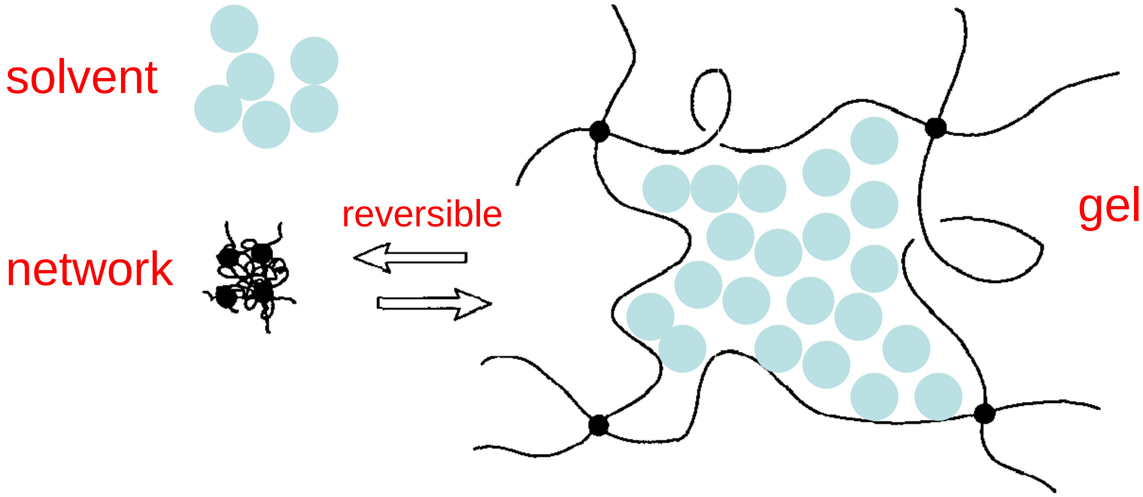
Soft Active Materials

dielectric elastomers
capable of
giant deformation of actuation

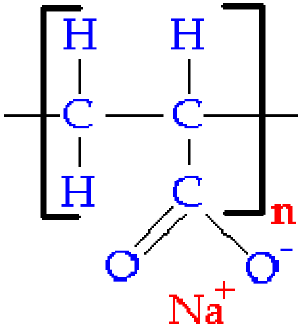
Zhigang Suo
Harvard University

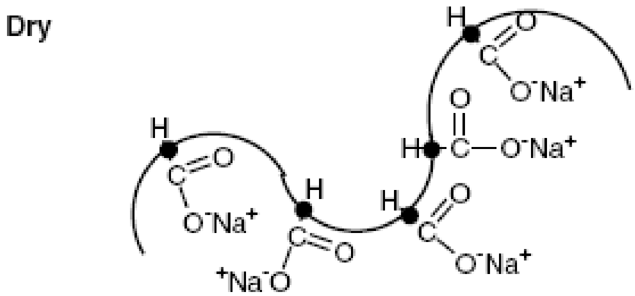
elastomer = network
gel = network + solvent

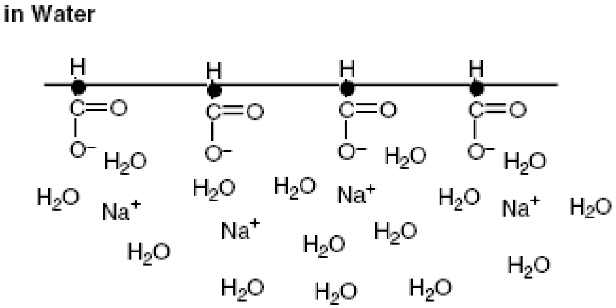


Super absorbent diaper

Sodium polyacrylate: polyelectrolyte

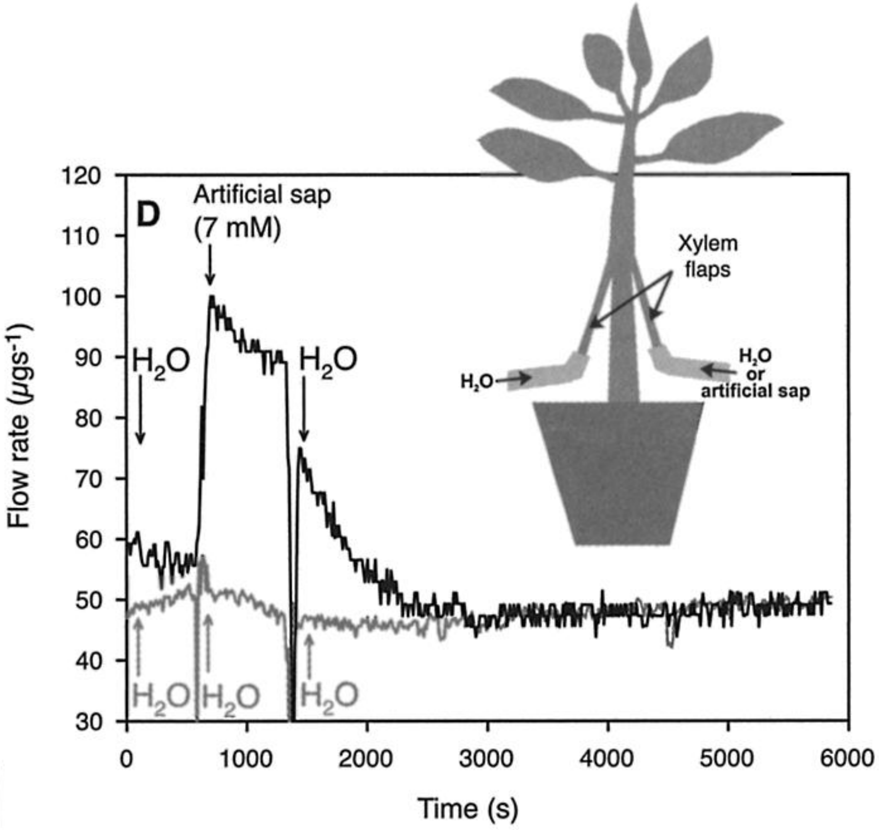


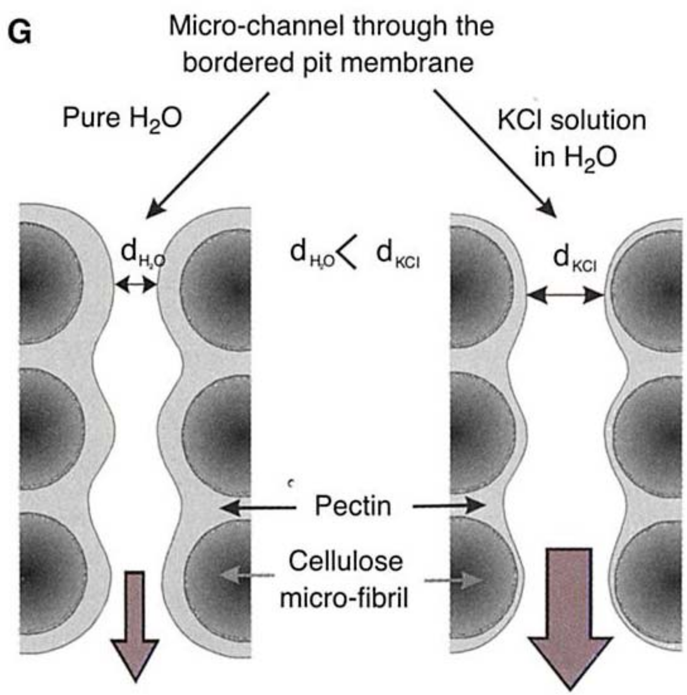




Gels regulate flow in plants

Missy Holbrook



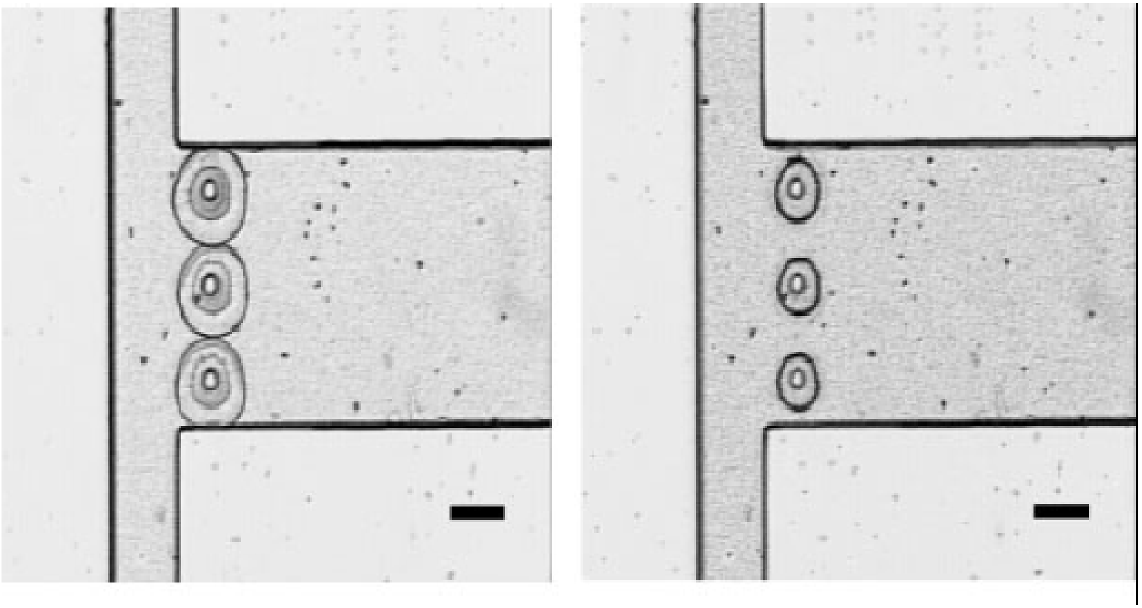


Zwieniecki, Melcher, Holbrook,
Hydrogel control of xylem hydraulic resistance in plants
Science 291, 1095 (2001)

Plants are masters of microfluidics

Self-regulating fluidics


David Beebe

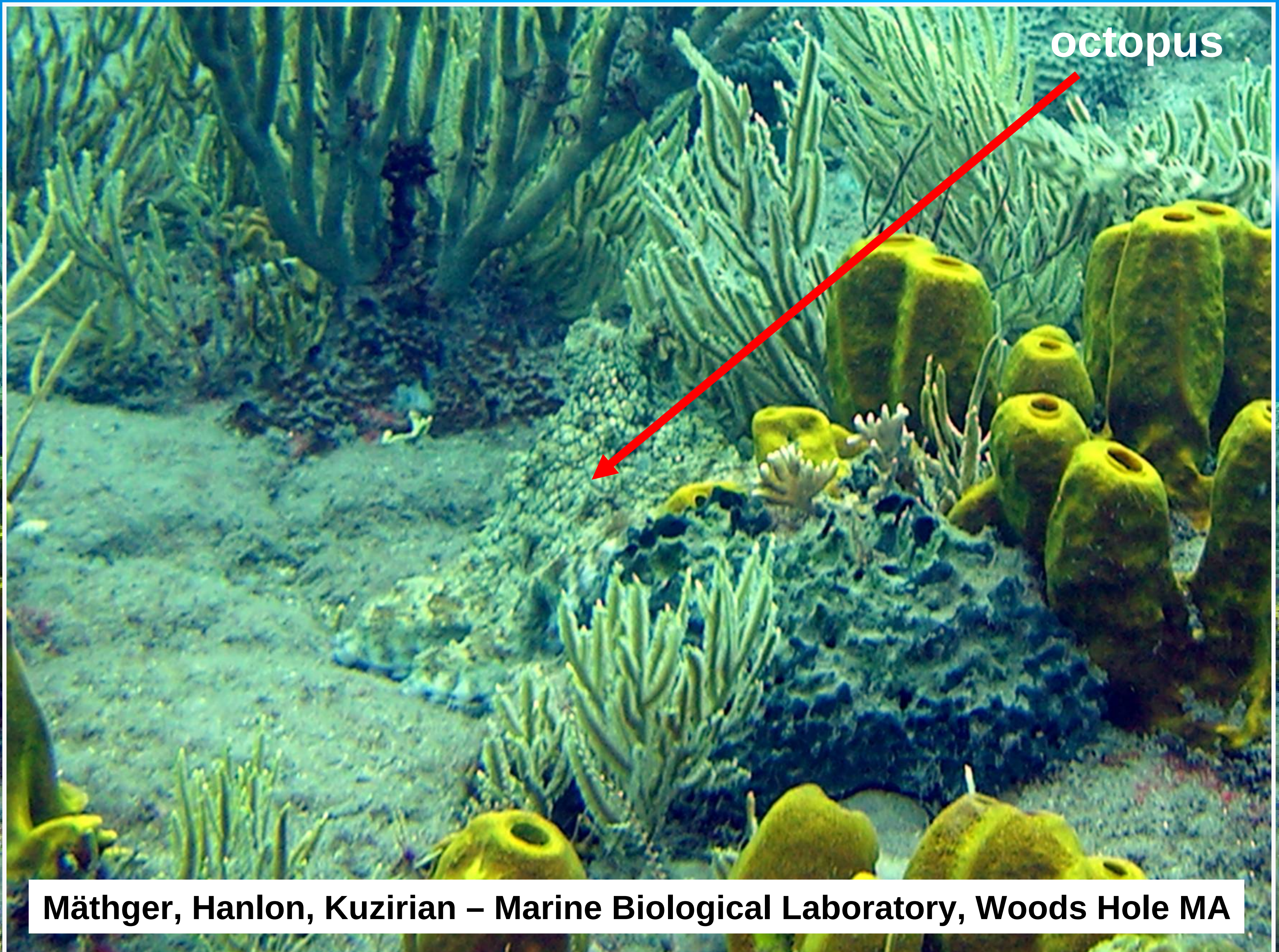


Responsive to Physiological variables:

- •pH
- •Salt
- •Temperature
- •light

•Many stimuli cause deformation.
•Deformation regulates flow.

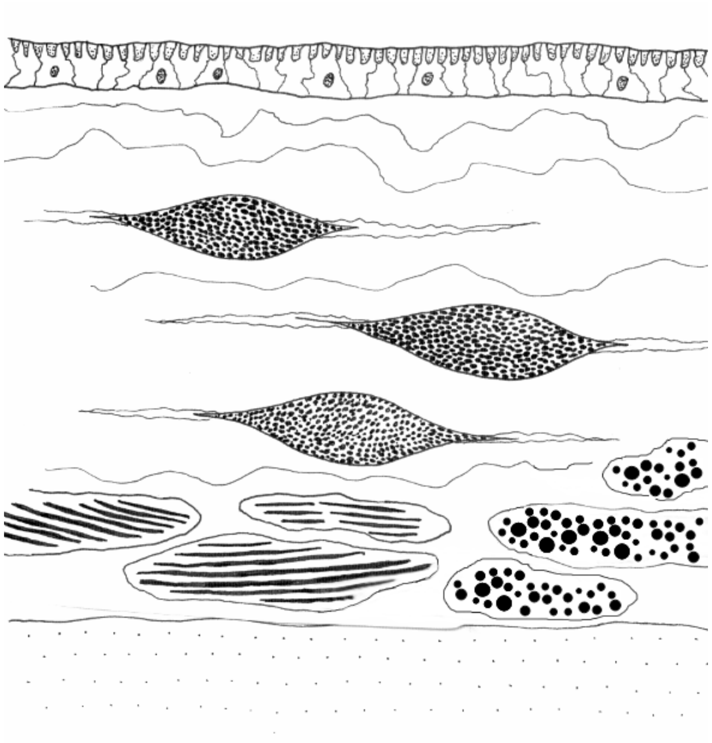
Beebe, Moore, Bauer, Yu, Liu, Devadoss, Jo, Nature 404, 588 (2000)

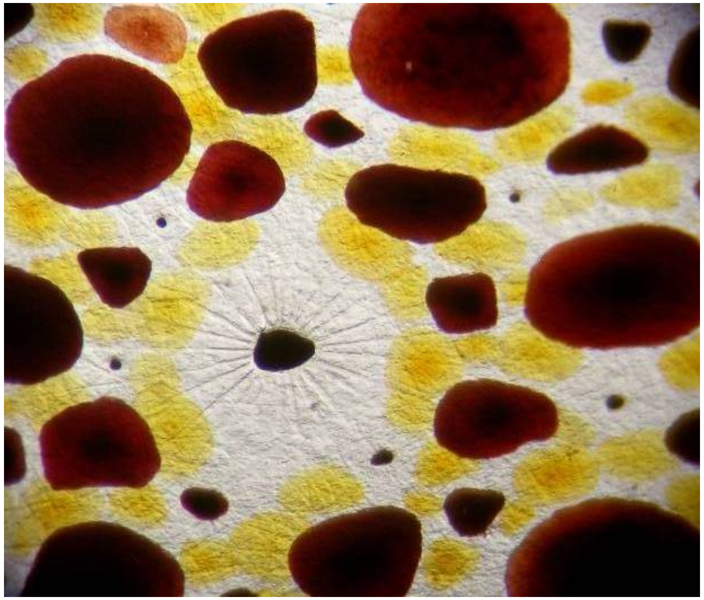


Mäthger, Hanlon, Kuzirian – Marine Biological Laboratory, Woods Hole MA

Squid changes color

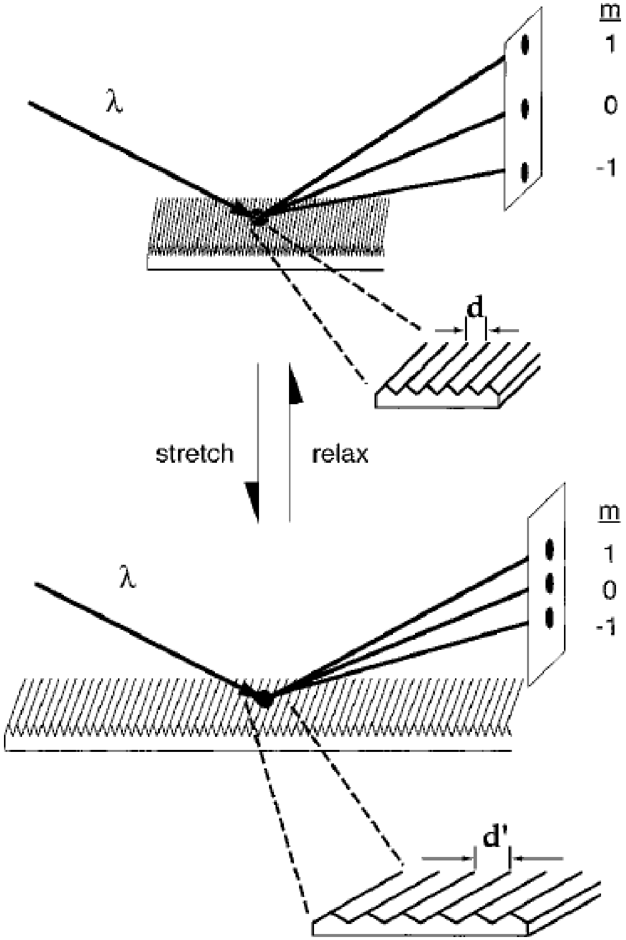
Expand pigmented sacs by contracting muscles

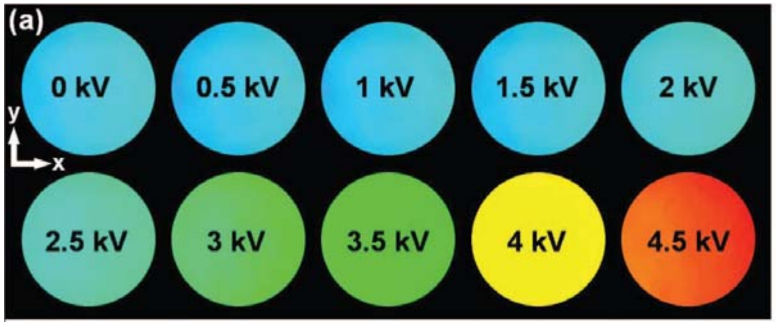




Mathger, Denton, Marshall, Hanlon, J. R. Soc. Interface 6, S149 (2009)

Adaptive Optics





- Many stimuli cause deformation.
- Deformation affects optics.

Wilbur, Jackman, Whitesides, Cheung, Lee, Prentiss
Elastomeric optics
Chem. Mater. 1996, 8, 1380-1385

Aschwanden, Stemmer
Optics letters 31, 2610 (2006)

Soft Active Materials (SAM)

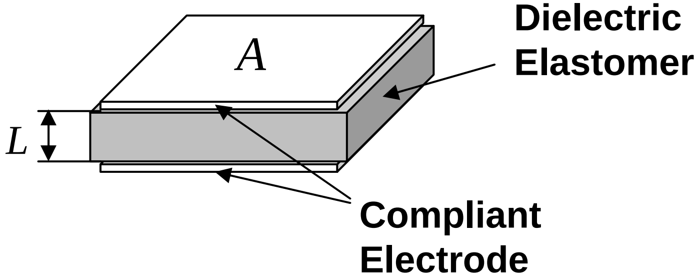
Soft: large deformation in response to small forces
(rubbers, gels,…)

Active: large deformation in response to diverse stimuli
(electric field, temperature, pH, salt,…)

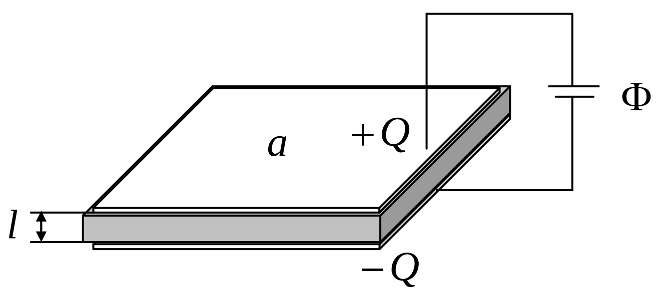
A stimulus causes deformation. Deformation enables a function.

Dielectric elastomer

Reference State

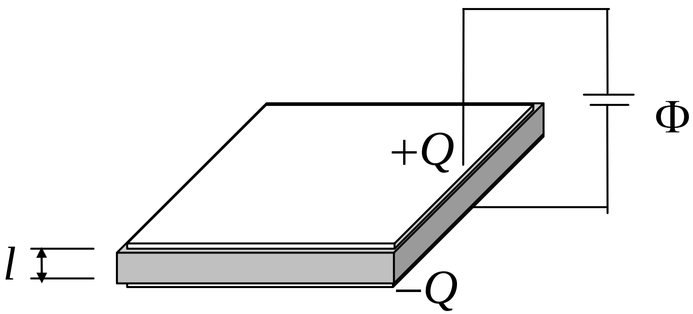


Current State

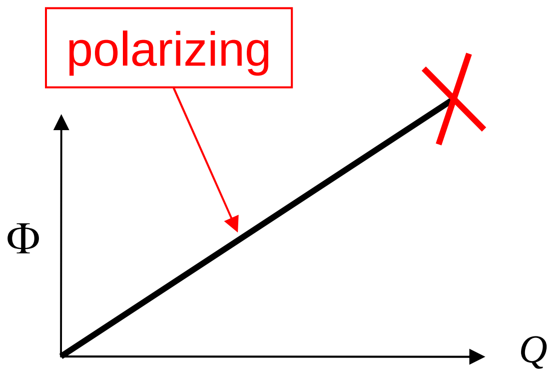


Pelrine, Kornbluh, Pei, Joseph
High-speed electrically actuated elastomers with strain greater than 100%.
Science 287, 836 (2000).

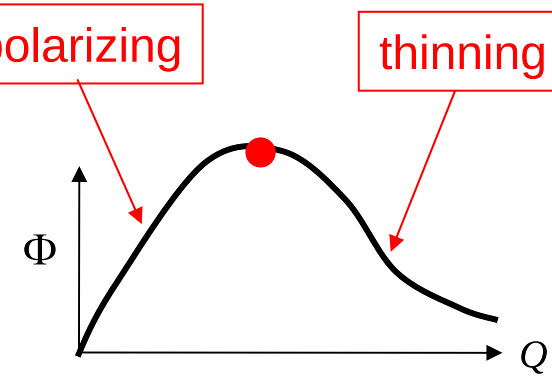
Two modes of failure



Electrical breakdown
Hard material



Electromechanical instability
Soft material



Stark & Garton, Nature 176, 1225 (1955)

The Essential Dilemma (TED)

•To deform appreciably without electrical breakdown, the elastomer must be soft.

•But a soft elastomer is susceptible to electromechanical instability.

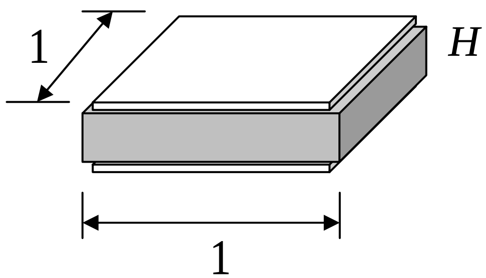
How large can deformation of actuation be?

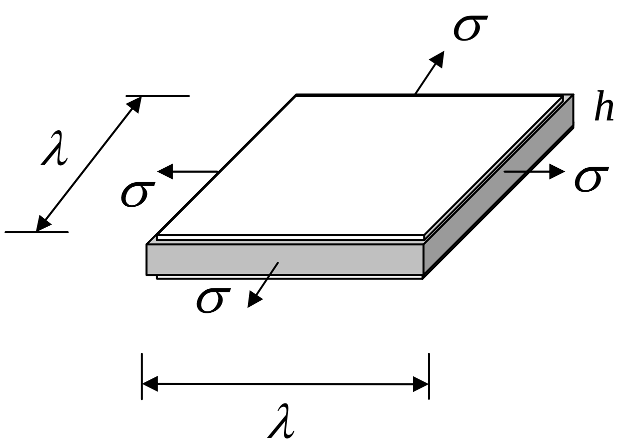
Experimentally observed large deformation of actuation

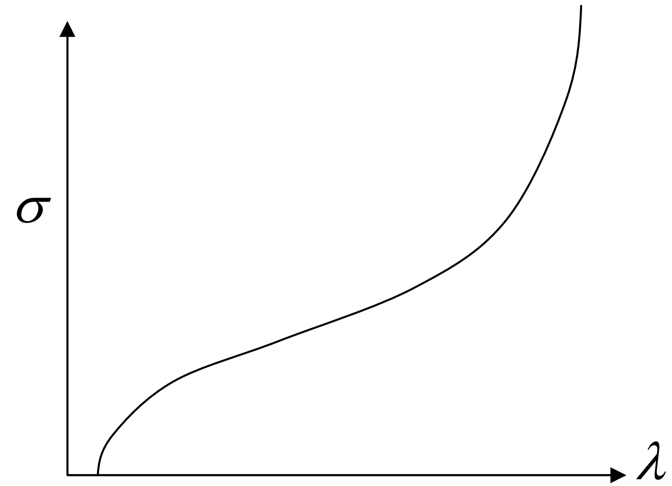
- Zhenyi, et al. (1994), ~3%.
- Pelrine, et al. (1998), low modulus, high dielectric strength, ~26%.
- Pelrine, et al. (2000), pre-stress, ~100%.
- Ha, et al. (2006), interpenetrating networks, ~100%.

- How do we understand these experiments?
- What is the theoretical limit?
- How about 1000%?

Mechanics







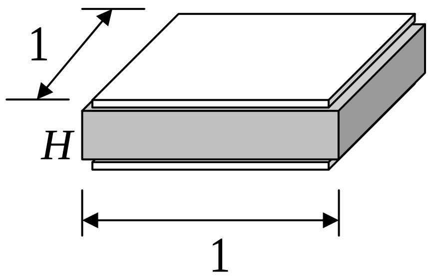
Equation of state $\sigma = f(\lambda)$

Example:
neo-Hookean model $\sigma = \mu\left(\lambda^2 - \lambda^{-4}\right)$

Incompressibility $H = h\lambda^2$

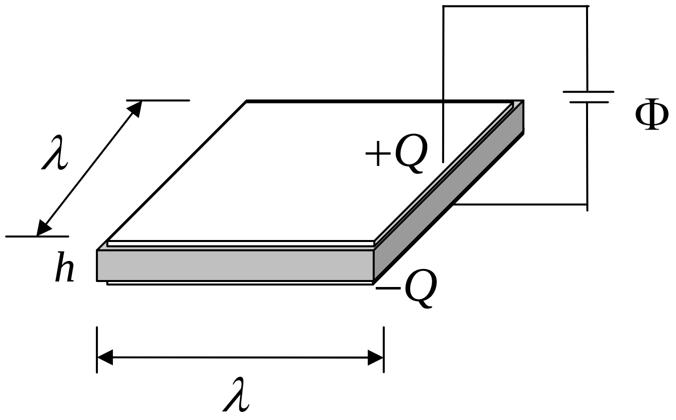
Electromechanics

$H = h\lambda^2$ $\sigma = f(\lambda)$



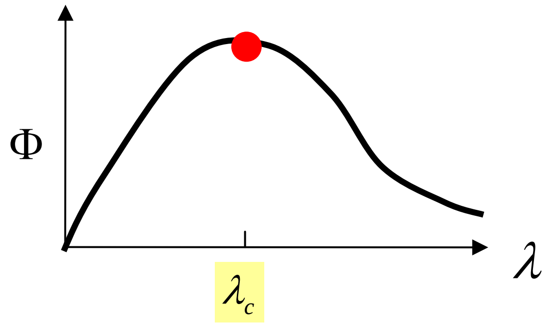
Maxwell stress $\sigma = \varepsilon E^2$

voltage $\Phi = Eh$



Equation of state $\Phi = H\lambda^{-2}\sqrt{\frac{f(\lambda)}{\varepsilon}}$

Electromechanical instability limits deformation of actuation



$$\Phi = H\sqrt{\frac{\mu}{\varepsilon}}\left(\lambda^{-3} - \lambda^{-6}\right)^{1/2}$$

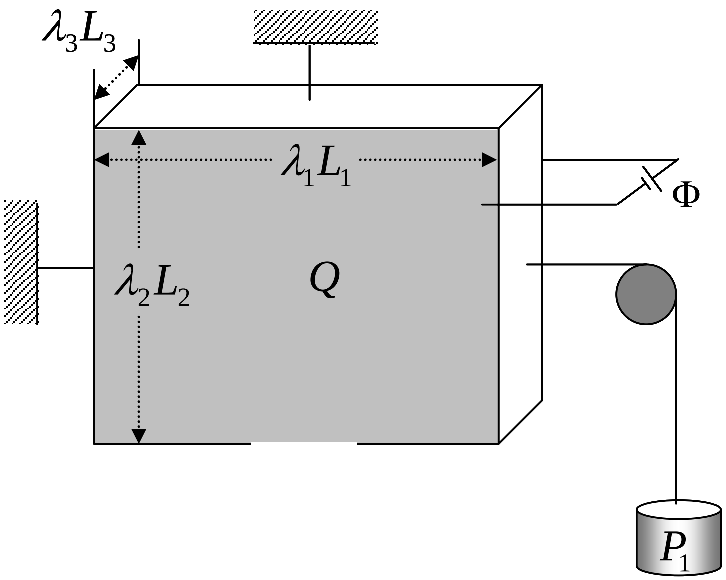
$$\lambda_c = 2^{1/3} \approx 1.26$$

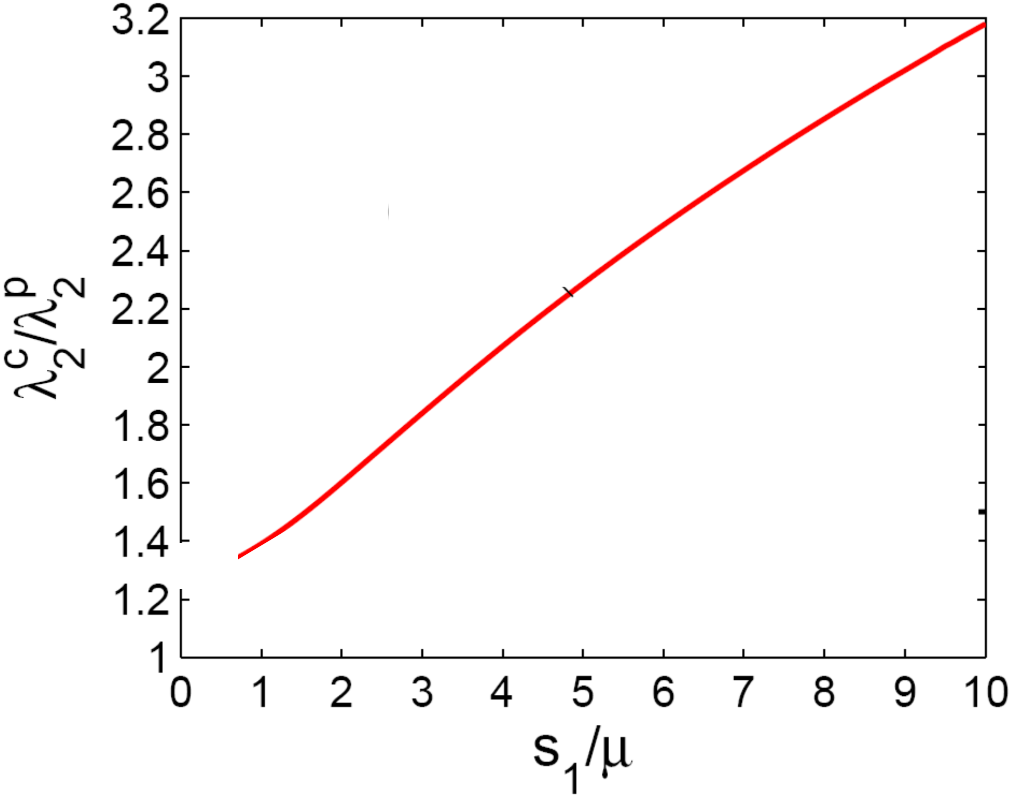
Experiment: Pelrine, Kornbluh, Joseph, Sensors & Actuators A 64, 77 (1998)

Calculation: Zhao & Suo Appl. Phys Lett. 91, 061921 (2007)

Pre-stretch

increases deformation of actuation

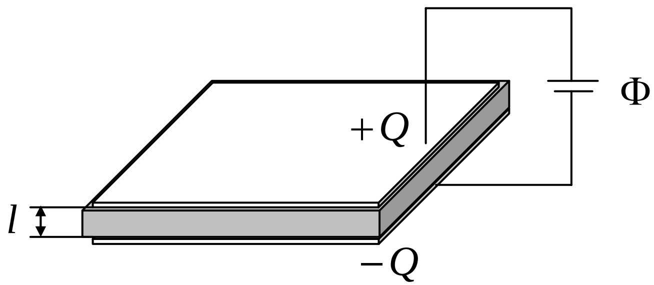


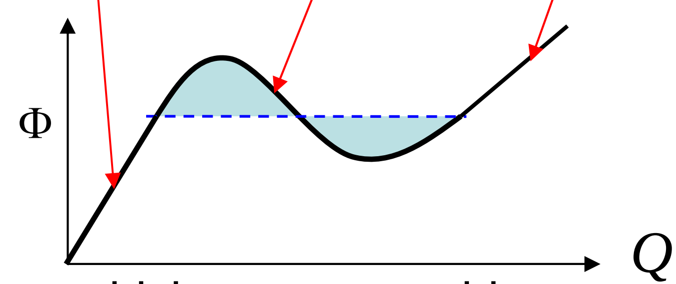


Experiment: Pelrine, Kornbluh, Pei, Joseph
Science 287, 836 (2000).

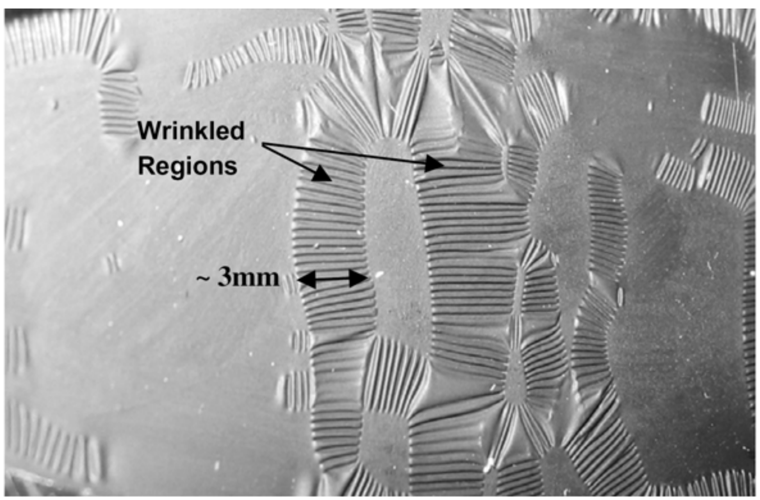
Theory: Zhao, Suo
APL 91, 061921 (2007)

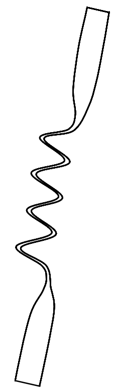
Coexistent states





Top view





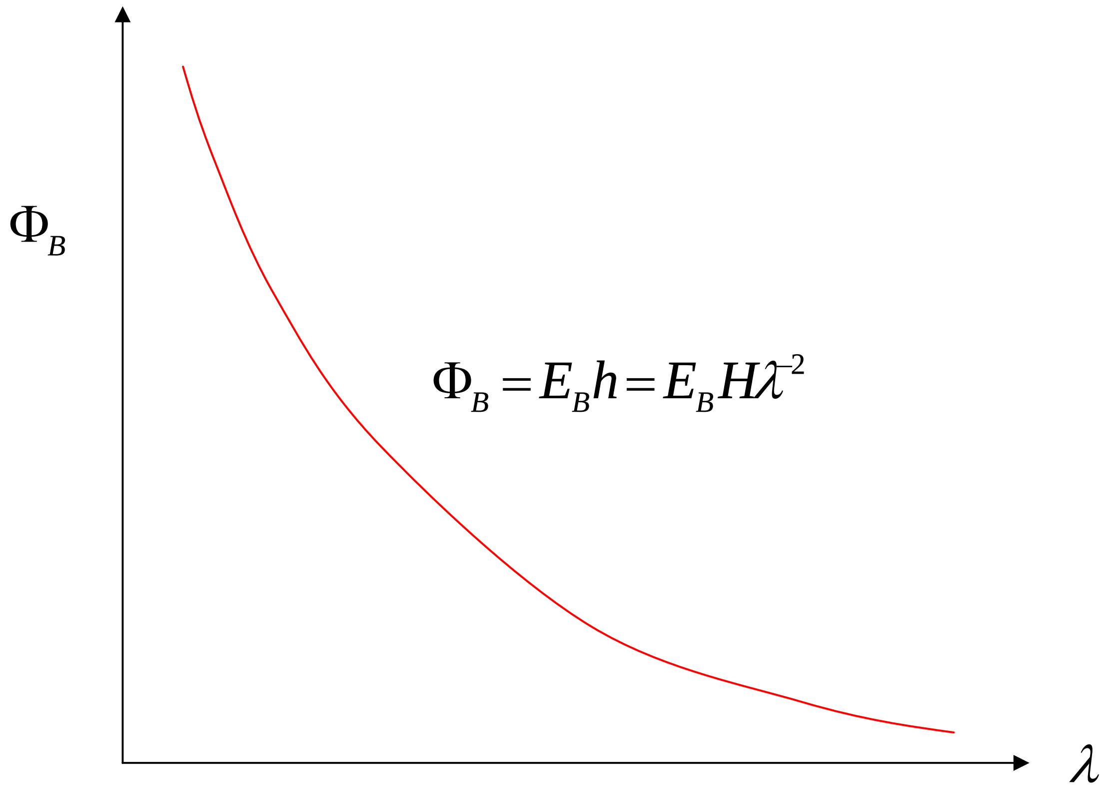
Cross section

Coexistent states: flat and wrinkled

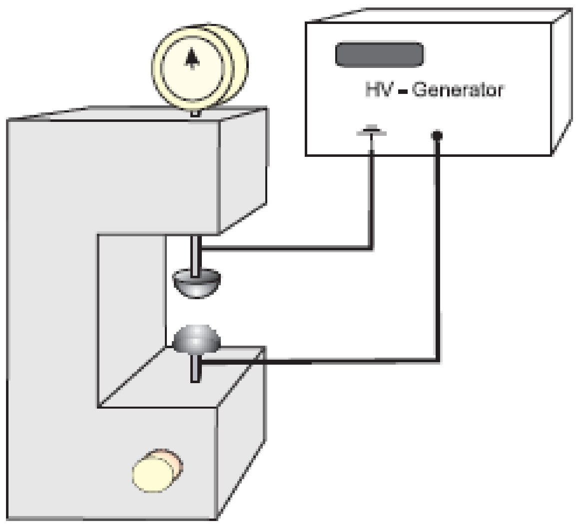
Observation: Plante, Dubowsky,
Int. J. Solids and Structures **43**, 7727 (2006)

Interpretation: Zhao, Hong, Suo
Physical Review B 76, 134113 (2007)

Electrical breakdown



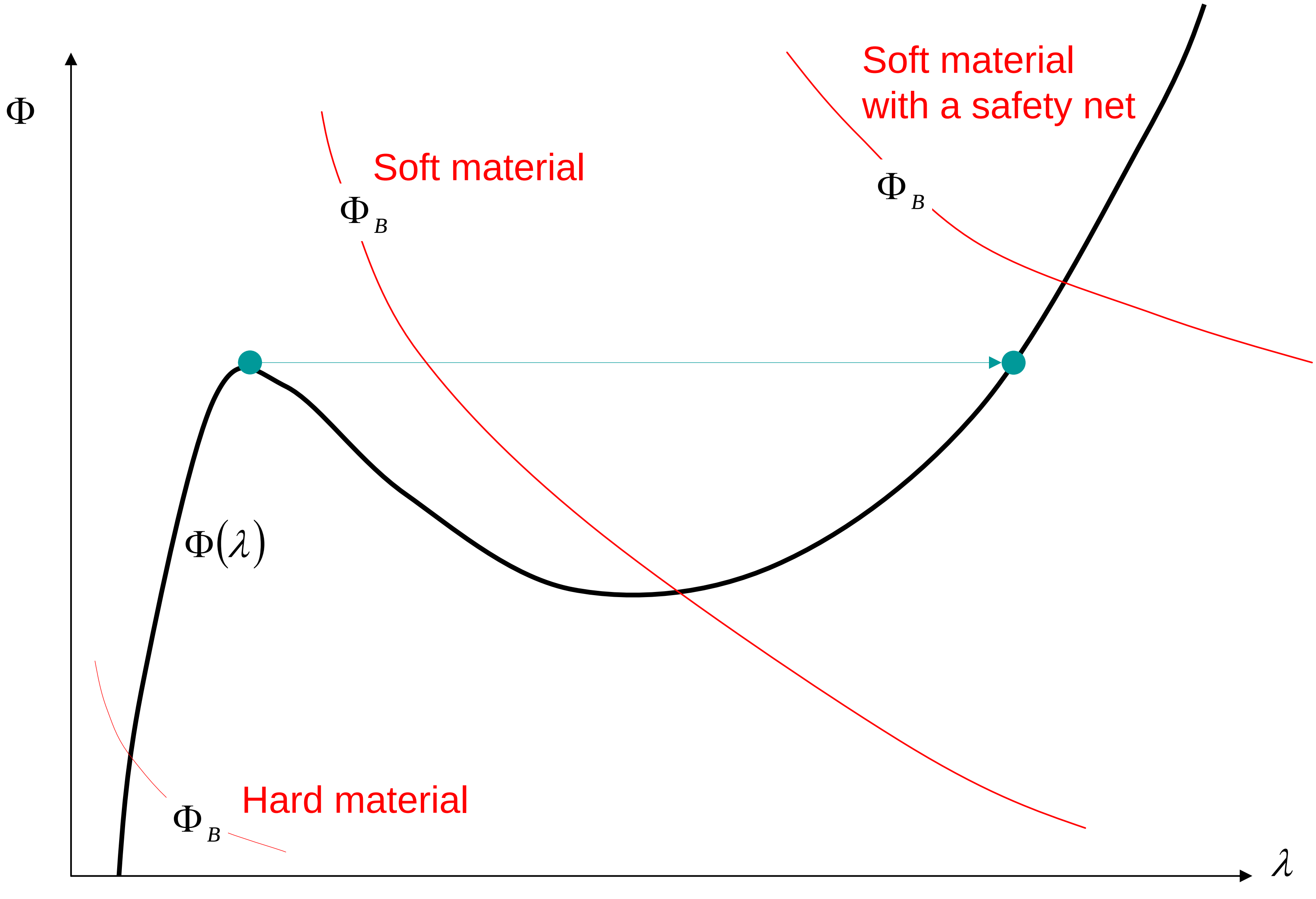
$$\Phi_B = E_B h = E_B H \lambda^{-2}$$



Kofod, Plante…

To measure dielectric strength,
one must suppress electromechanical instability by fixing stretch.

Snap-through instability may enable an elastomer to achieve giant deformation of actuation



Theoretical limit of deformation of actuation

Experimental conditions voltage ramps up;
voltage stays below electrical breakdown, $\Phi_B(\lambda)$

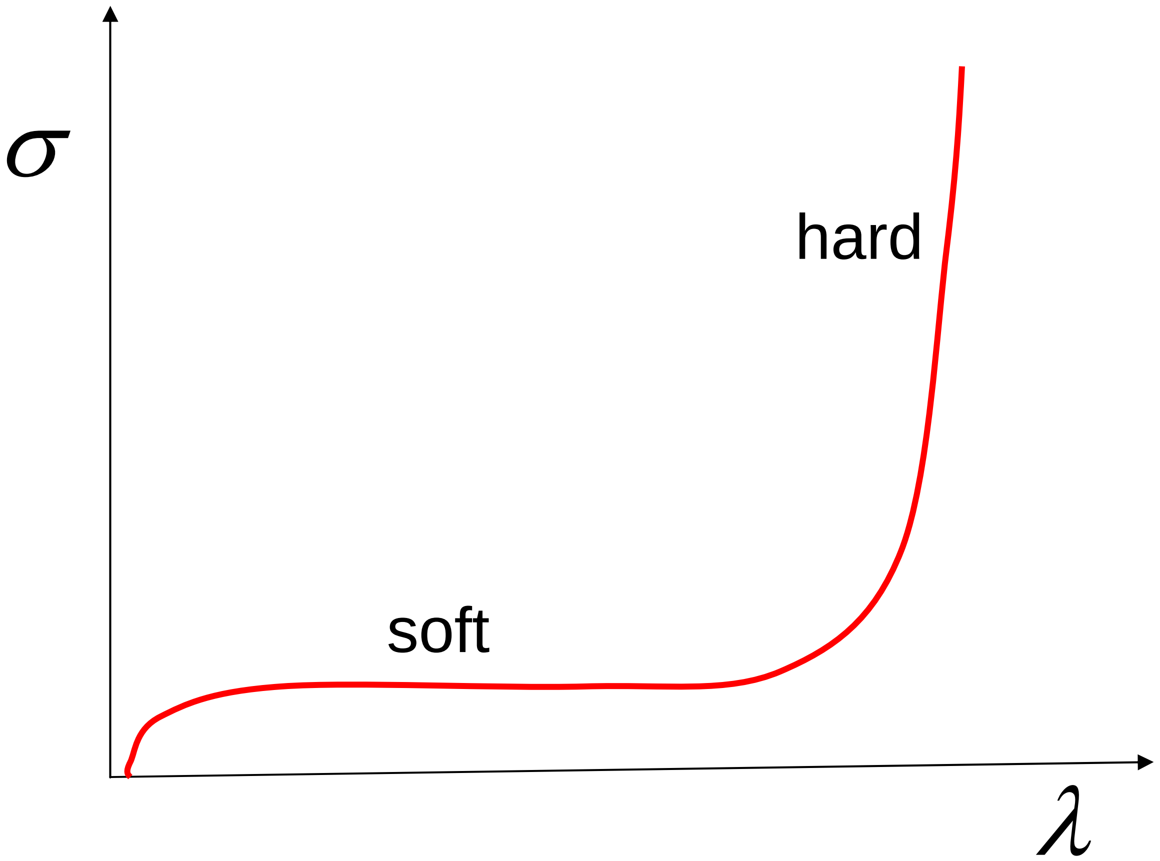
Equations of state

$$\Phi(\lambda) = H\lambda^{-2}\sqrt{\frac{f(\lambda)}{\varepsilon}}$$

Game: Find a material with

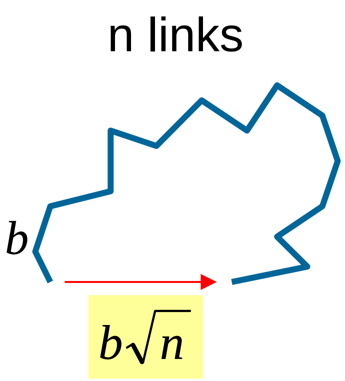
- high dielectric strength,
- suitable stress-strain curve.

Suitable stress-stretch curve

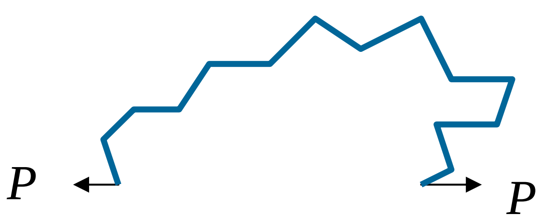


- Soft: enable large deformation at a voltage below electrical breakdown.
- Hard: provide a safety net to avert excessive deformation.

When stretched, a polymer stiffens

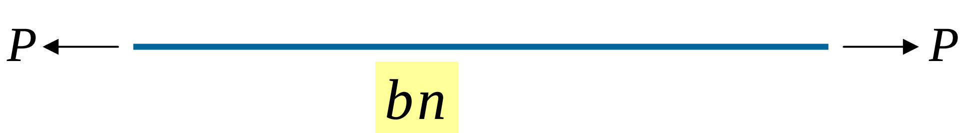


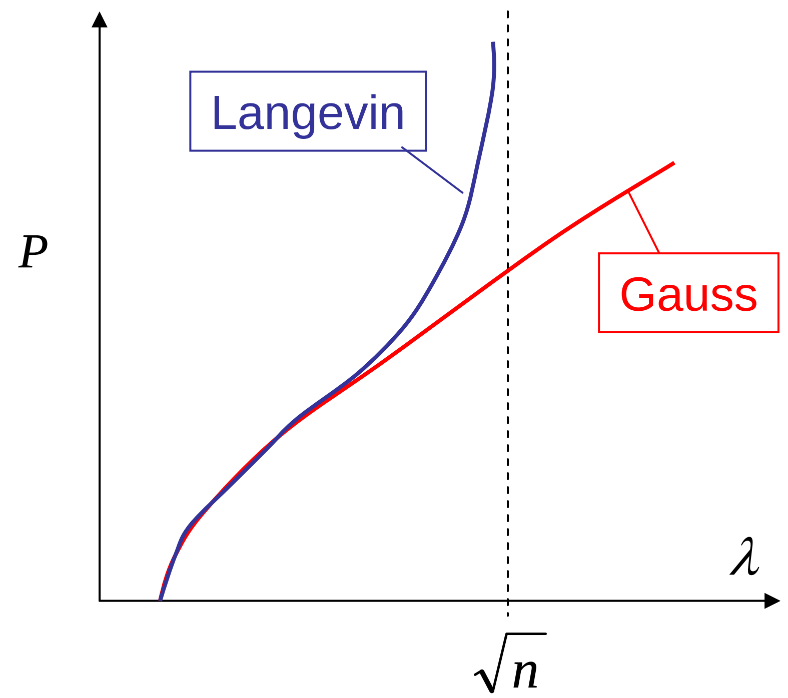
released



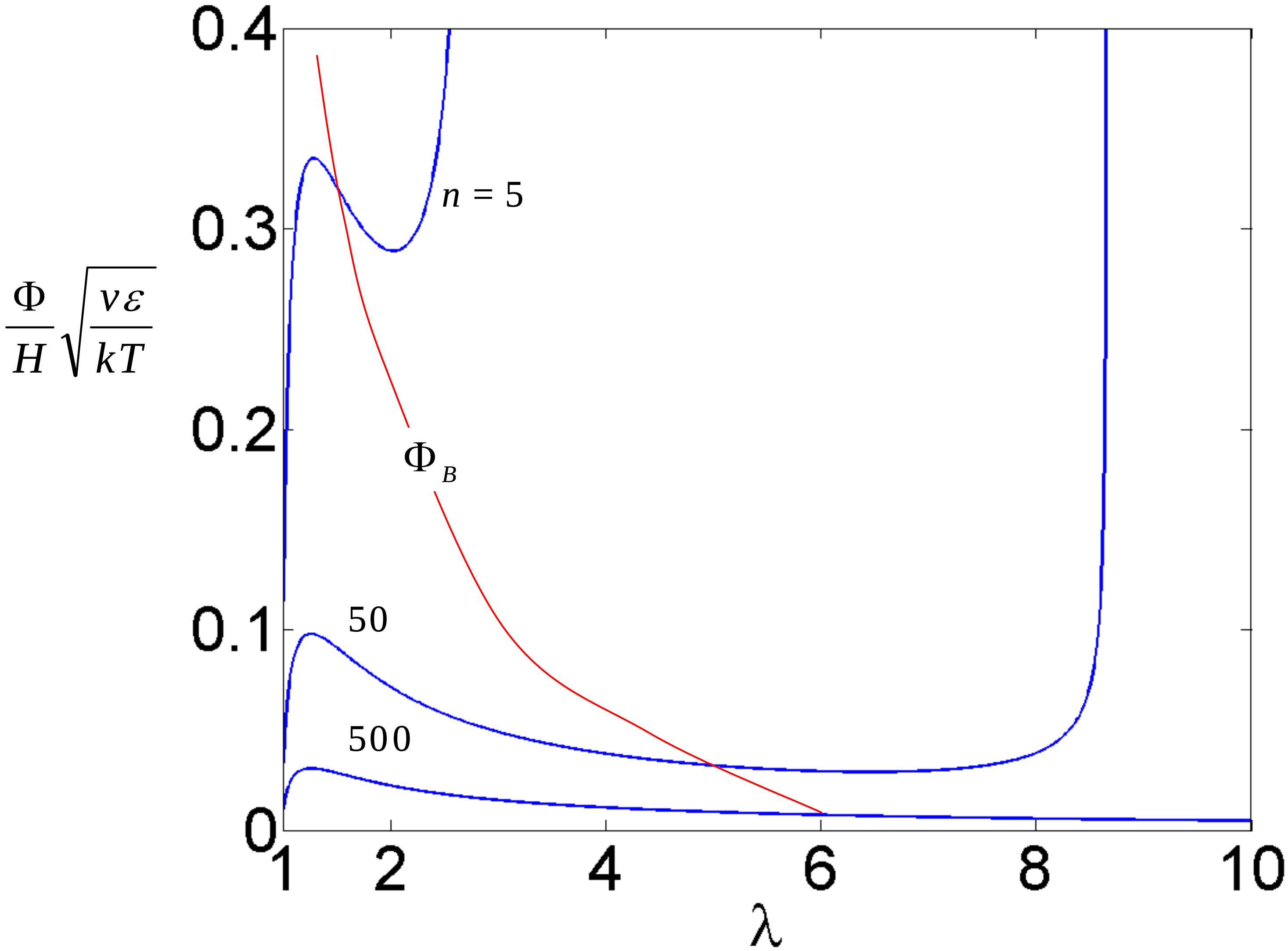
stretched

fully stretched

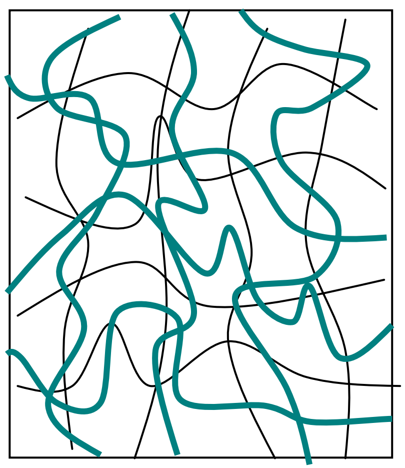


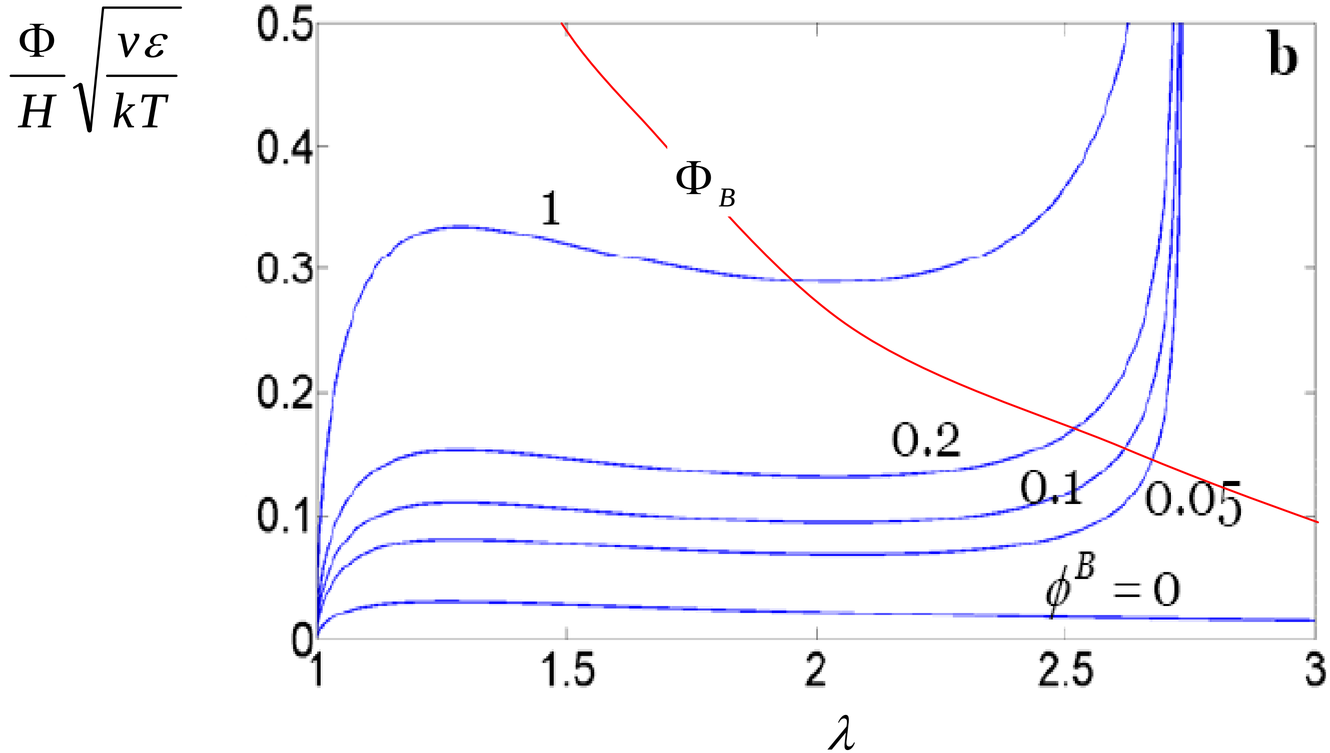


Change chain length



Interpenetrating networks



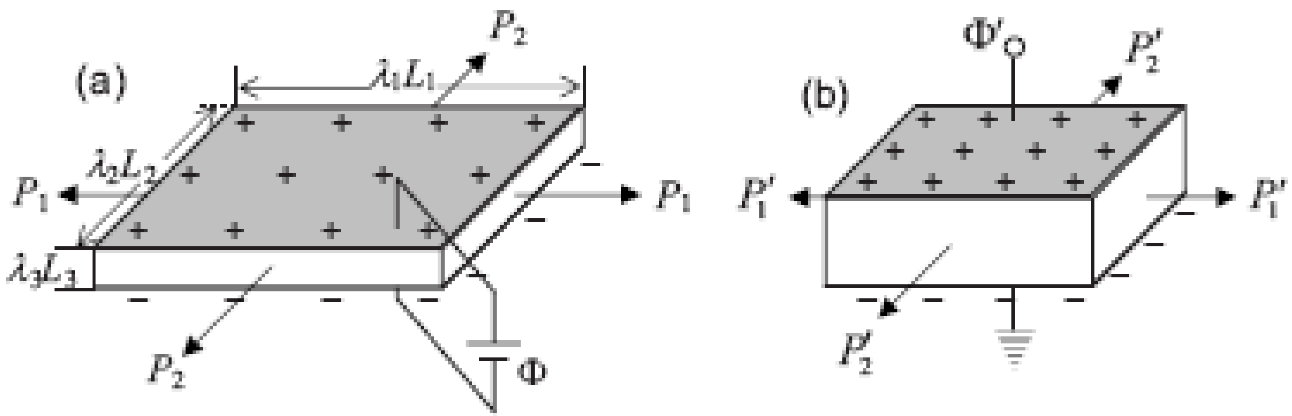


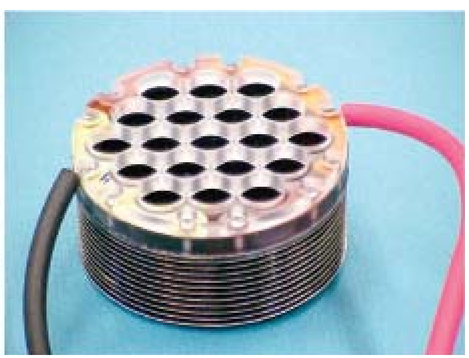
Experiment: Ha, Yuan, Pei, Pelrine
Adv. Mater. 18, 887 (2006).

Theory: Suo, Zhu. APL accepted.

- Short chains provide a safety net.
- Long chains fill the space.

Energy harvesting



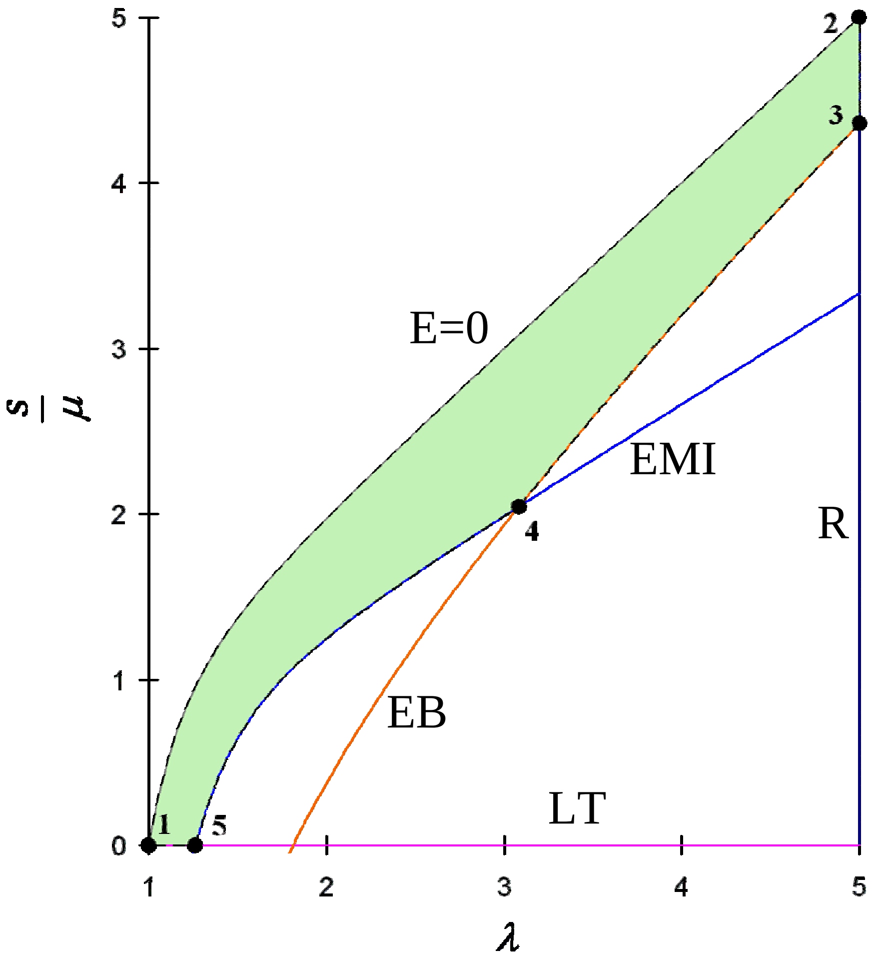


Generate electricity from walking

Generate electricity from ocean waves

Pelrine, Kornbluh…

Maximal energy that can be converted by a dielectric elastomer



6 J/g, Elastomer (theory)
0.4 J/g, Elastomer (experiment)
0.01 J/g ceramics

Koh, Zhao, Suo, Appl. Phys. Lett. 94, 262902 (2009)

Summary: Soft Active Materials

- Many stimuli (E, pH, salt, T...) cause deformation.
- Deformation enables many functions (soft robots, adaptive optics, self-regulating fluidics, programmable haptics, oil recovery, energy harvesting, drug delivery, tissue regeneration, low-cost diagnosis...).
- Snap-through instability may enable an elastomer to achieve giant deformation of actuation.

4 lectures on SAMs: http://imechanica.org/node/7048
•Dielectric elastomers
•Neutral gels
•Polyelectrolytes
•pH-sensitive gels