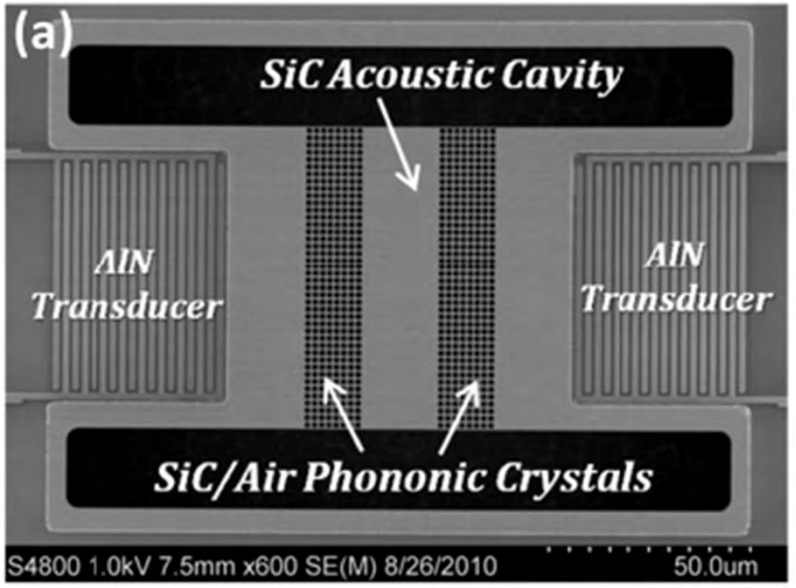


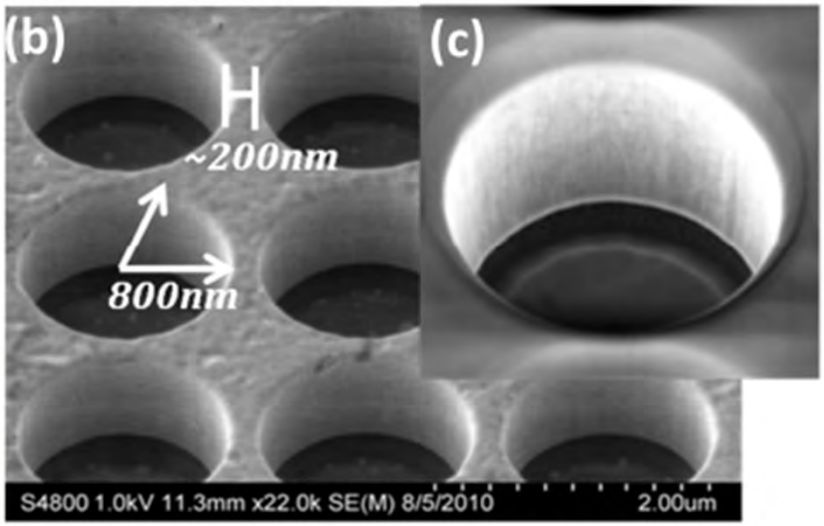


gold nanovoids

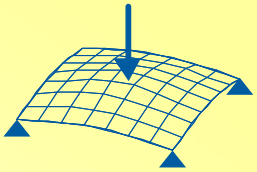


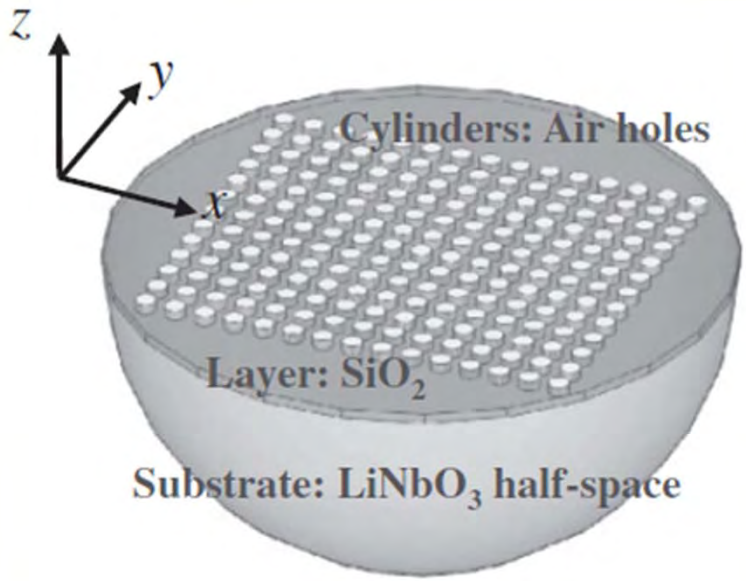
0.73 GHz

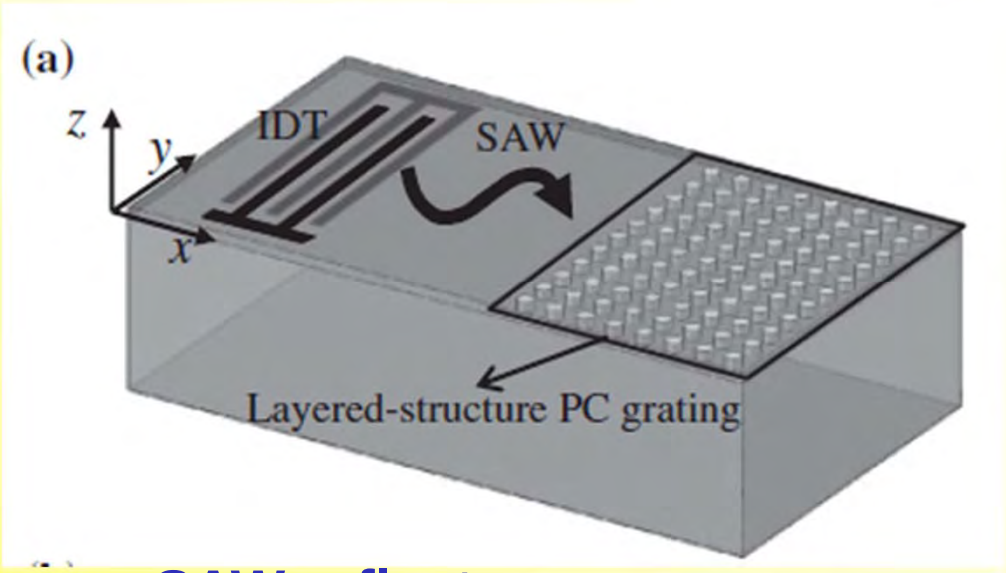




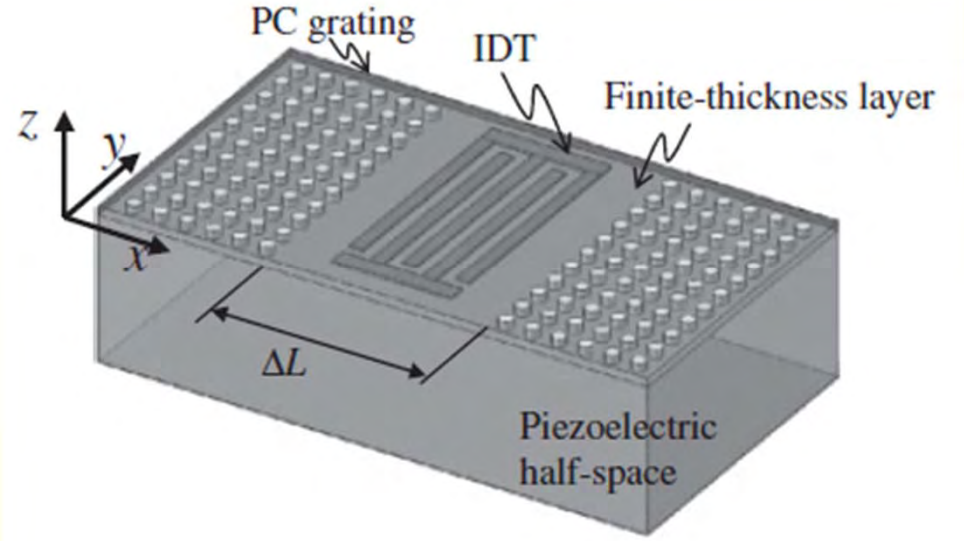
Surface acoustic waves in PNCs



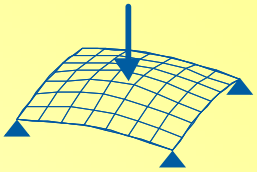




SAW reflector

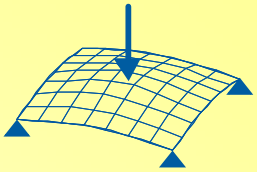


SAW resonator



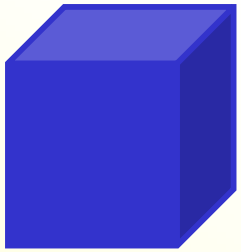
Smart materials and structures

Smart materials and structures



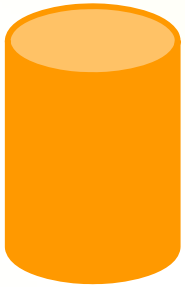
Mechanical energy

Piezoelectricity

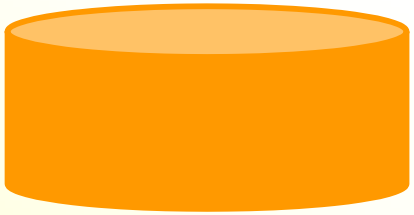


Electrical field

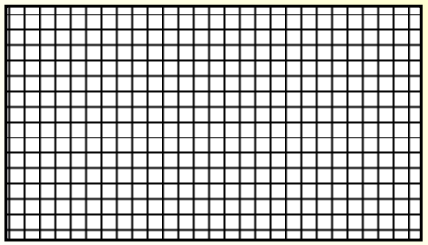
Magnetostrictive materials



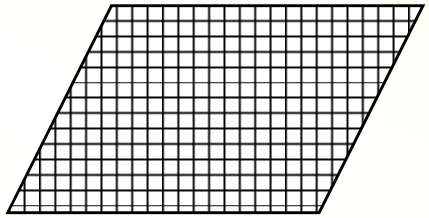
Magnetization



Shape memory alloy



Temperature



Actuator

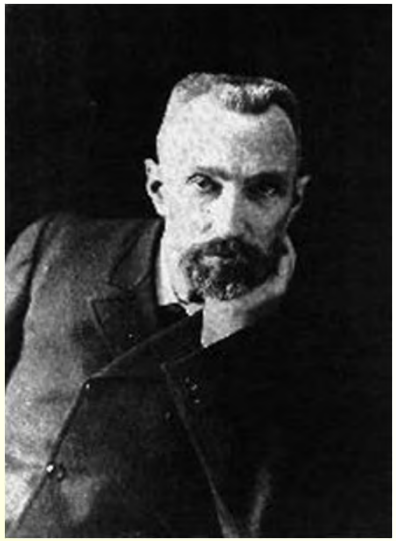
Sensor

Electrical energy

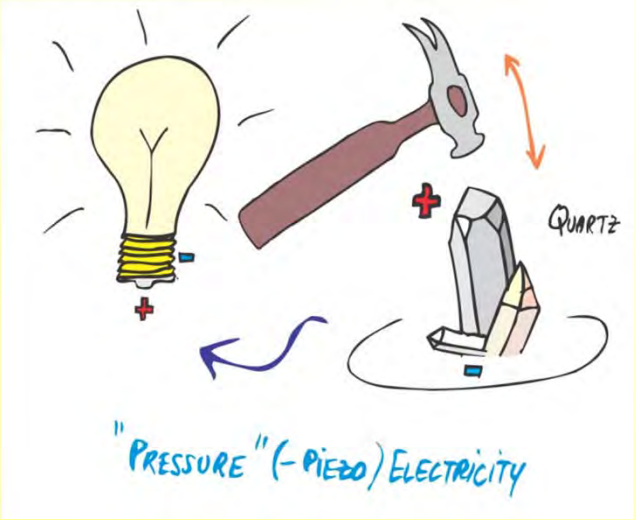
Magnetic energy

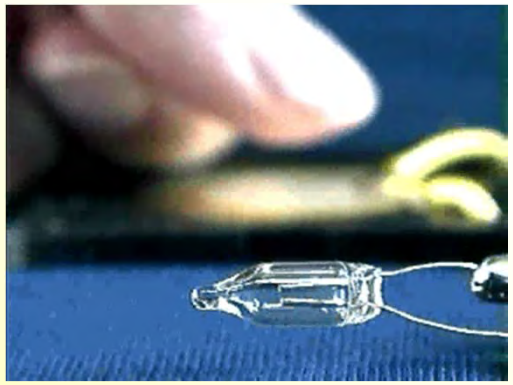
Thermal energy

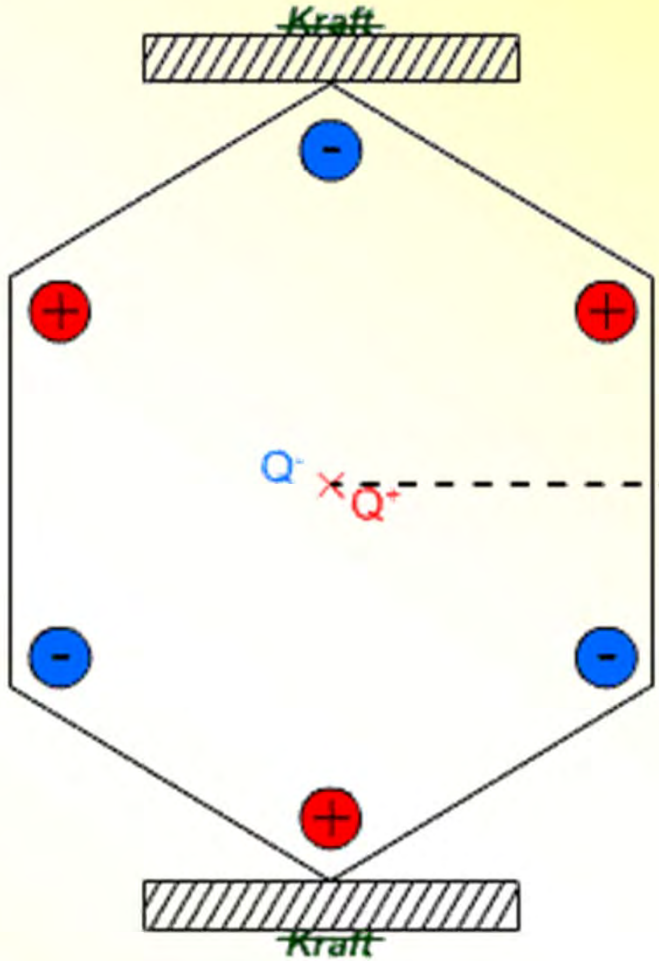
Smart materials and structures



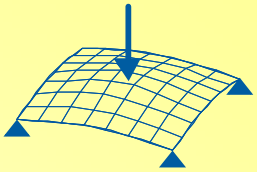
Pierre and Jacques Curie: 1880







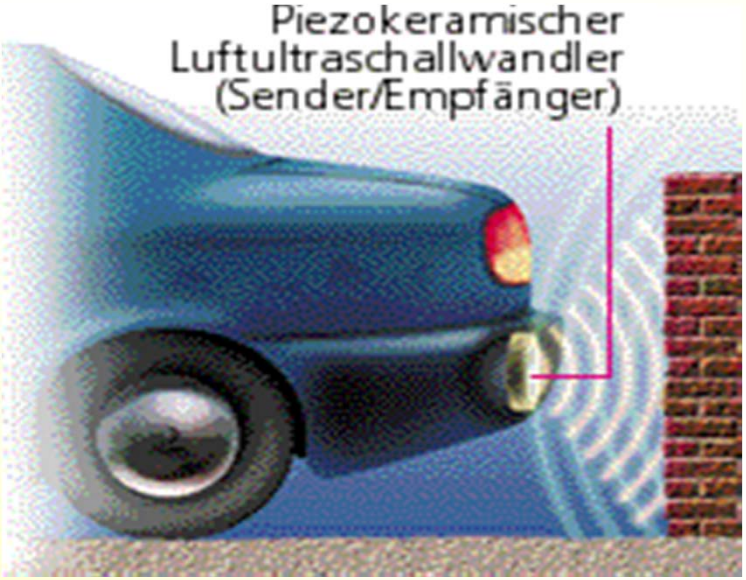
Smart materials and structures



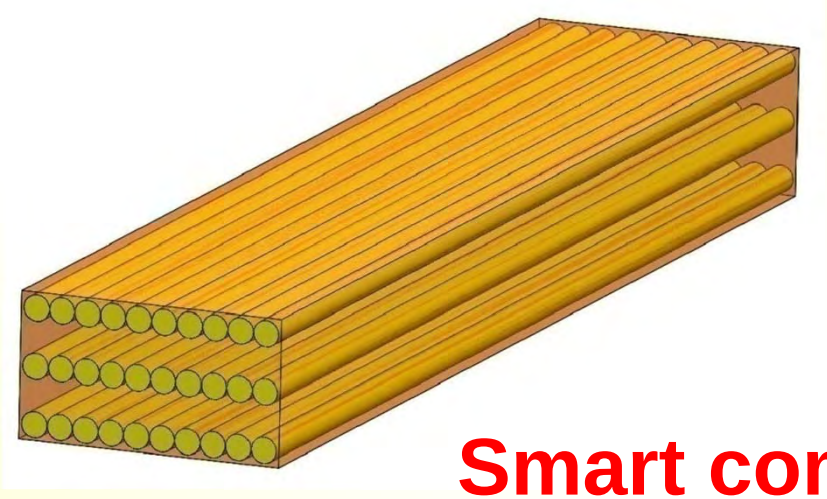
Applications:

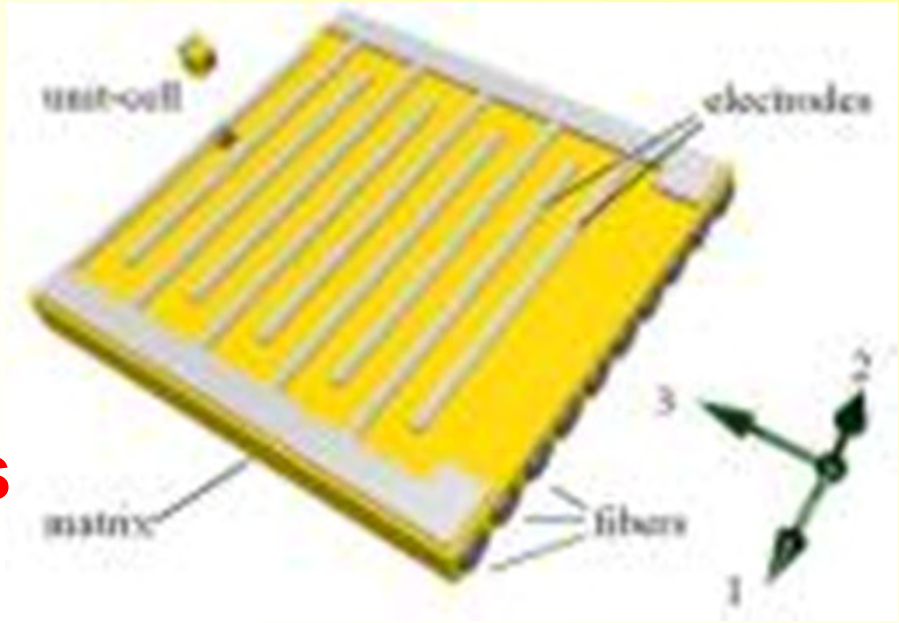
- Sensor
- Actuator
- Transducer
- Sonar technology
- Smart structures
- Structural Health Monitoring (SHM)
- Medical diagnostics
- Energy harvesting
- …

Smart materials and structures

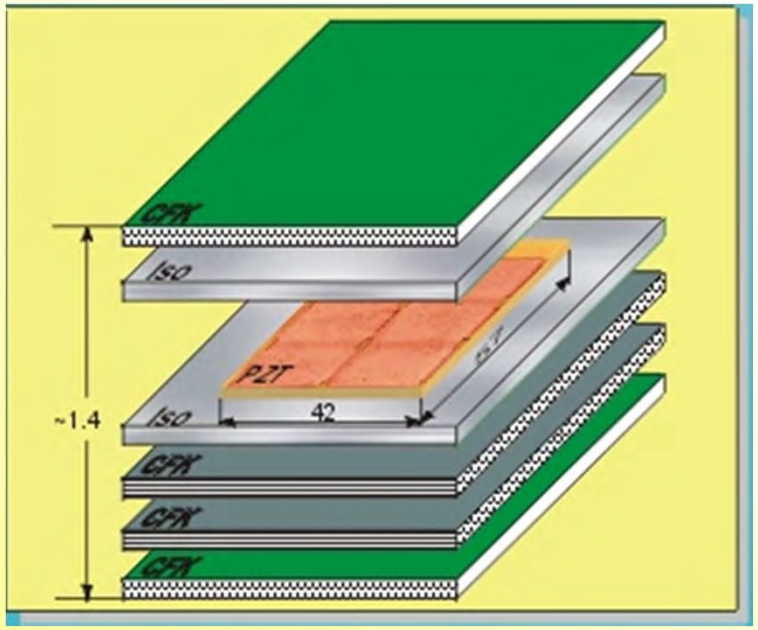


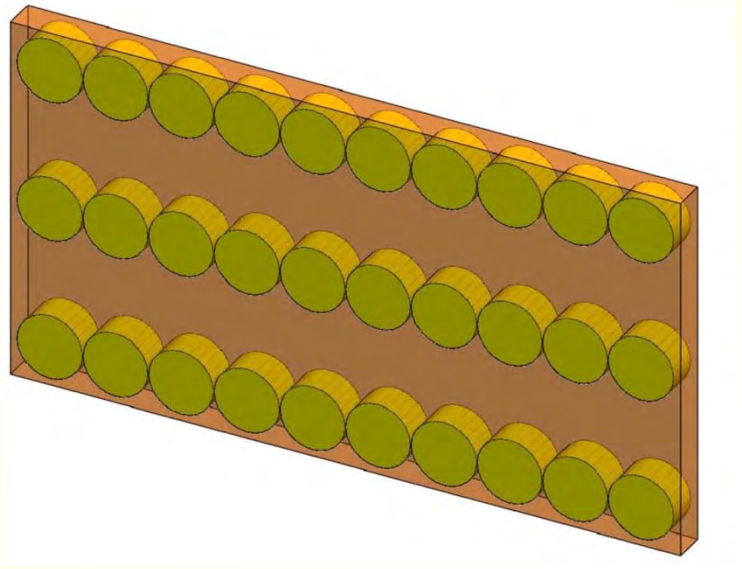
Smart materials and structures



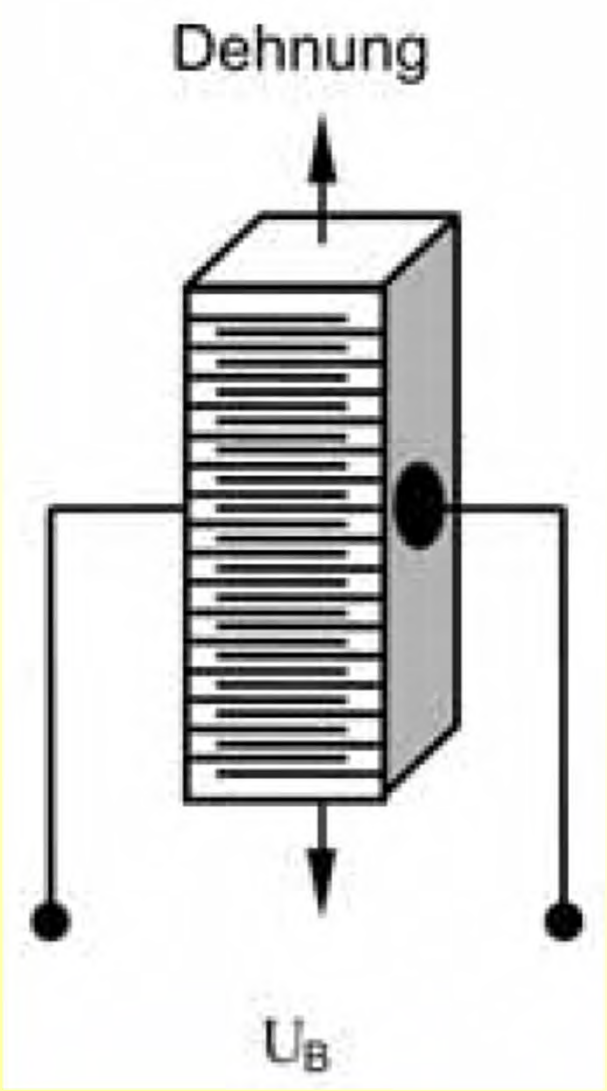


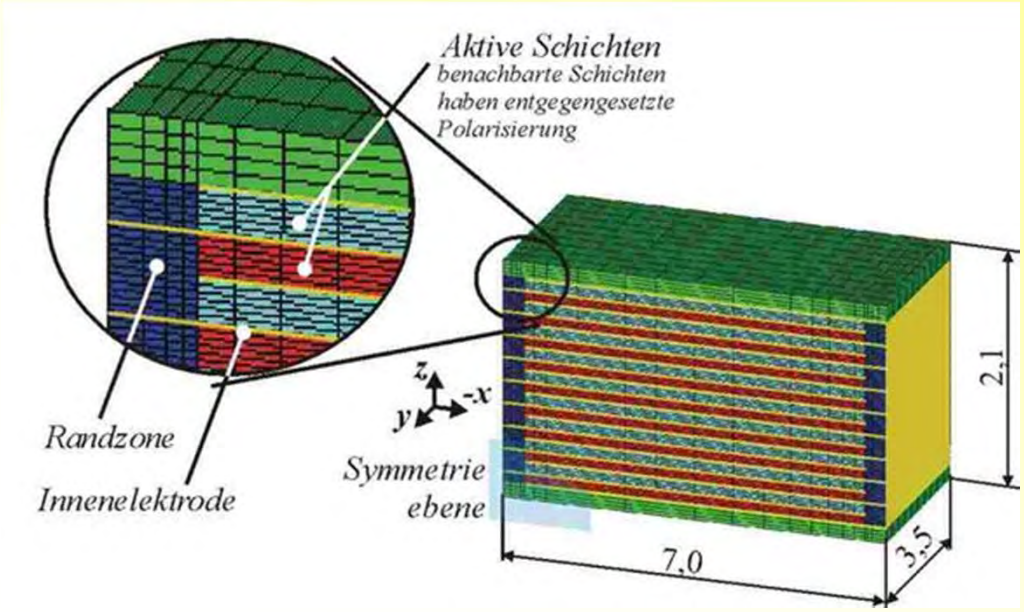
Smart composites

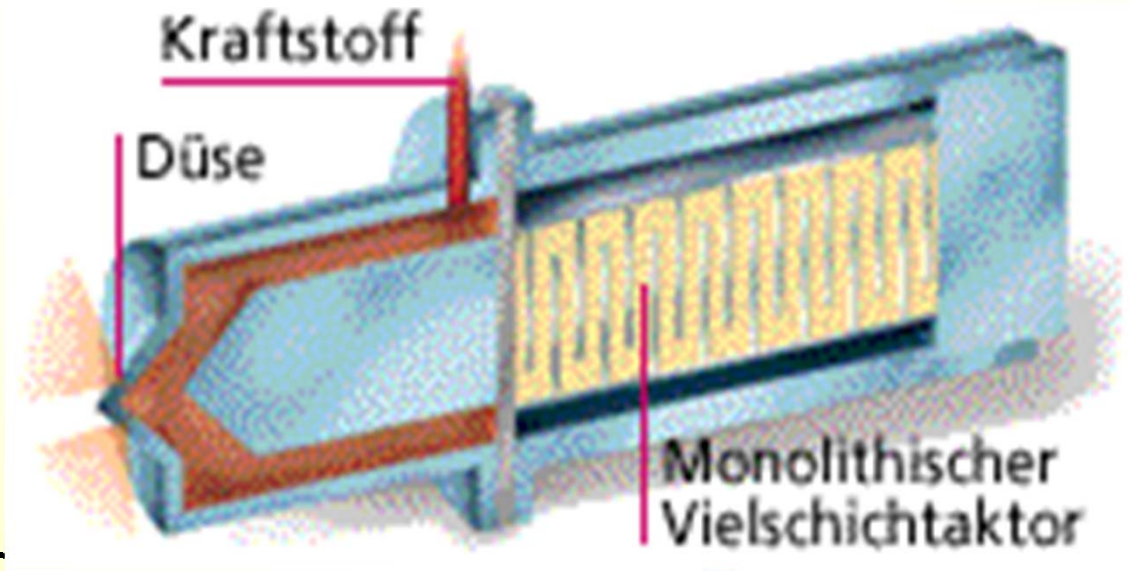




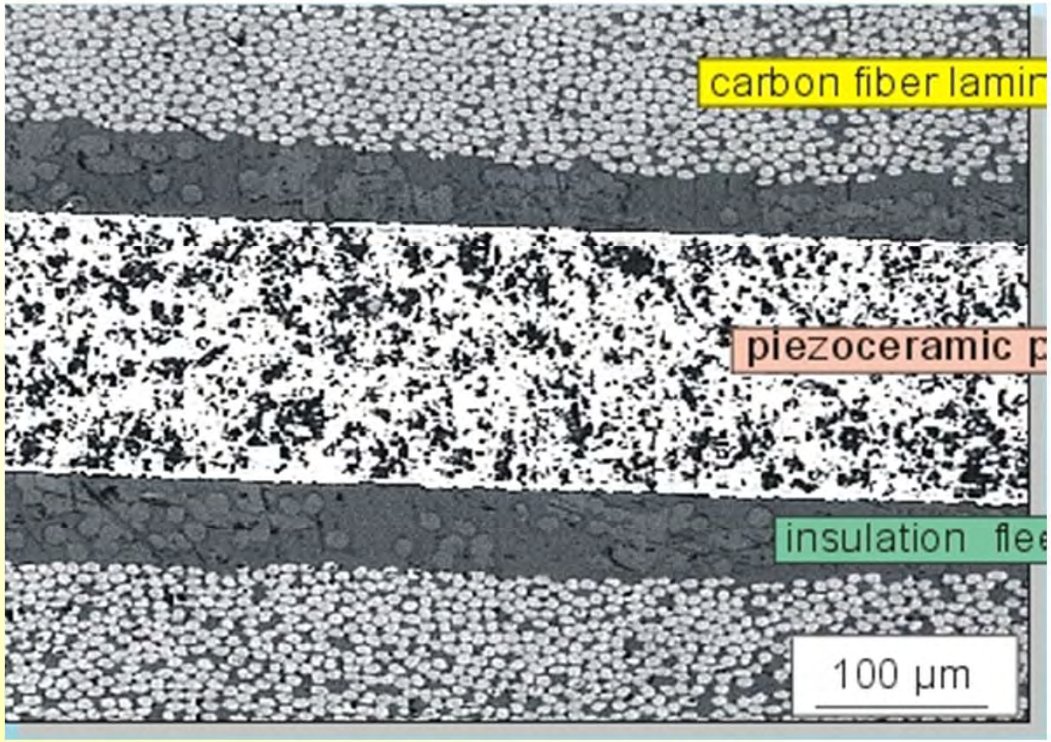
Smart materials and structures

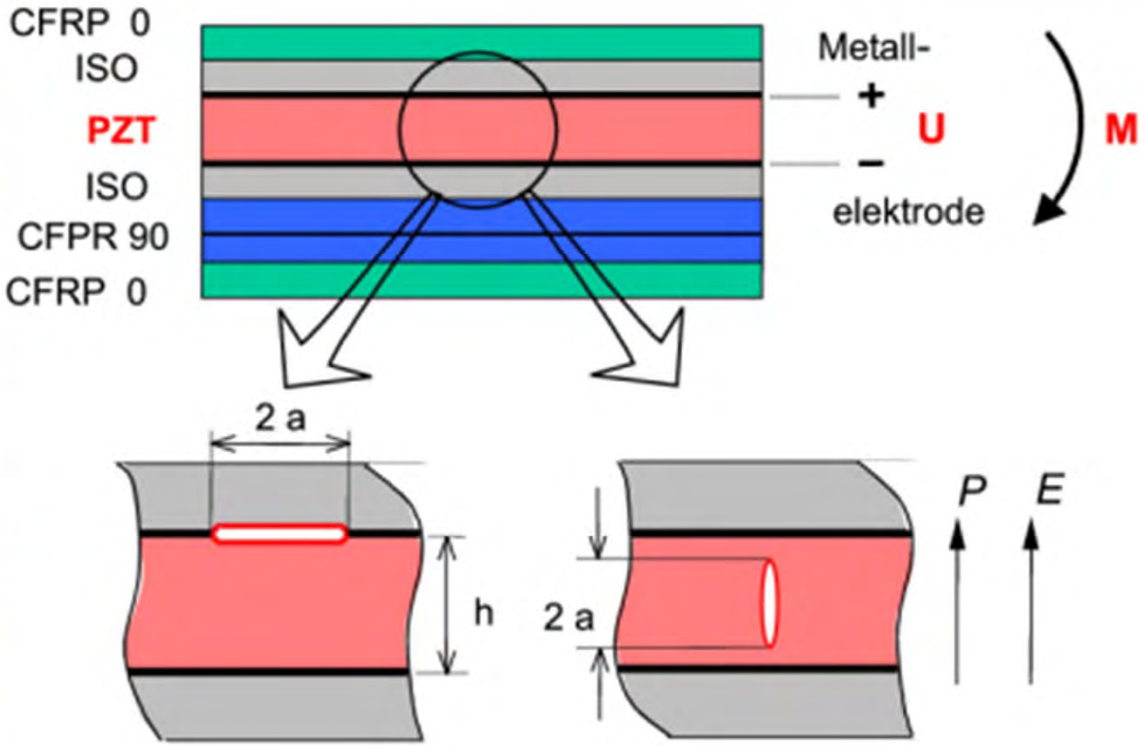


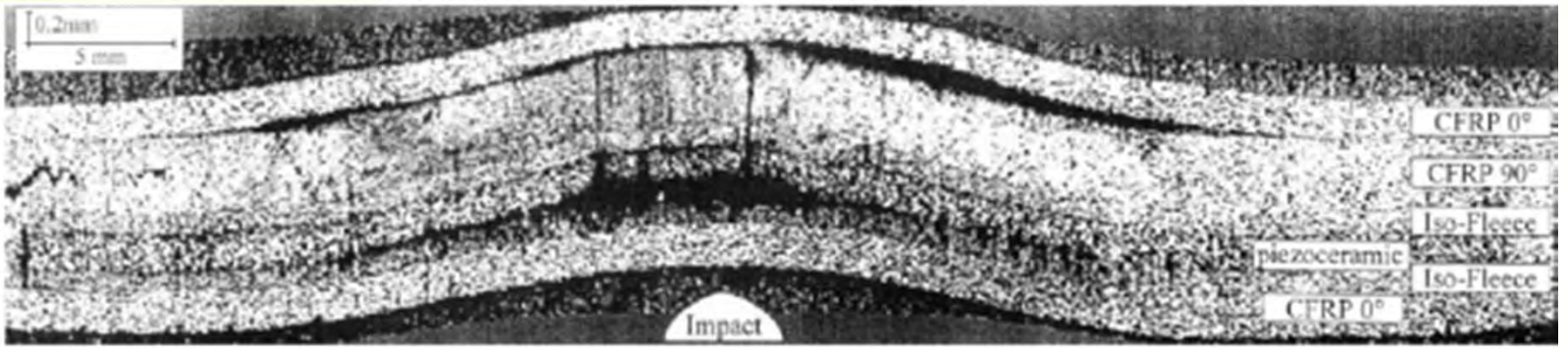




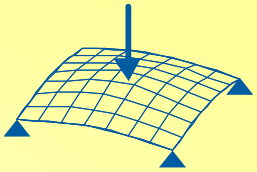
Smart materials and structures







Smart materials and structures

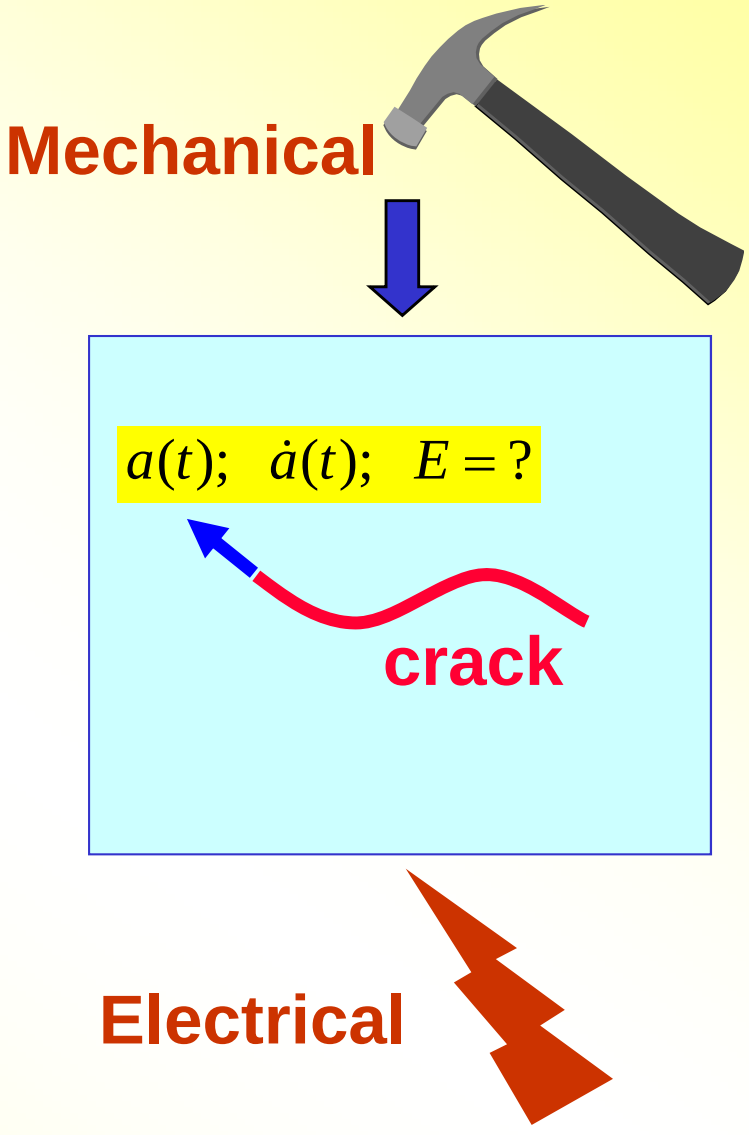


Effects on crack propagation ?

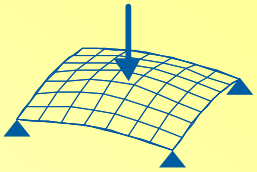
- Crack initiation ?
- Crack growth velocity & direction ?
- Crack arrest through electrical loading ?

Disturbance of electric signals ?

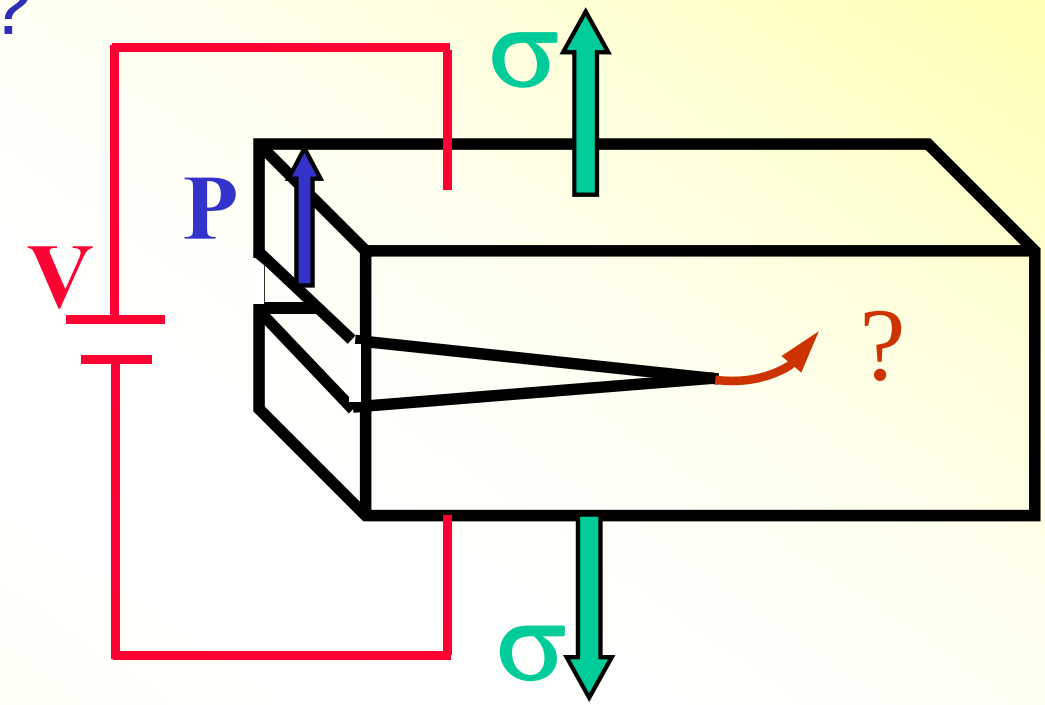
- Loss of functionality and reliability ?
- Adaptivity through mechanical loading ?



Smart materials and structures

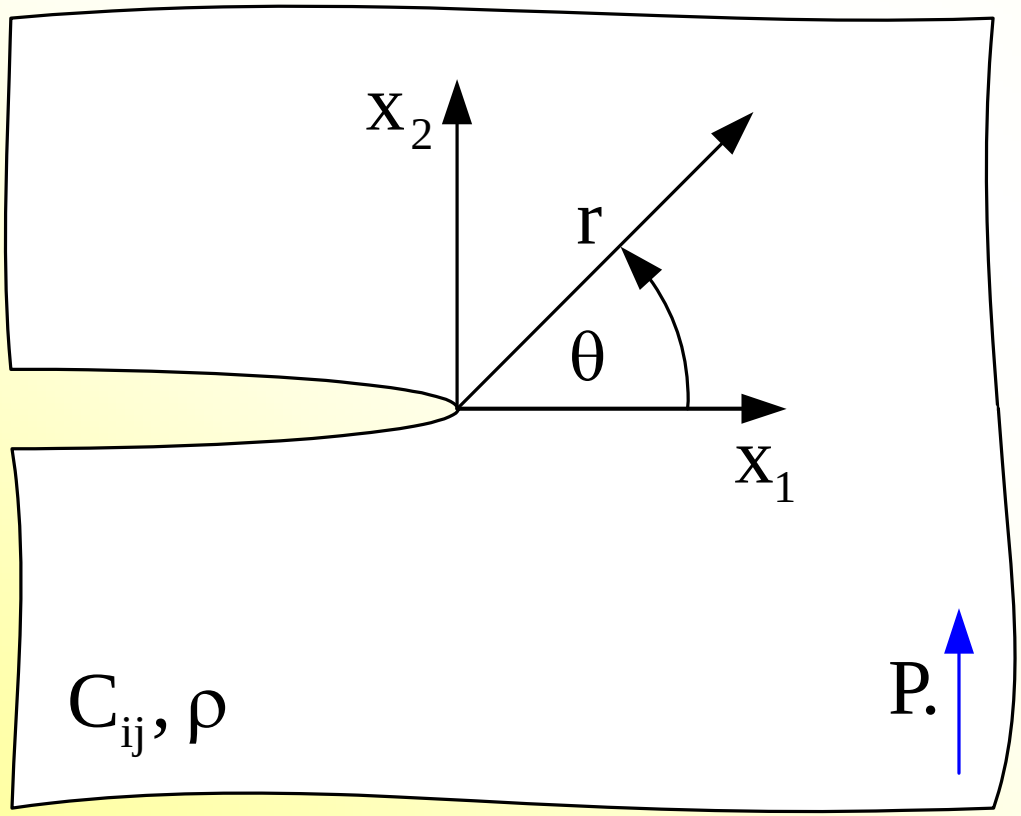


- Effect of the dynamic loading ?
- Effect of the interface ?
- Influence of the material mismatch ?
- Effect of the poling direction ?
- Influence of the loading combination ?



Crack characterization

Crack-tip field and intensity factors (interior crack)



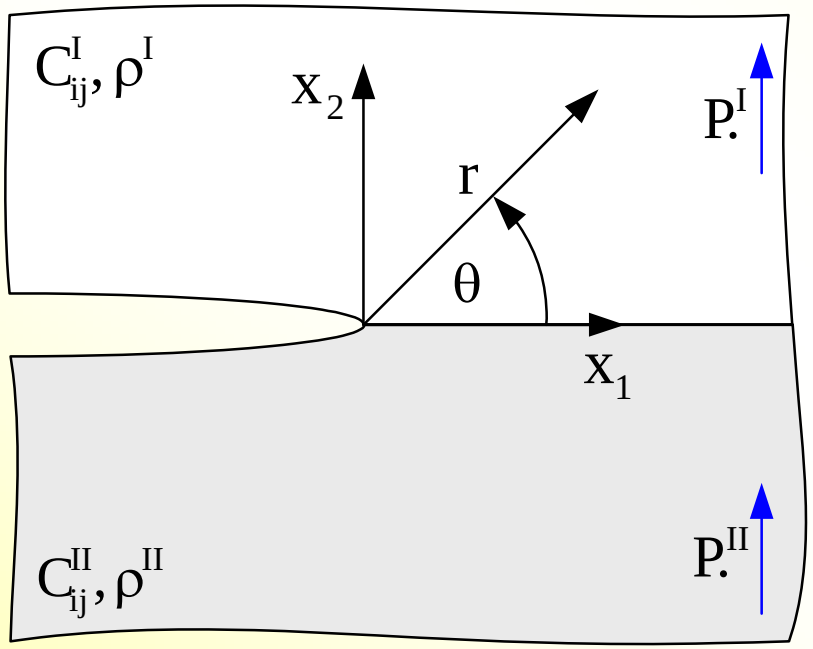
$$u_i \sim \sqrt{r}, \quad \varphi \sim \sqrt{r}$$

$$\sigma_{ij} \sim \frac{1}{\sqrt{r}}, \quad D_i \sim \frac{1}{\sqrt{r}}$$

$$\begin{Bmatrix} K_{II}(t) \\ K_I(t) \\ K_{IV}(t) \end{Bmatrix} = \sqrt{\frac{2\pi}{l}}\mathbf{H} \begin{Bmatrix} \Delta u_1(l,t) \\ \Delta u_2(l,t) \\ \Delta \varphi(l,t) \end{Bmatrix}$$

Crack characterization

Crack-tip field and intensity factors (interface crack)



$$u_i \sim r^{\frac{1}{2}+i\varepsilon_1}, \quad \varphi \sim r^{\frac{1}{2}-\varepsilon_2}$$

$$\sigma_{ij} \sim r^{-\frac{1}{2}+i\varepsilon_1}, \quad D_i \sim r^{-\frac{1}{2}+\varepsilon_2}$$

$$\Delta\mathbf{u}(r) = (\mathbf{H}+\overline{\mathbf{H}})\sqrt{\frac{r}{2\pi}}\left[\frac{K r^{i\varepsilon_1}\mathbf{w}}{(1+2i\varepsilon_1)\cosh(\pi\varepsilon_1)} + \frac{\overline{K} r^{-i\varepsilon_1}\overline{\mathbf{w}}}{(1-2i\varepsilon_1)\cosh(\pi\varepsilon_1)} + \frac{K_4 r^{-\varepsilon_2}\mathbf{w}_4}{(1-2\varepsilon_2)\cos(\pi\varepsilon_2)}\right]$$

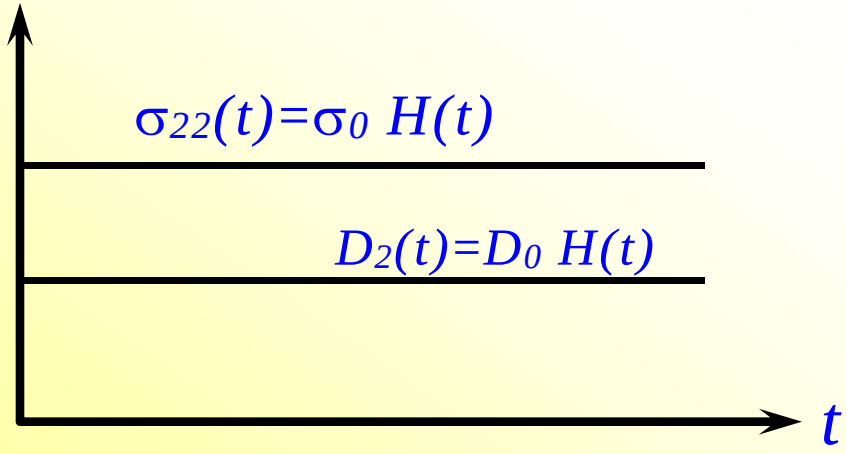
$$\boldsymbol{\sigma}(r) = \frac{1}{\sqrt{2\pi r}}\left[K r^{i\varepsilon_1}\mathbf{w} + \overline{K} r^{-i\varepsilon_1}\overline{\mathbf{w}} + K_4 r^{-\varepsilon_2}\mathbf{w}_4\right]$$

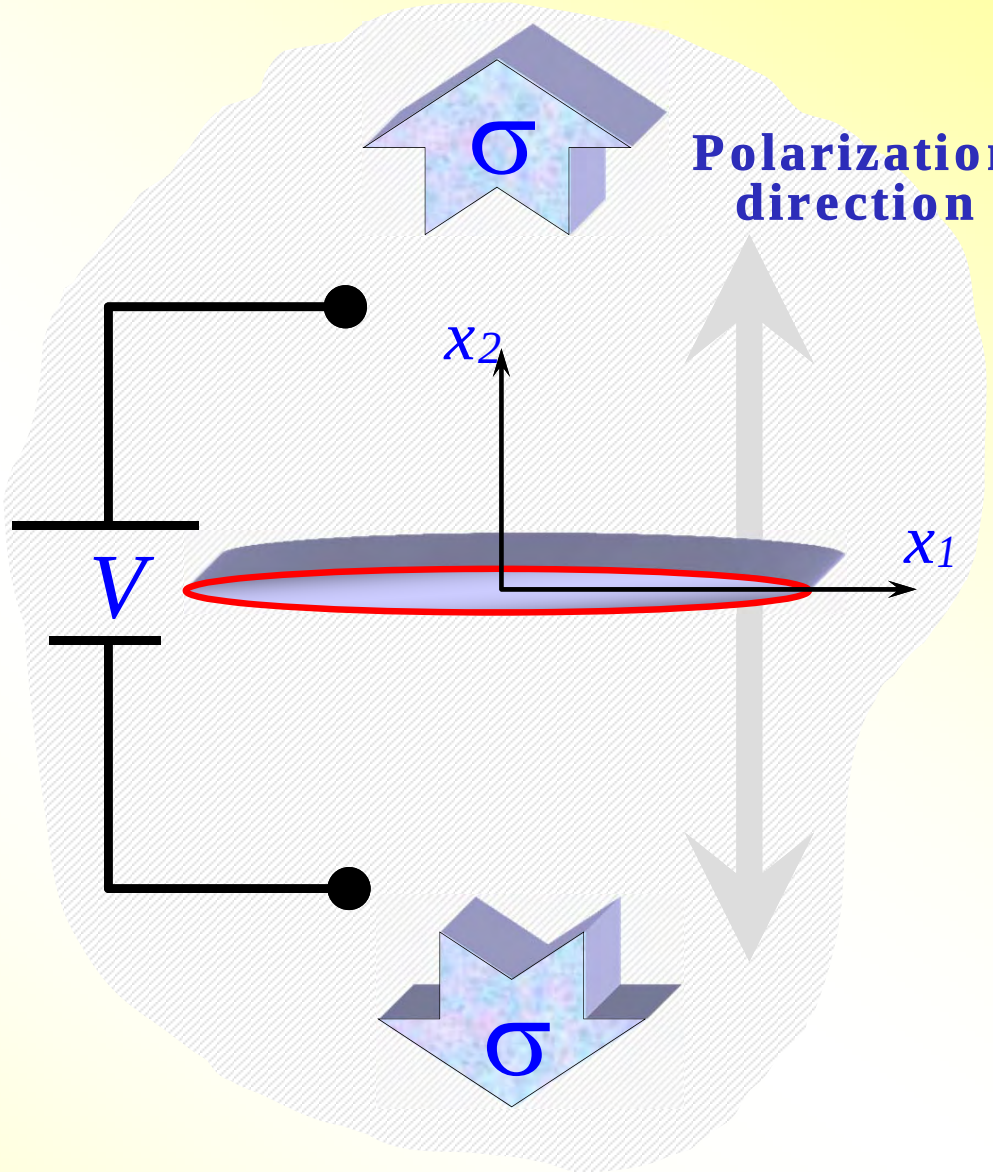
Examples

Loading parameter

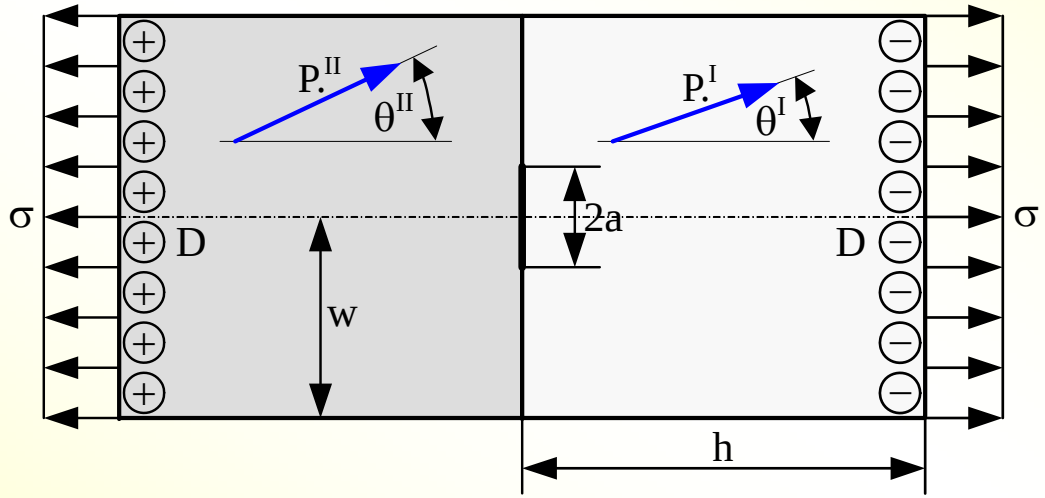
$$\chi = \frac{e_{22}}{\varepsilon_{22}} \frac{D_2}{\sigma_{22}}$$

Load





Examples



Geometry:

$h = 20\text{mm}, \quad 2w = h, \quad 2a = 4.8\text{mm}$

Loading:

σ : mechanical

D : electrical

Material I: PTZ-5H

$C_{11} = 126.0\,\text{GPa}, \quad C_{12} = 53.0\,\text{GPa}$

$C_{22} = 117.0\,\text{GPa}, \quad C_{66} = 35.3\,\text{GPa}$

$e_{21} = -6.5\,\text{C/m}^2, \quad e_{22} = 23.3\,\text{C/m}^2,$

$e_{16} = 17.0\,\text{C/m}^2$

$\varepsilon_{11} = 15.04\,\text{C/(GVm)}, \quad \varepsilon_{22} = 13.0\,\text{C/(GVm)}$

Material II: $BaTiO_3$

$C_{11} = 150.0\,\text{GPa}, \quad C_{12} = 66.0\,\text{GPa}$

$C_{22} = 146.0\,\text{GPa}, \quad C_{66} = 44.0\,\text{GPa}$

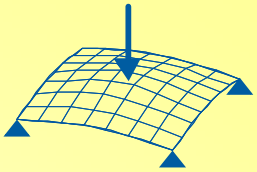
$e_{21} = -4.35\,\text{C/m}^2, \quad e_{22} = 17.5\,\text{C/m}^2$

$e_{16} = 11.4\,\text{C/m}^2$

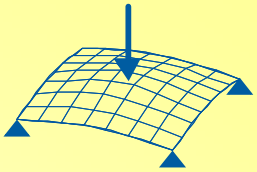
$\varepsilon_{11} = 9.87\,\text{C/(GVm)}, \quad \varepsilon_{22} = 11.2\,\text{C/(GVm)}$

A rectangular plate with a central interface crack

Key questions

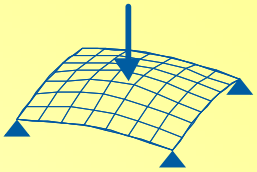


- Effect of the interface ?
- Effect of the polling direction ?
- Effect of the material mismatch ?
- Effect of the electrical loading ?
- Effect of the mechanical loading ?
- Effect of the dynamic loading (impact) ?
- Effect of the loading combination ?



Conclusions

Conclusions



- New discoveries of multifunctional materials and structures will lead to promising and exciting fundamental breakthroughs.

- Transfer of scientific knowledge and principles to engineering technologies is important and demanding.

- Cutting edge applications of novel multifunctional materials and structures are important for the sustainable development.

- Novel multifunctional materials and structures will greatly influence our society, economy and ecology (environment).

- Novel multifunctional materials and structures will improve our life quality and make our life happy!