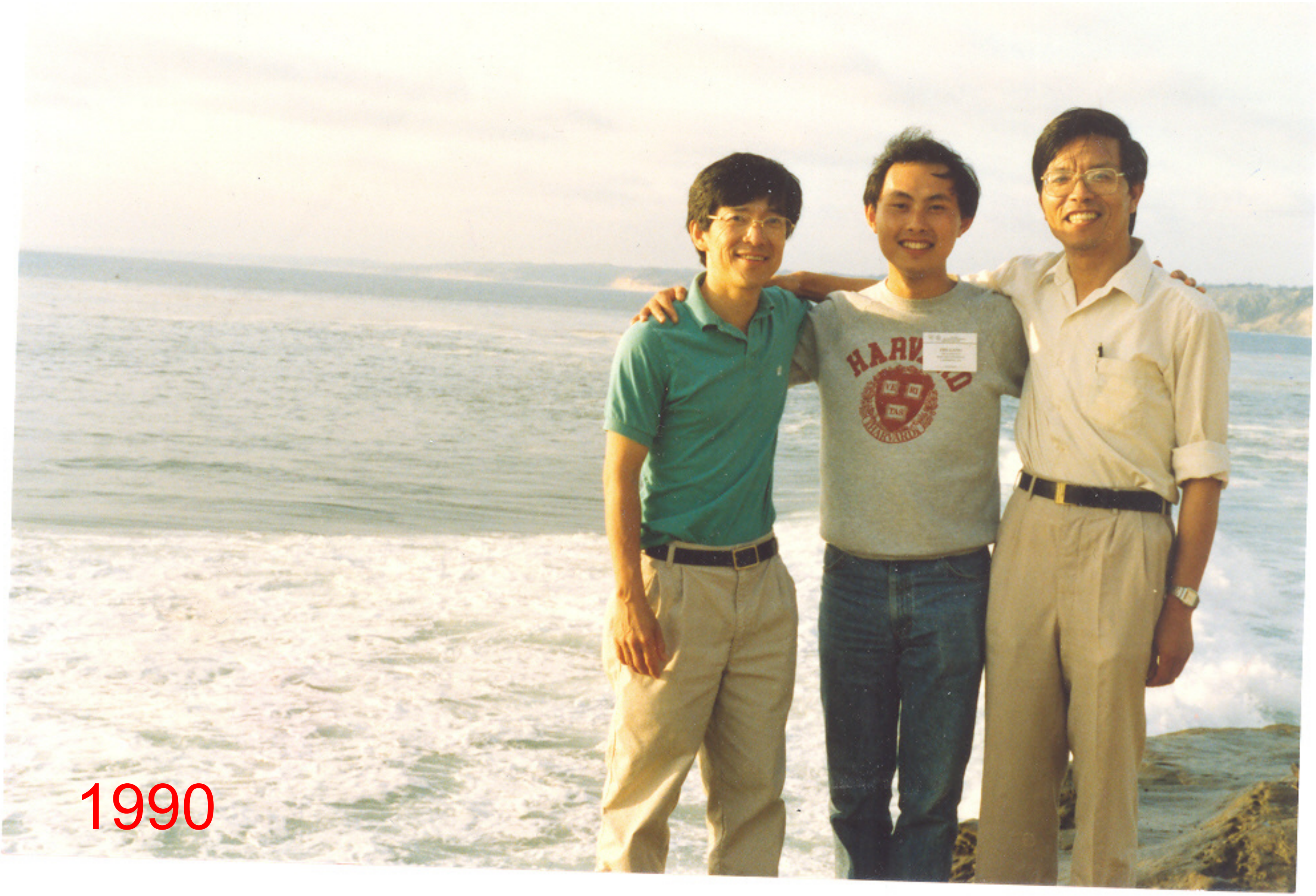

1990

1. A.G. Varias, Z. Suo and C.F. Shih. Ductile failure of a constrained metal foil. J. Mech. Phys. Solids, 39, 963-986 (1991).

2. T.C. Wang, C.F. Shih and Z. Suo. Crack extension and kinking in laminates and bicrystals. Int. J. Solids Structures. 29, 327-344 (1992).

3. W. Yang, Z. Suo and C.F. Shih. Mechanics of dynamic debonding. Proc. R. Soc. London. A 433, 679-697 (1991).

4. A.G. Varias, Z. Suo and C.F. Shih. Mode mixity effect on the damage of a constrained ductile layer. J. Mech. Phys. Solids. 40, 485-509 (1992).

5. Z. Suo, C.F. Shih, and A.G. Varias. A theory for cleavage cracking in the presence of plastic flow. Acta Metall. Mater, 41, 1551-1557 (1993).

6. Z. Suo and C. F. Shih. Models for metal/ceramic interface fracture. in Metal-Matrix Composites, Ed. S. Suresh, A. Mortensen and A. Needleman, Butterworth-Heinemann, Stoneham, MA. 217-232 (1993)

7. L. Xia, A.F. Bower, Z. Suo, and C.F. Shih A finite element analysis of the motion and evolution of void due to strain and electromigration induced surface diffusion. Journal of the Mechanics and Physics of Solids 45, 1473-1493 (1997).


2009/06/02 19:13

mechanics of soft materials

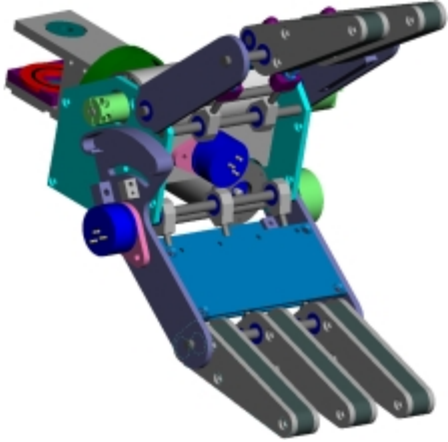
Zhigang Suo
Harvard University

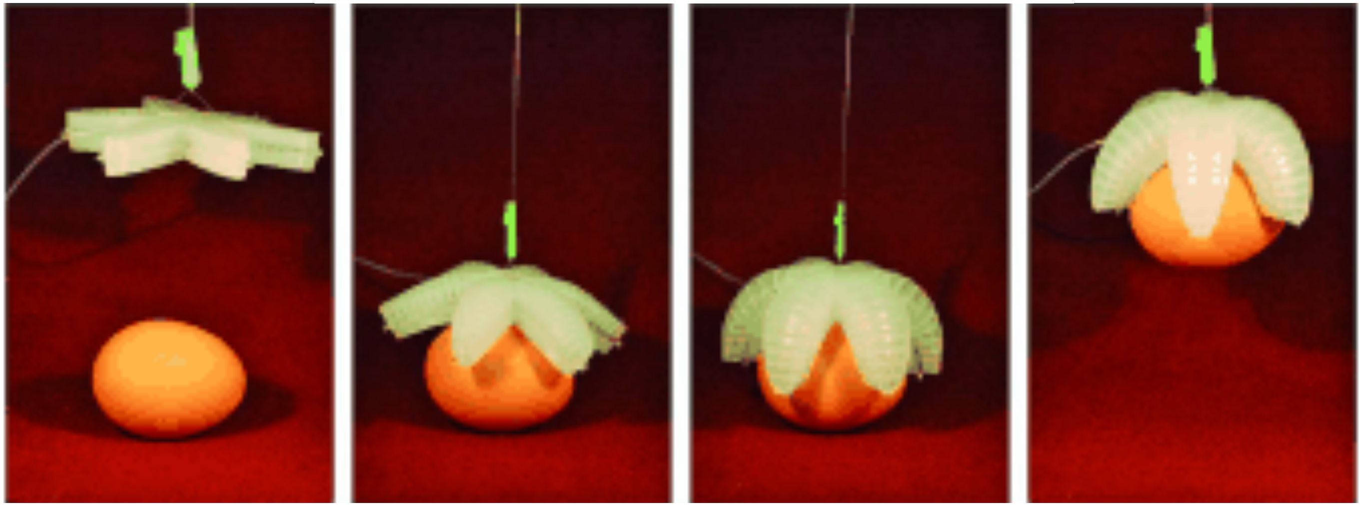
Why soft materials?

Plasticity

Elasticity

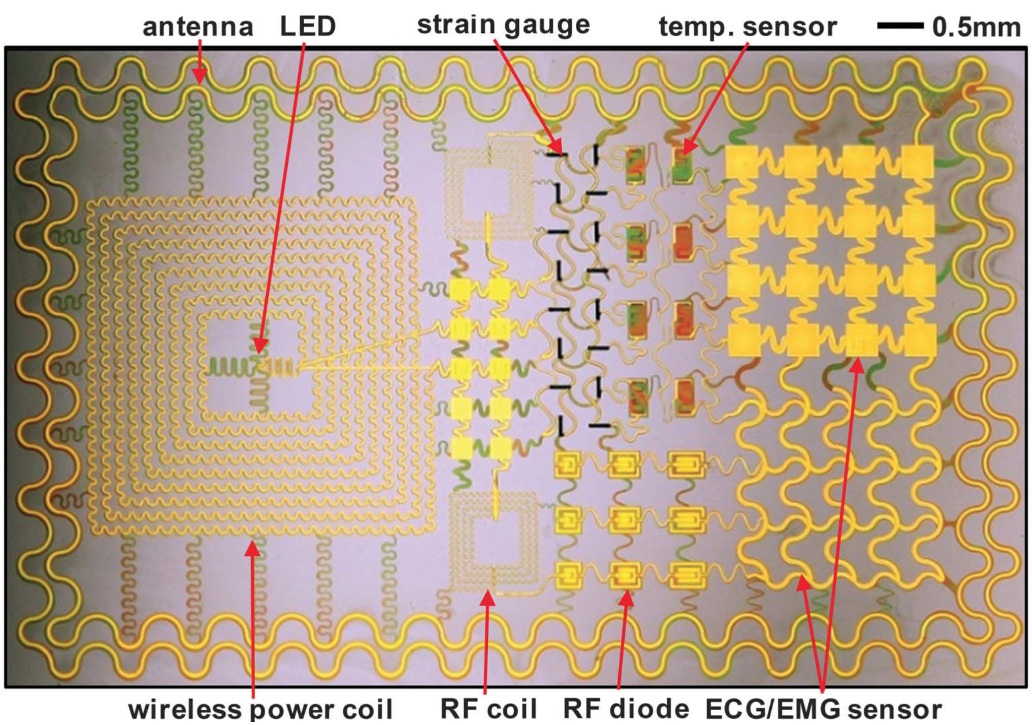
Soft machines



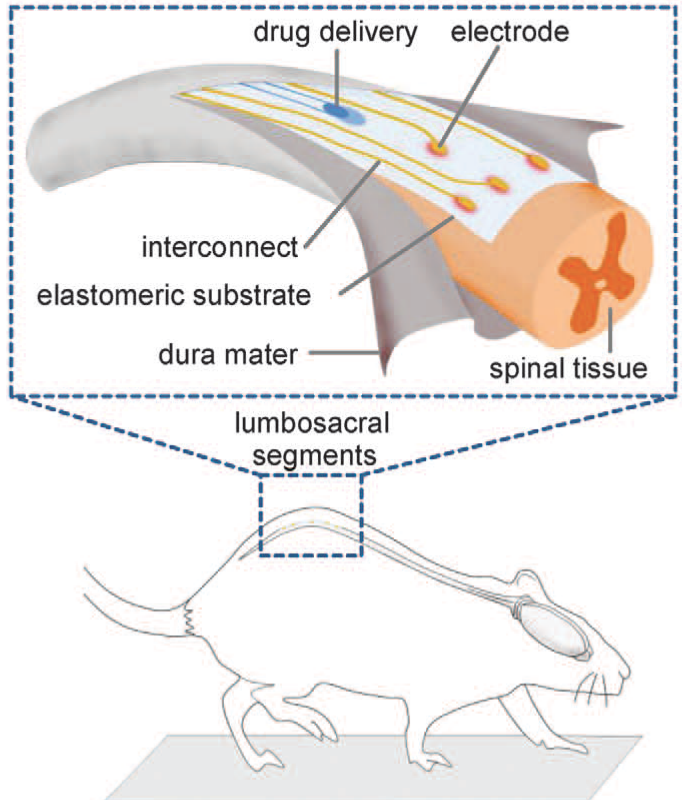


Ilievski, Mazzeo, Shepherd, Chen, Whitesides, Angew. Chem. Int. Ed. 50, 1 (2011)

Stretchable electronics

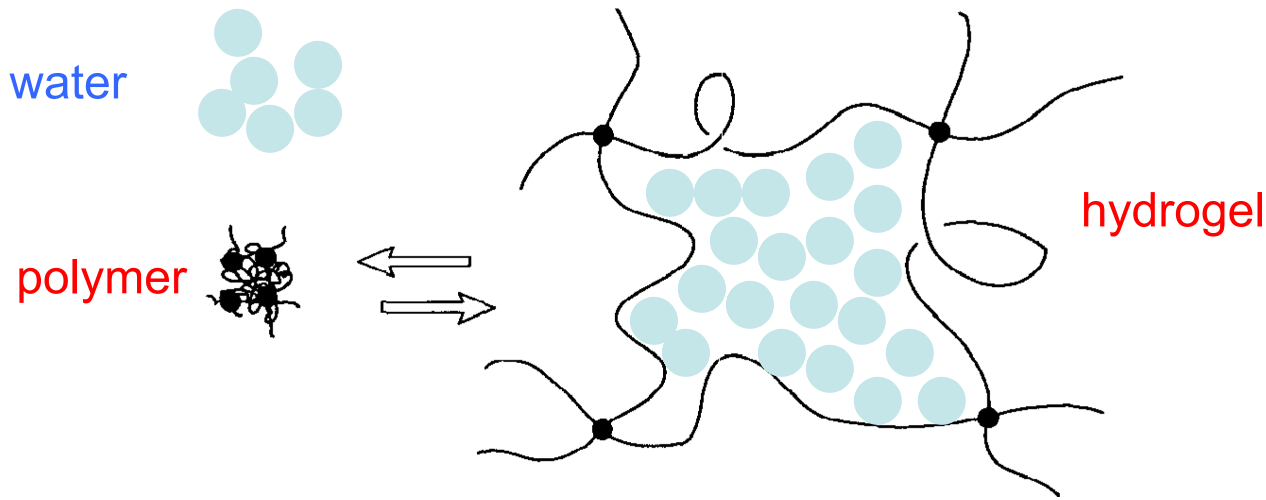


Epidermal electronics
Kim et al. Science 333, 838 (2011)

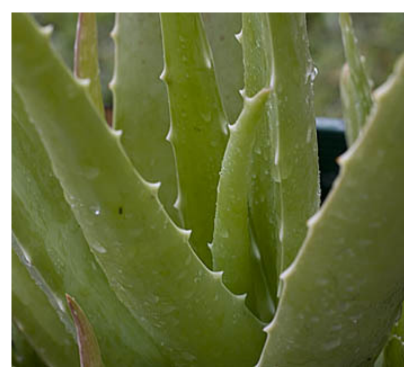


Electronic dura mater
Minev et al., Science 347, 159 (2015)

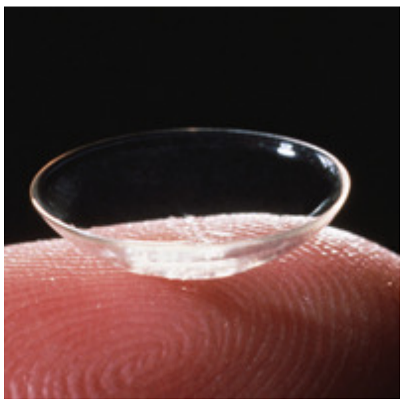
Hydrogel



Liquid like: water and polymers aggregate by weak bonds. Enable transport
Solid-like: polymers crosslink by strong bonds. Retain shape

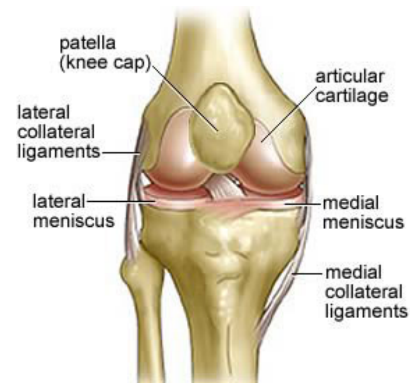


applications of hydrogels



Contact lens (1960s)

Superabsorbent diaper (1980s)

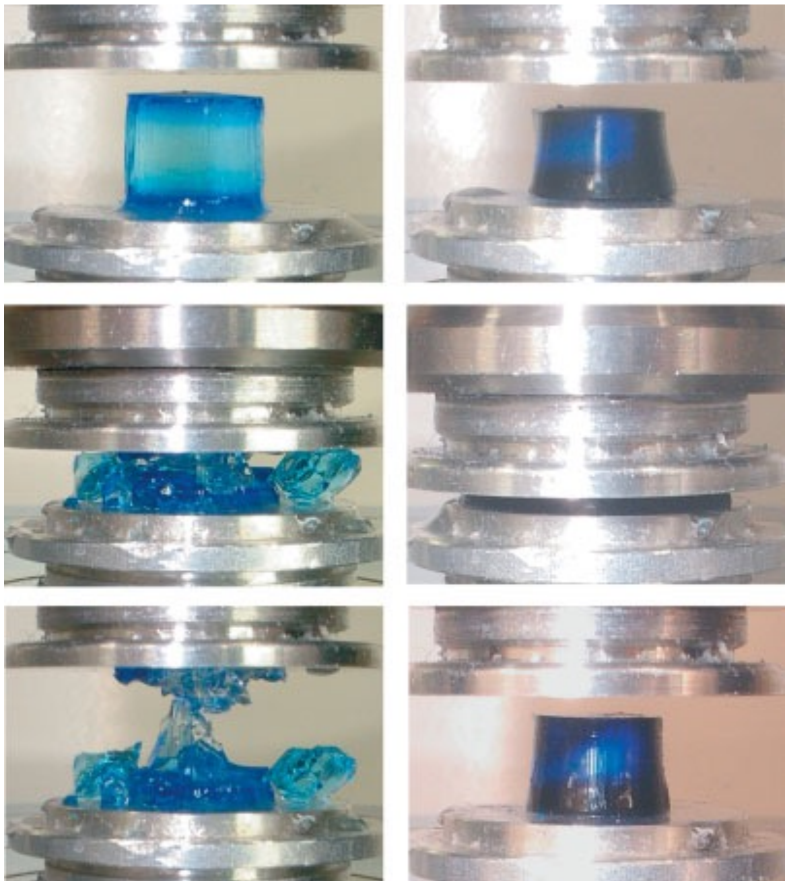


Artificial tissues

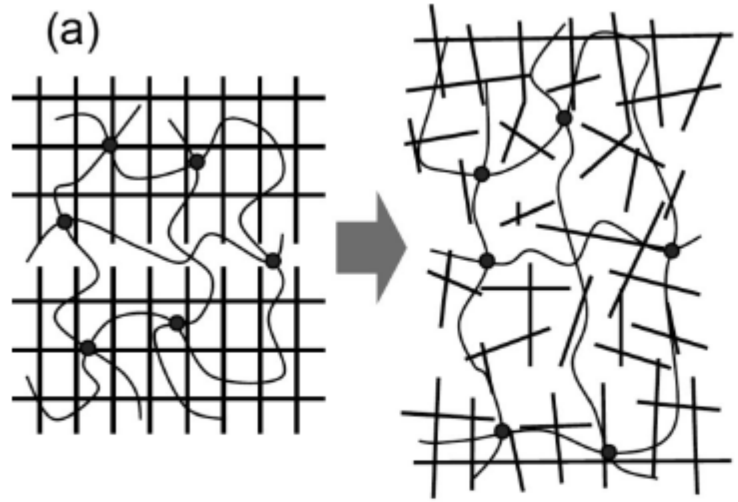
Wichterle and Lim, Hydrophilic gels for biological use. Nature 185, 117 (1960)

MasudaTrends in the development of superabsorbent polymers for diapers pp. 88-89, Superabsorbent polymers: science and technology (1994).

Double-network gels



Single-network gel Double-network gel

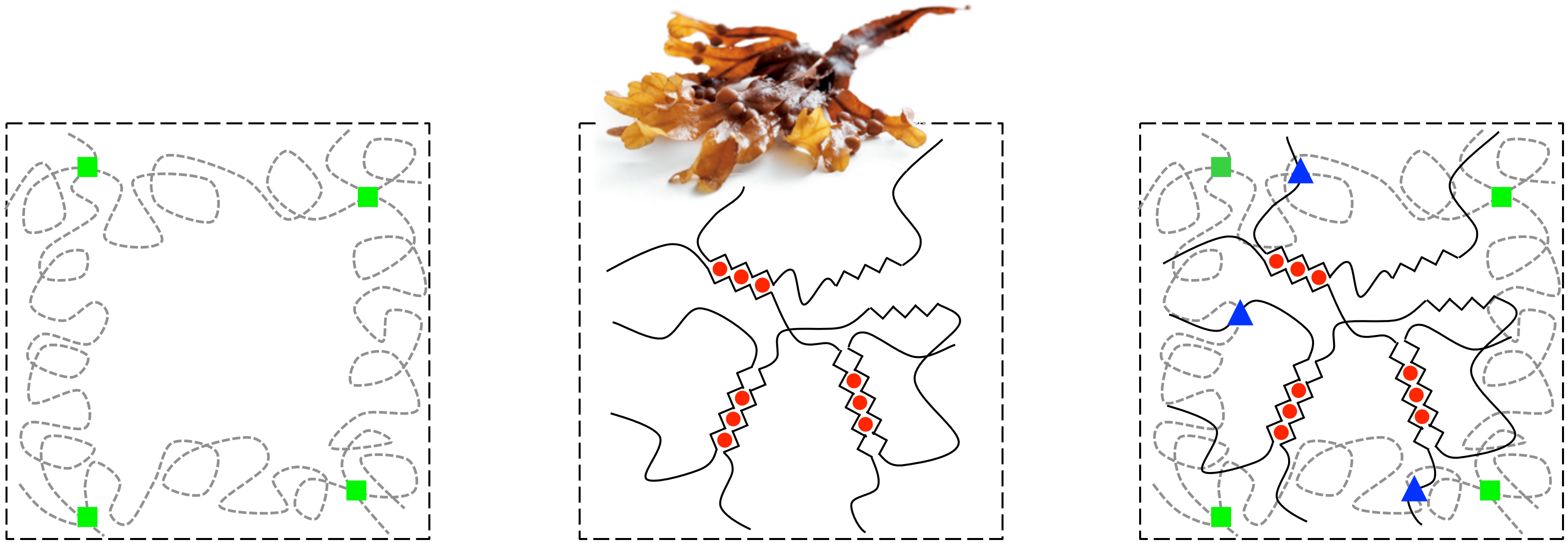


Network of long chains
Network of short chains

High toughness by sacrificing the network of short chains

Gong, Katsuyama, Kurokawa, Osada, Advanced Materials 15, 1155 (2003)

Three types of gels



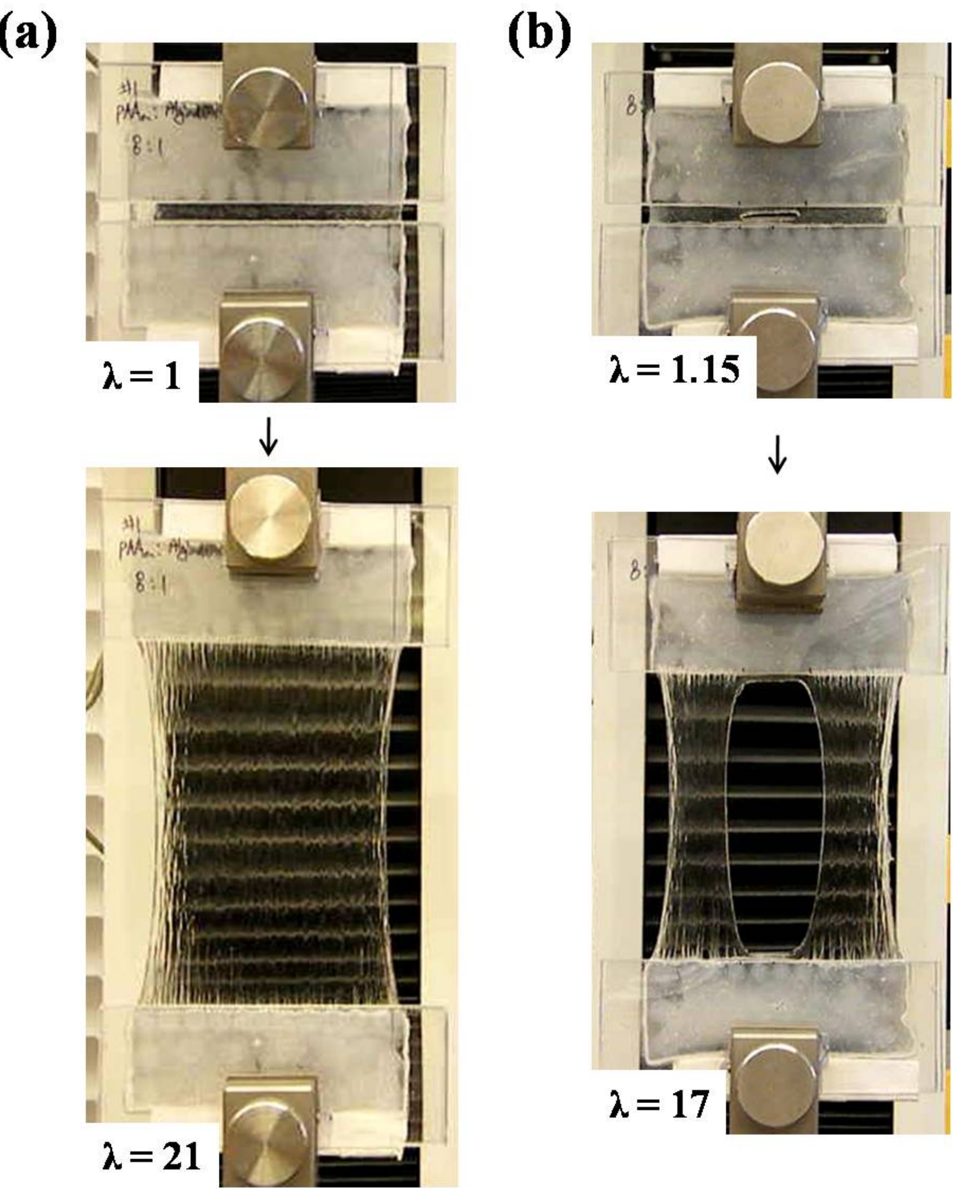
Polyacrylamide gel Alginate gel Hybrid gel

Acylamide
CrossInker: MBAA
Photoinitiator: Ammonium persulphate
Crosslinking accelerator: TEMED

Alginate
$(CaSO_4)(2H_2O)$

Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Highly stretchable and tough hydrogels



- Water: 90%
- Stretch: 21
- Fracture energy: 9000 J/m^2

~10 J/m^2, tofu, jello
~10 J/m^2, most gels
~100 J/m^2, contact lenses
~1000 J/m^2, cartilage
~1000 J/m^2, double network gels (Gong 2003)
~1000 J/m^2, VHB
~10,000 J/m^2, natural rubber

Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Stretchy!

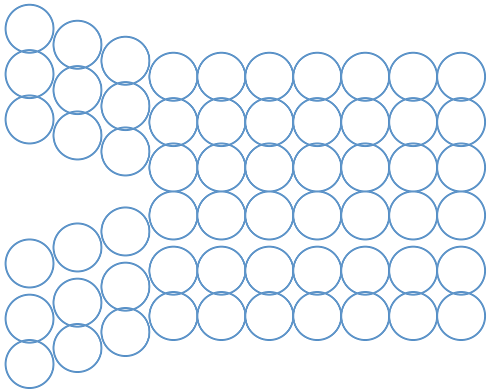
Steel ball
Diameter 2.54 cm
Mass 64 g
Drop from 1.86 m

Gel
Thickness 1 mm

Videos
http://www.nature.com/nature/journal/v489/n7414/full/nature11409.html#/supplementary-information

Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Rupture of glass

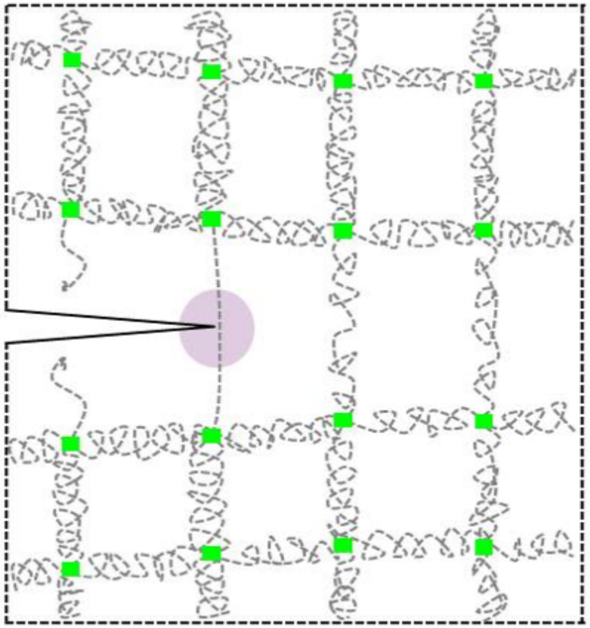


$$\text{fracture energy} = \frac{\text{covalent energy of a single layer of atoms}}{\text{area}}$$

$$\Gamma \approx 1\,\mathrm{J/m^2}$$

Griffith (1921)

Rupture of a network

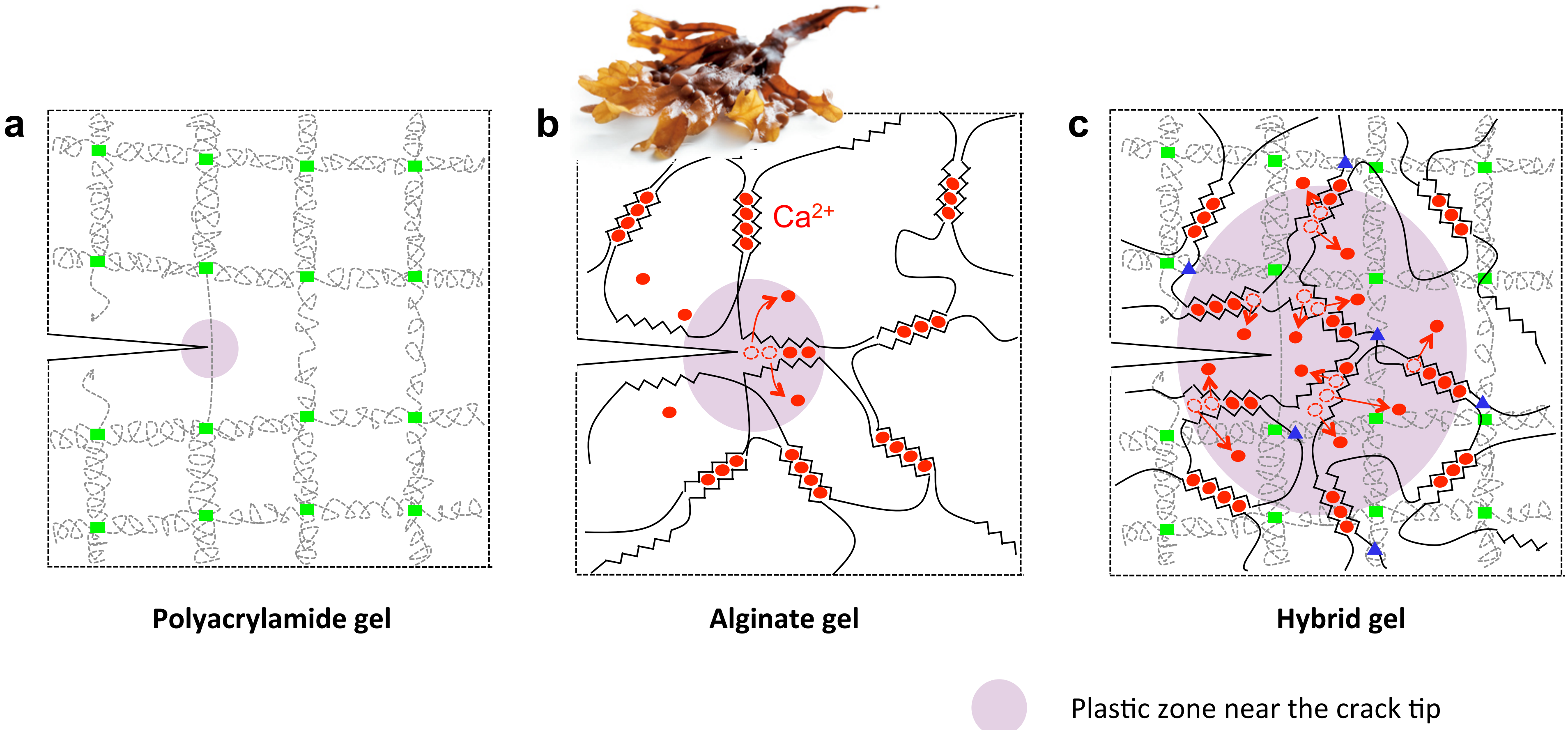


$$\text{fracture energy} = \frac{\text{covalent energy in a layer of chains}}{\text{area}}$$

$$\Gamma \approx 50 \text{J/m}^2$$

Lake and Thomas, Proceedings of the Royal Society of London 300, 108 (1967)

brittle + brittle = tough



Polyacrylamide gel

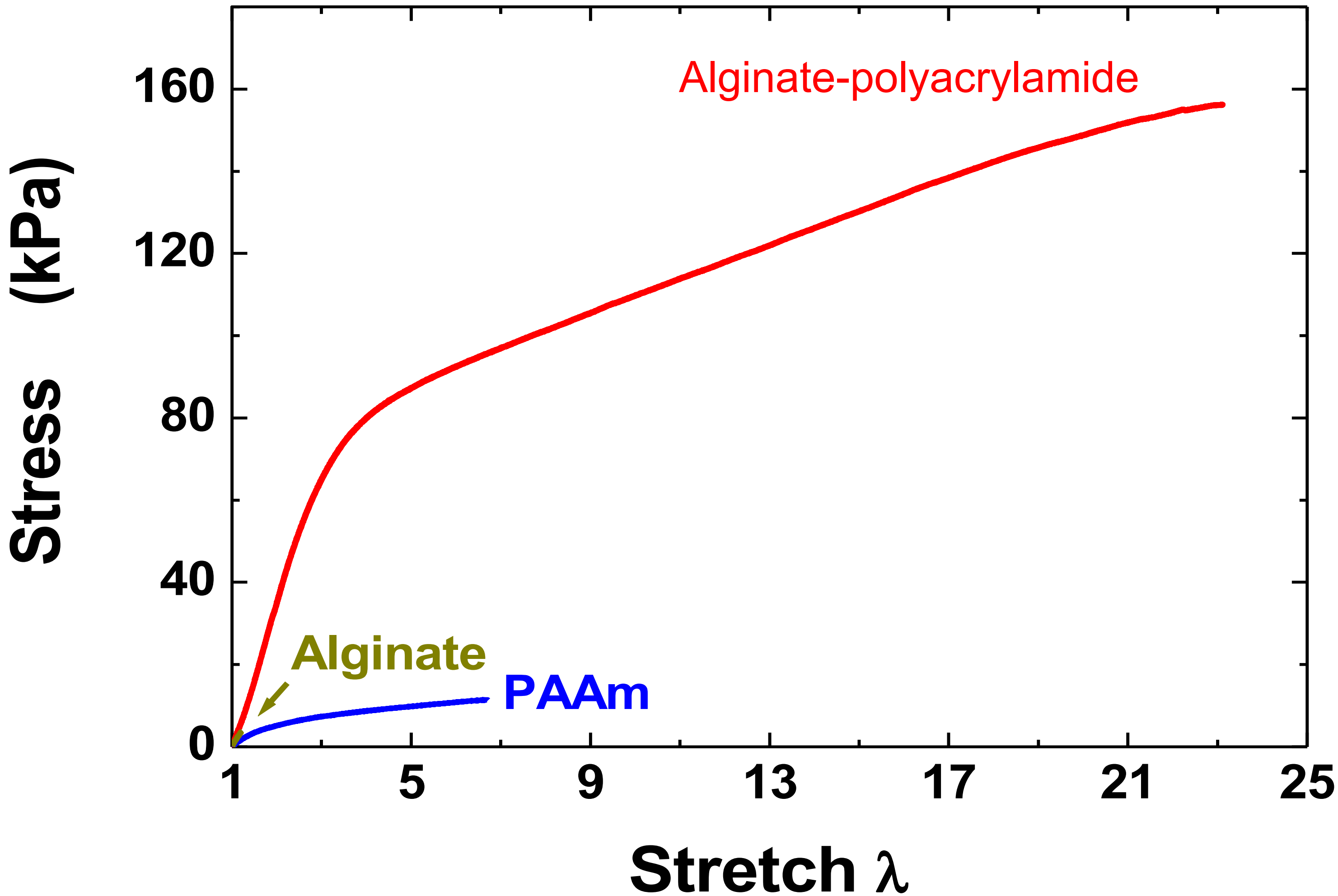
Alginate gel

Hybrid gel

Plastic zone near the crack tip

Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Synergy of the hybrid



Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

Hydrogel = tough water.

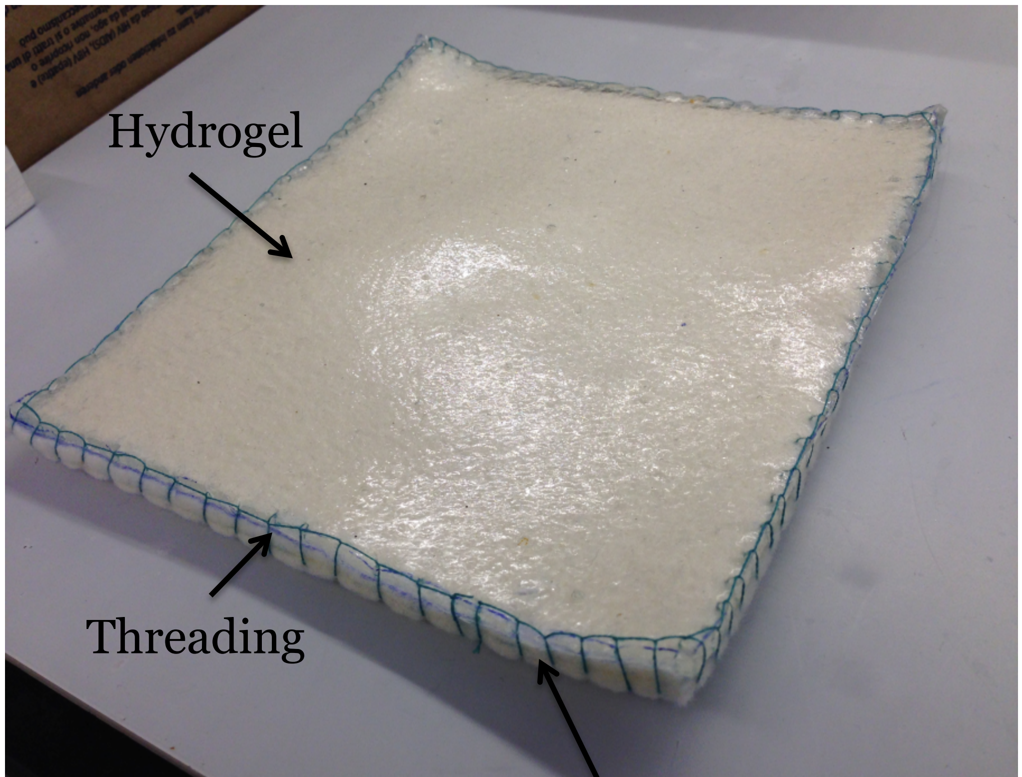
Can we use water in new ways?

Hydrogels outperform existing fire-retarding materials

Videos:
http://pubs.acs.org/doi/suppl/10.1021/acsami.5b10538

Illeperuma, Rothemund, Suo, Vlassak. ACS Applied Materials and Interfaces, 2016

Hydrogel-fabric laminate

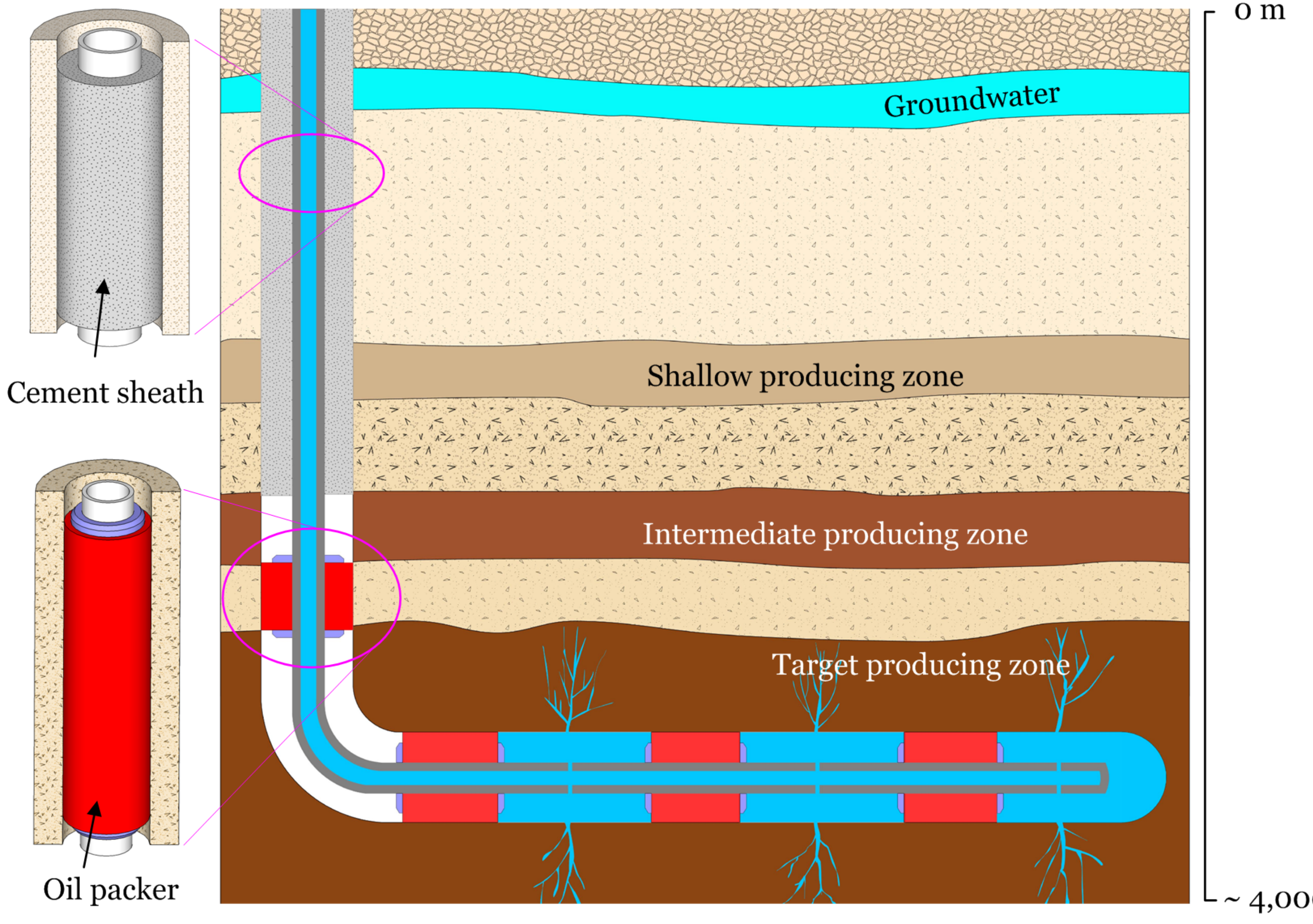


Illeperuma, Rothemund, Suo, Vlassak. ACS Applied Materials and Interfaces 8, 2071 (2016)

Cool jacket

Illeperuma, unpublished

Drilling, sealing and fracking

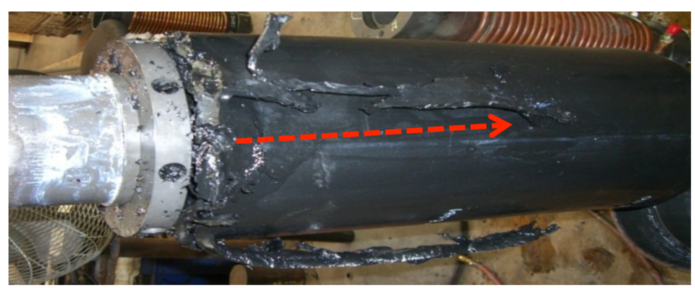


Postmortem observation of leaked packers

nearly no damage

damage at the end

damage along the packer



Transparent, desktop oilfield

Full-scale tests

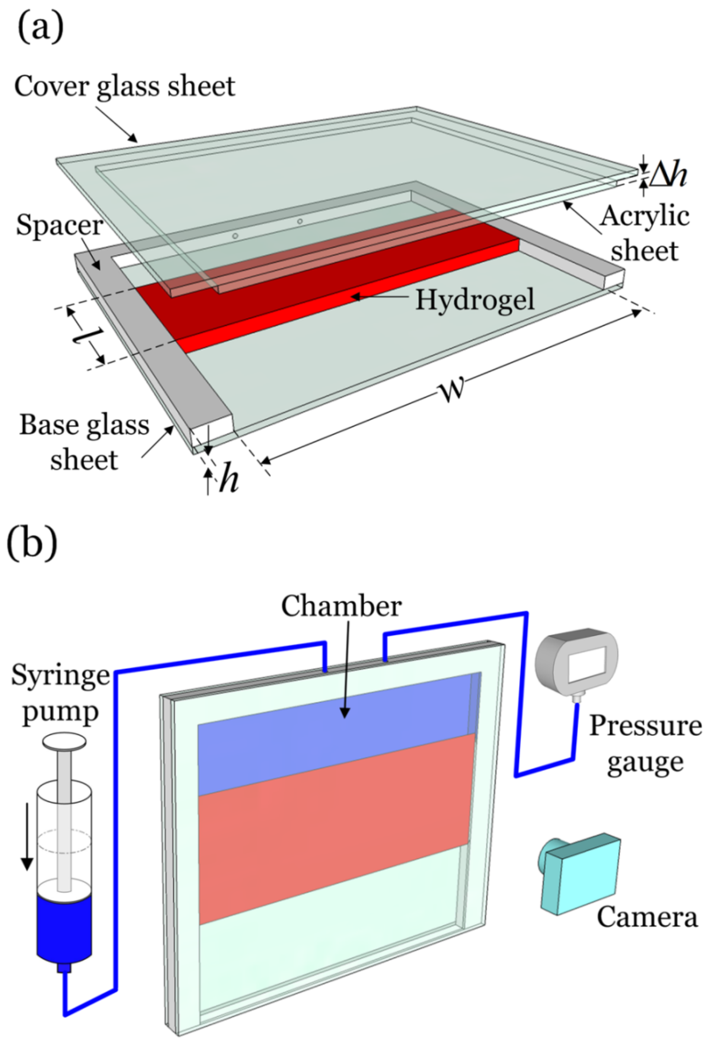
- Expensive and time-consuming
- Difficult to monitor
- High pressure (modulus ~ MPa, P = 10 MPa-GPa)

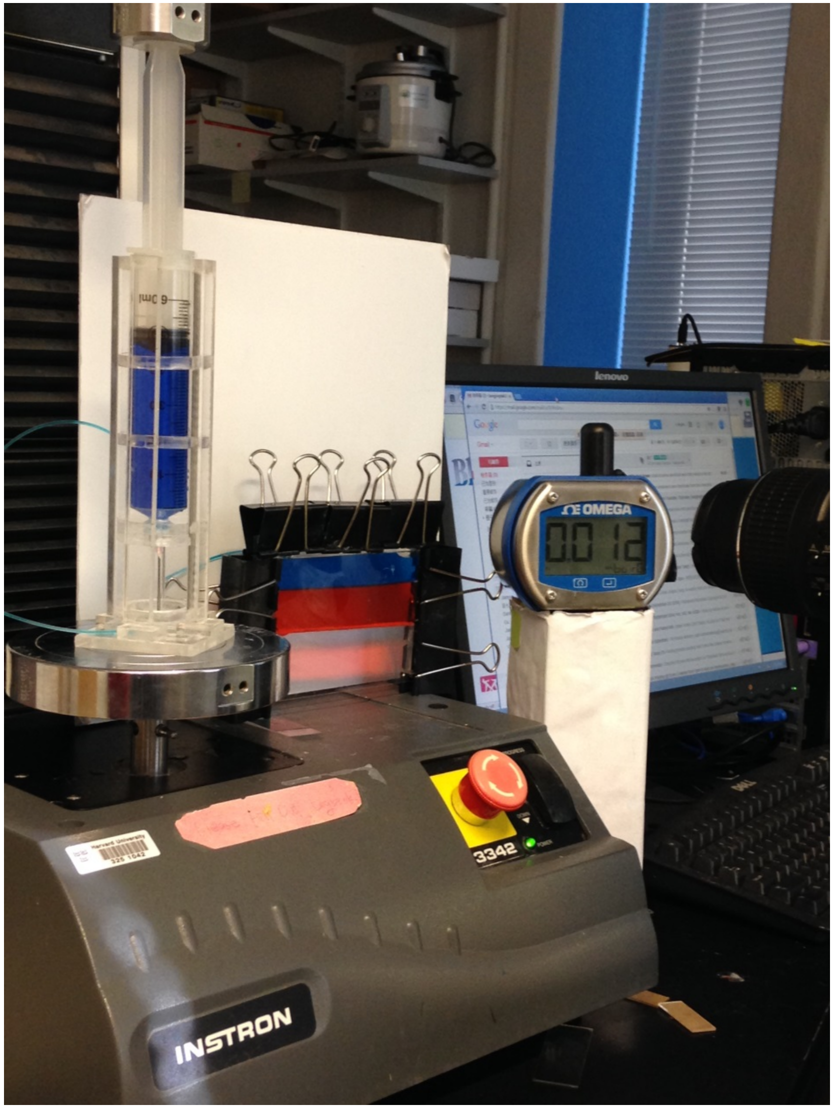
Desktop experiments

- Low-cost and fast
- Transparent
- Low pressure (modulus ~ kPa, P = 10 kPa-100 kPa)

Druecke, Dussan, Wicks, Hosoi. Journal of Applied Physics 117, 104511 (2015)
Liu, Wang, Lou, Suo. Extreme Mechanics Letters 1, 54 (2015)

Experimental setup

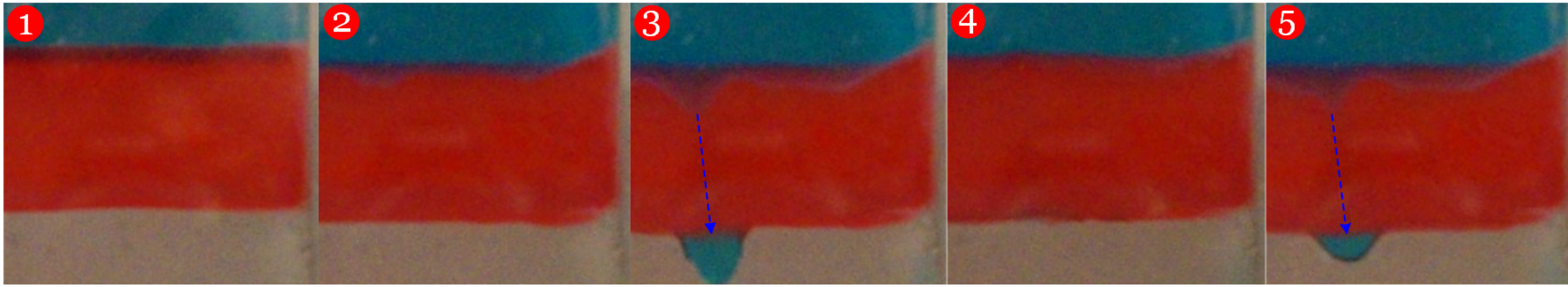


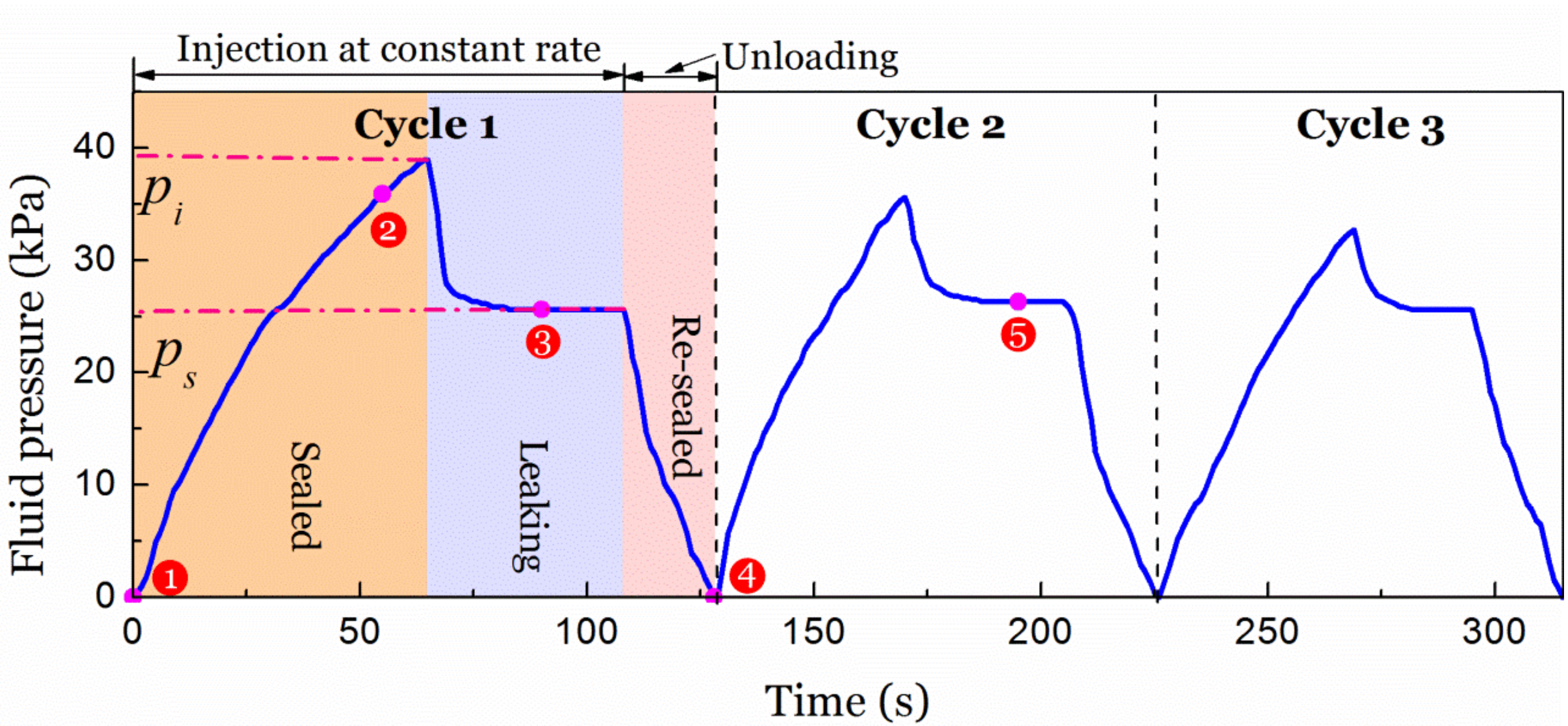


w=120 mm, h=4.5mm l=10~30mm,
Δh=0.45~1.65mm, μ=1.03kPa

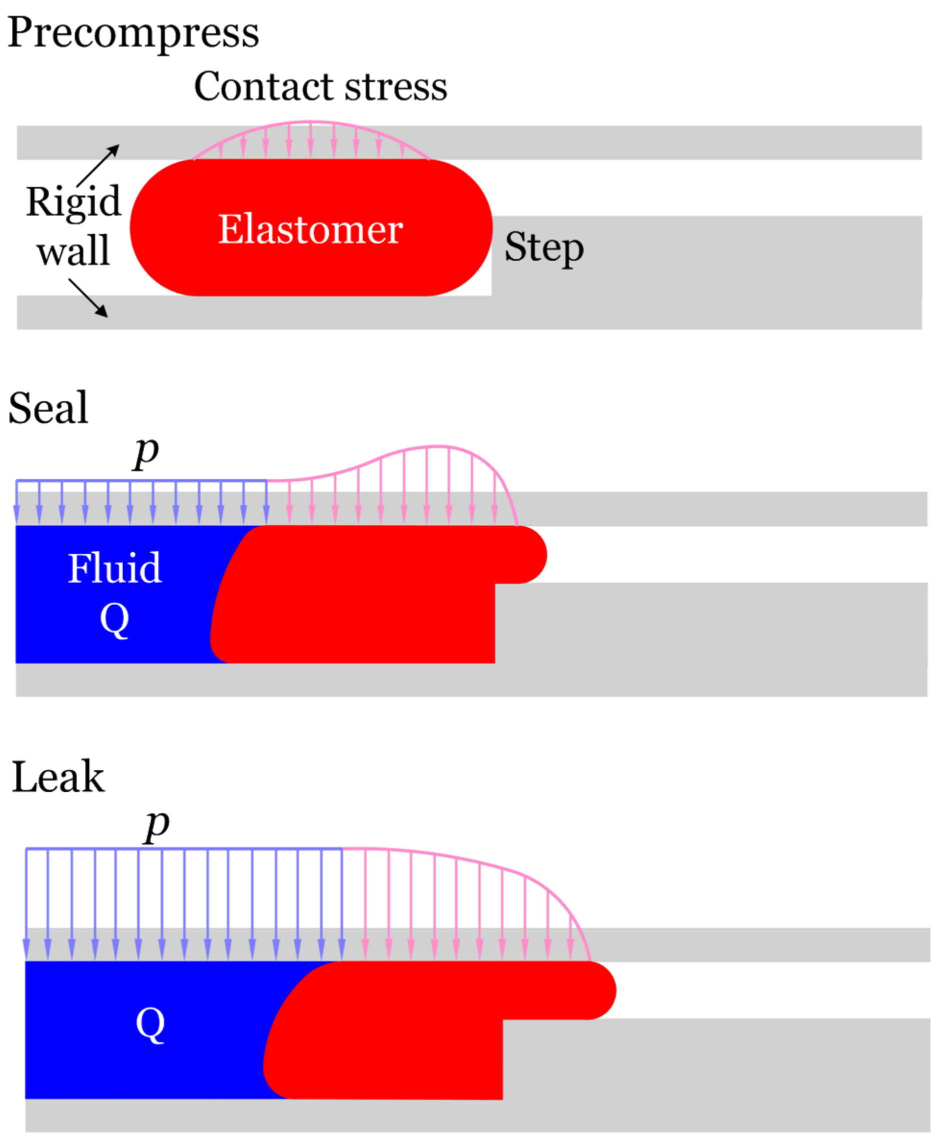
Liu, Wang, Lou, Suo. Extreme Mechanics Letters 1, 54 (2015)

Experimental observations



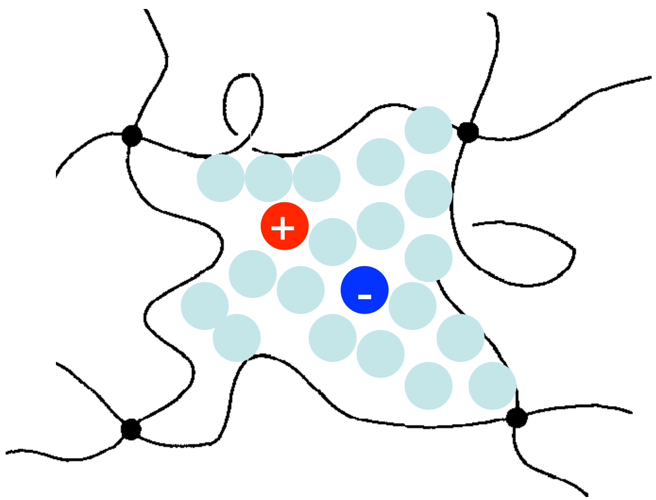


elastic leak



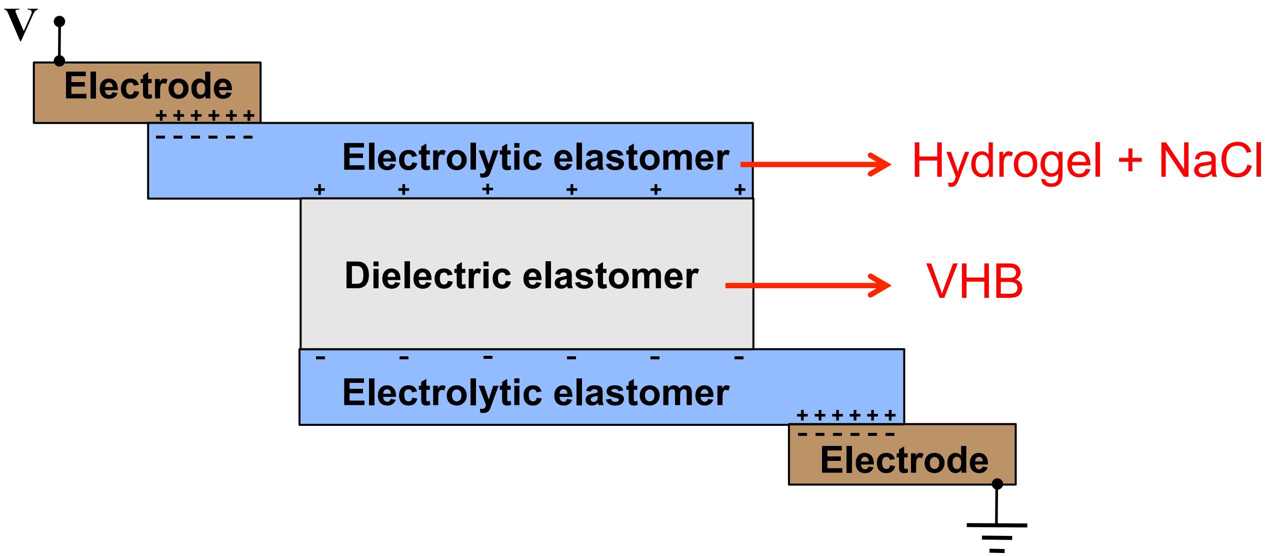
Liu, Wang, Lou, Suo. Extreme Mechanics Letters 1, 54 (2015)

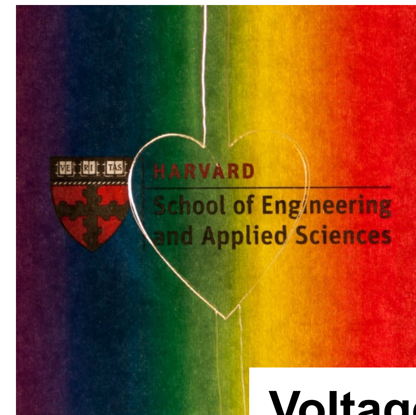
Hydrogel integrates stretchability and conductivity at molecular scale



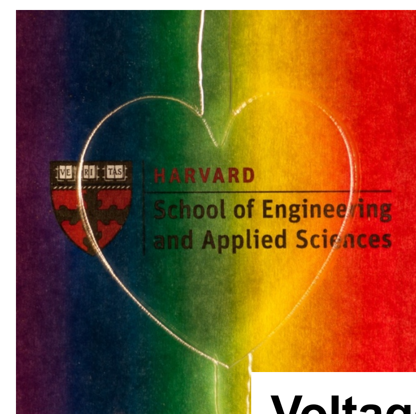
Artificial Muscles

mimic function, not anatomy





Voltage off



Voltage on

Keplinger, Sun, Foo, Rothemund, Whitesides, Suo. Science 341, 984 (2013)

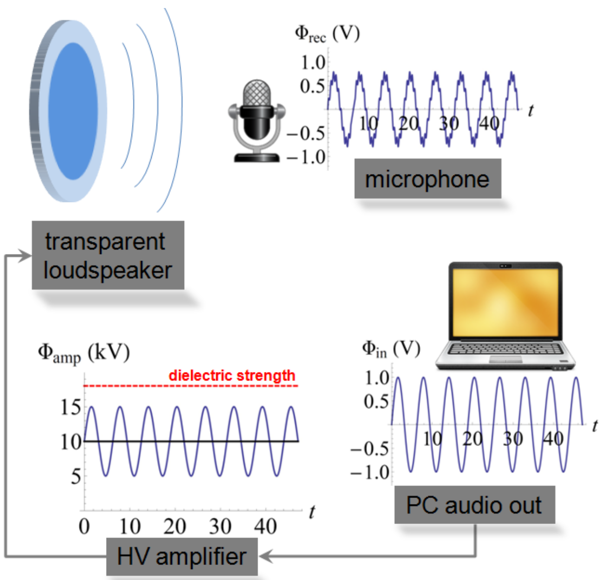
Challenges

A new context to study the science of hydrogels

- fragile?
- unstable? Water electrolyzes at ~ 1V. Dielectric deforms under ~10kV
- slow? Resistivity of saltwater is a million times that of copper.
- volatile?
- adhesion? Integrate dissimilar stretchable materials
- fatigue? Repeated large stretch

ionic music (iTune)

Transparent loudspeaker

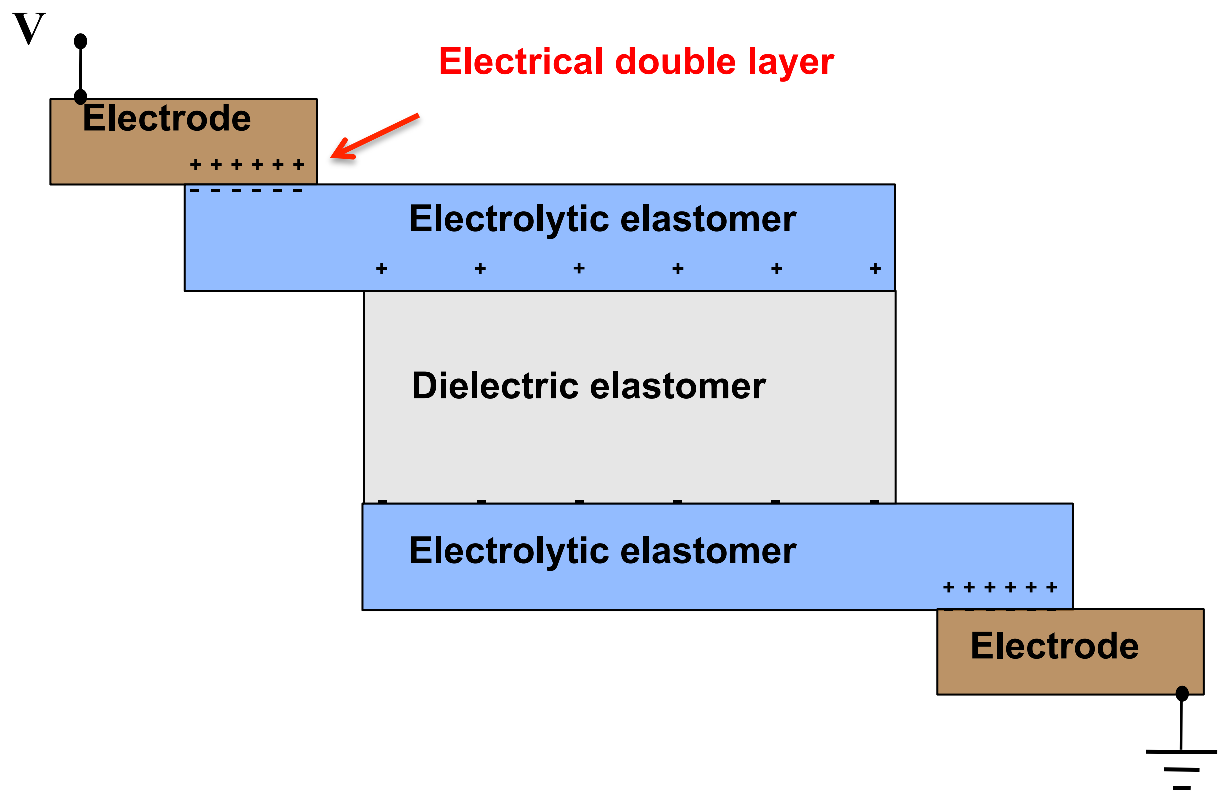


videos

http://science.sciencemag.org/content/341/6149/984/suppl/DC1

Keplinger, Sun, Foo, Rothemund, Whitesides, Suo. Science 341, 984 (2013)

Ionotronics: hybrid ionic-electronic circuits



Small voltage across electrical double layer—no electrolysis.

Large voltage across dielectric elastomer—electroactive strain.

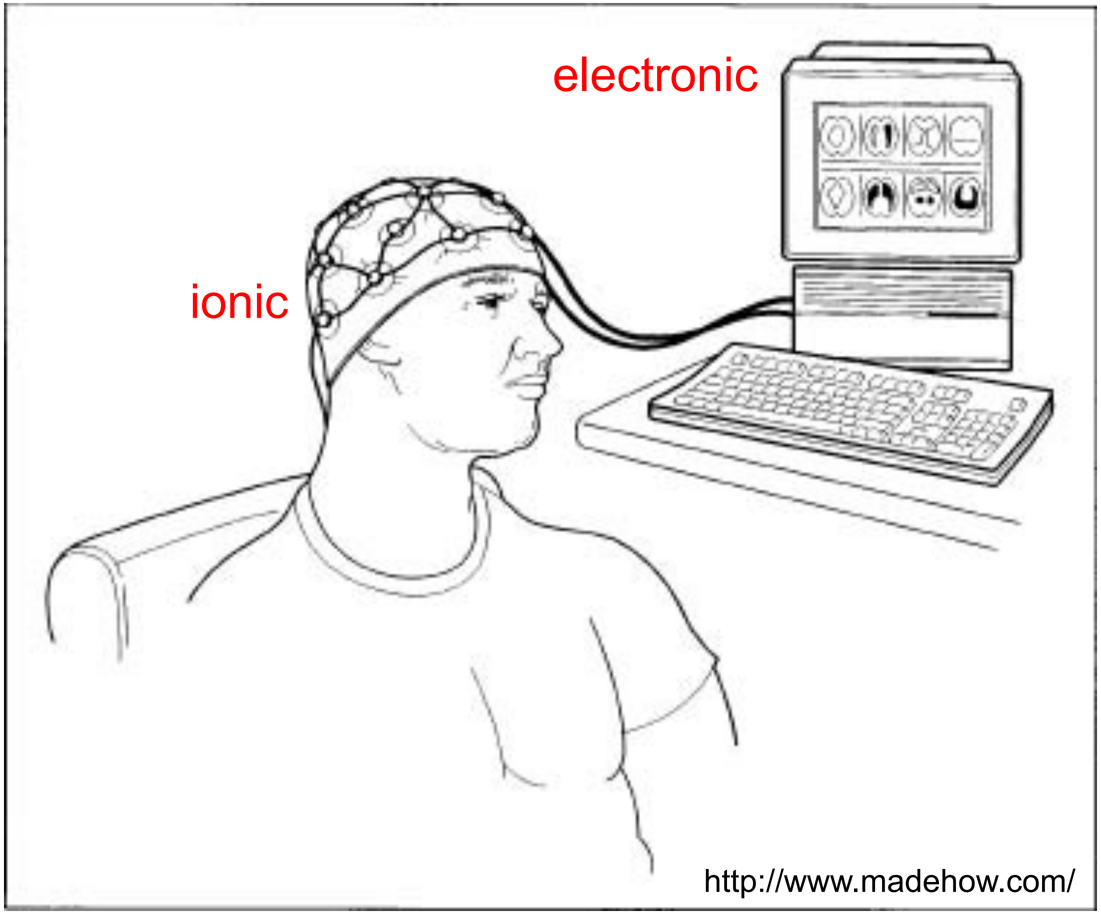
Keplinger, Sun, Foo, Rothemund, Whitesides, Suo. Science 341, 984 (2013)

Water-retaining hydrogels

Saturated aqueous solution	Relativity humidity at 25 C
NaCl	75%
LiCl	11%

Bai, Jiang, Chen, Foo, Zhou, Xiang, Zhou, Wang, Suo, Applied Physics Letters 104, 062902 (2014).
Chen, Bai, Xiang, Su, Chen, Wang, Zhou, Suo, Journal of Polymer Science B 52, 1055 (2014).
Bai, Chen, , Xiang, Zhou, Zhou, Wang, Suo, Applied Physics Letters. 105, 191903 (2014).

Hybrid ionic-electronic circuits
Ionotronics



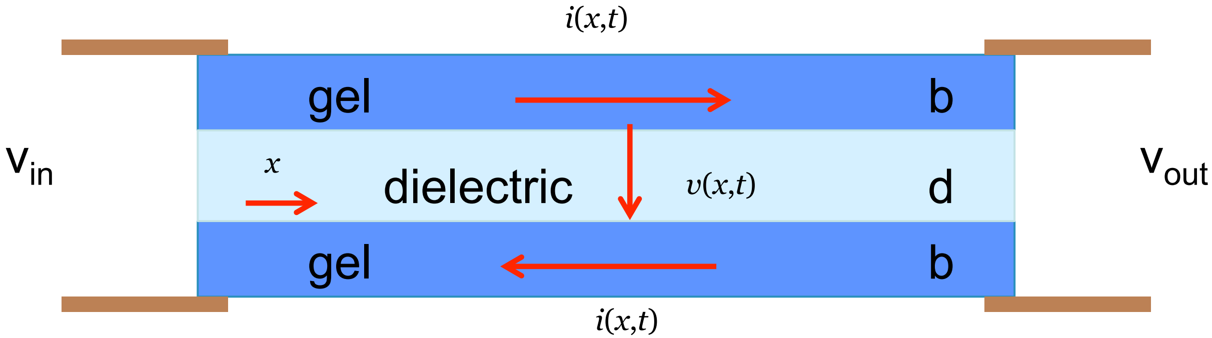
Yang, Chen, Lu, Yang, Zhou, Chen, Suo. Extreme Mechanics Letters 3, 59 (2015)

Ionic cable: artificial axon

Video
https://www.youtube.com/watch?v=2AXQ3p64CEY&feature=youtu.be

Yang, Chen, Lu, Yang, Zhou, Chen, Suo. Extreme Mechanics Letters 3, 59 (2015)

Signal diffuses fast



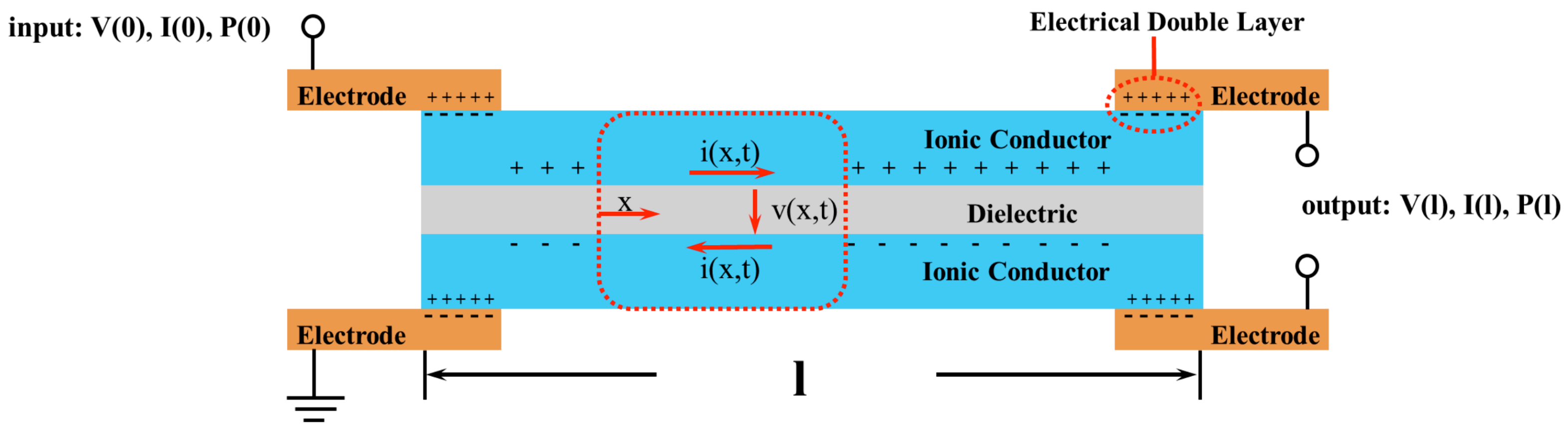
$$\frac{\partial v}{\partial t} = D\frac{\partial^2 v}{\partial x^2}$$

$$D \approx \frac{bd}{\varepsilon\rho} \approx \frac{\left(10^{-3}\mathrm{m}\right)\left(10^{-3}\mathrm{m}\right)}{\left(10^{-11}\mathrm{F/m}\right)\left(10^{-2}\Omega\mathrm{m}\right)} = 10^{7}\mathrm{m}^2/\mathrm{s}$$

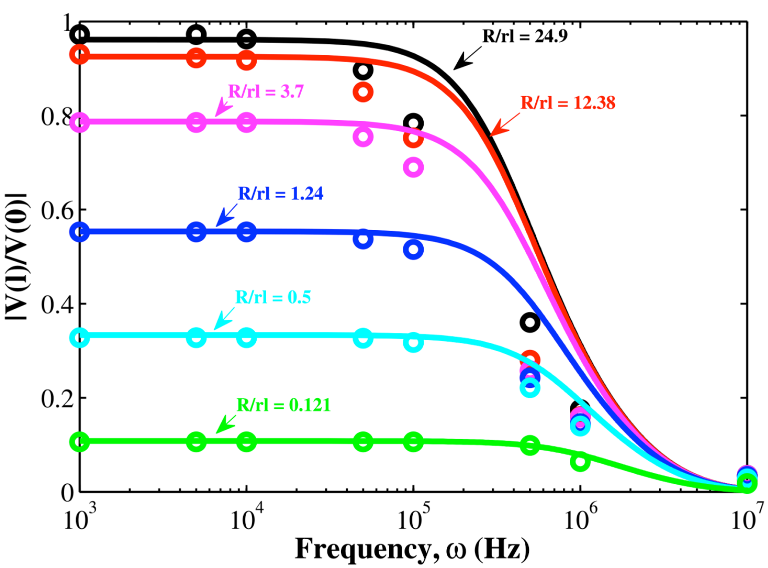
Ion diffuses slowly $D_{ion} \approx 10^{-9}\mathrm{m}^2/\mathrm{s}$

Yang, Chen, Lu, Yang, Zhou, Chen, Suo. Extreme Mechanics Letters 3, 59 (2015)

Ionic cable



$$\omega \propto \frac{1}{\rho\varepsilon}\frac{bd}{L^2}$$



Yang, Chen, Lu, Yang, Zhou, Chen, Suo. Extreme Mechanics Letters 3, 59 (2015)

TOUGH WATER

Can we use water in new ways?

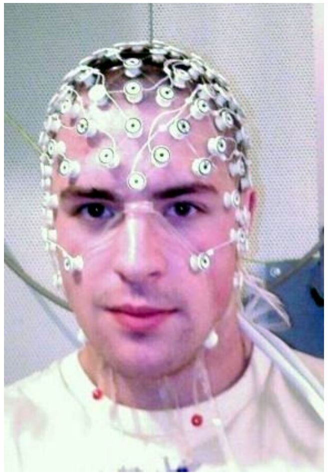
- Fire-retarding blanket (phase-transforming material)
- Transparent, desktop oilfields (soft material)
- Artificial axons (stretchable conductor)

Why soft materials, again?

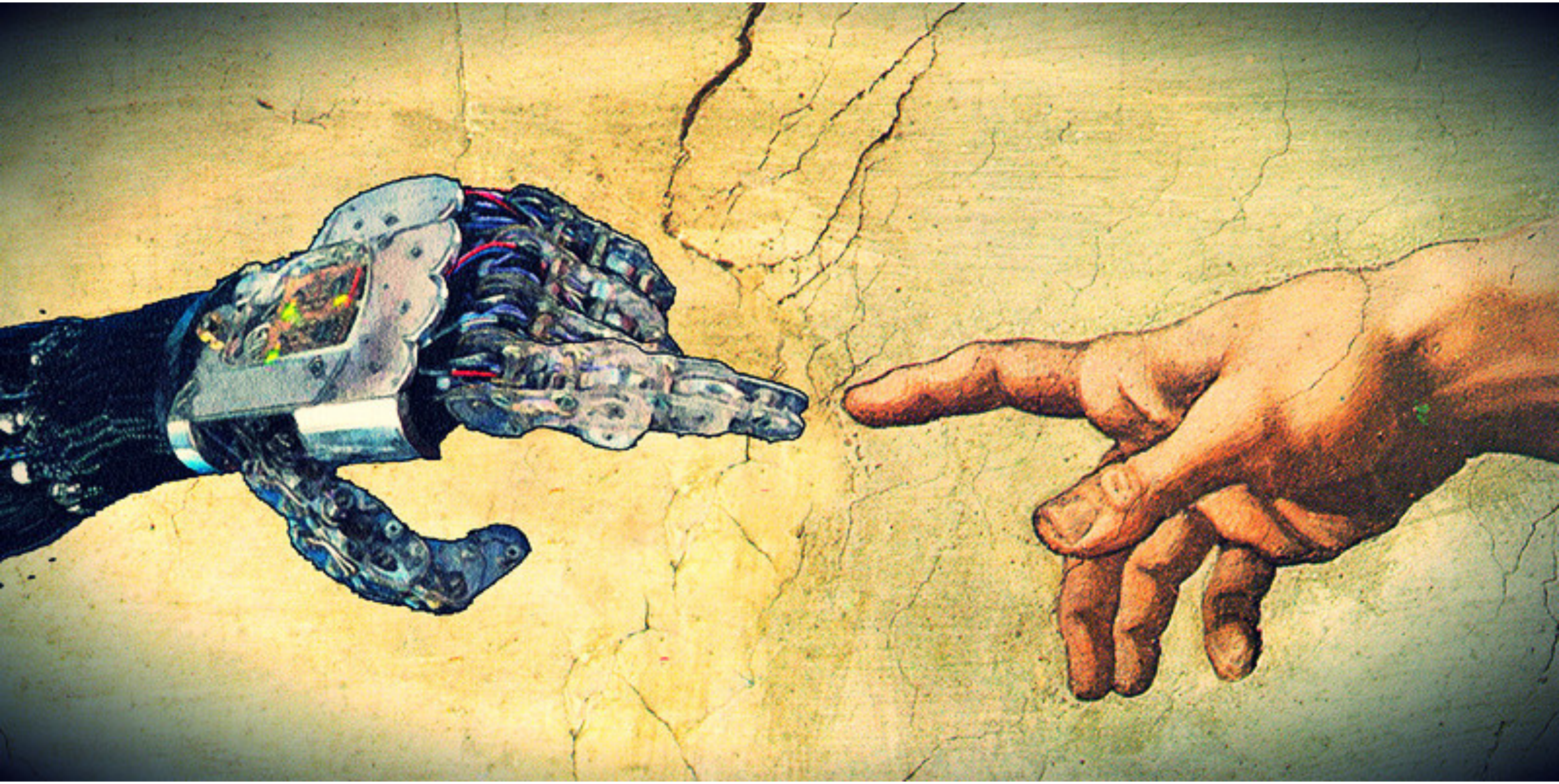
Create a new context for mechanics.

machine meets life

The Internet of Things
Wearable electronics
Biometric sensors
Mobile health
Neural recording
Neural stimulation
Computer-brain interface
Stretchable electronics
Implantable electronics
Injectable electronics
Soft robots
Soft machines



machine	**life**
hard	soft
dry	wet
electronic	ionic



http://elitedaily.com/news/technology/the-10-things-technology-will-allow-you-to-do-in-the-next-50-years/