Corso “Materiali intelligenti e biomimetici”

Electroactive Polymers

18 – 05 – 18

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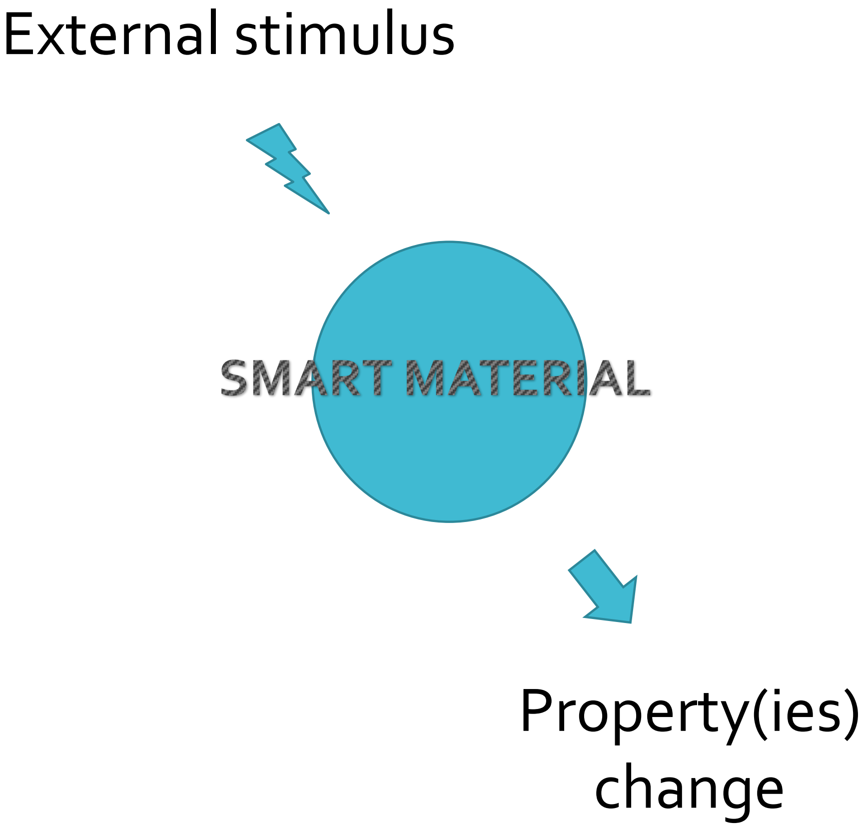
OUTLINE

- Electroactive Polymers
- General applications of EAP's
- Ionic vs Electronic EAP's
- Ionic EPS's
- Electronic EAP's
  - DEA's
    - Requirements
    - Examples
    - Case of study: a bioreactor for mechanical stimulation of cells

Braille display from the University of Tokyo

Electroactive polymers

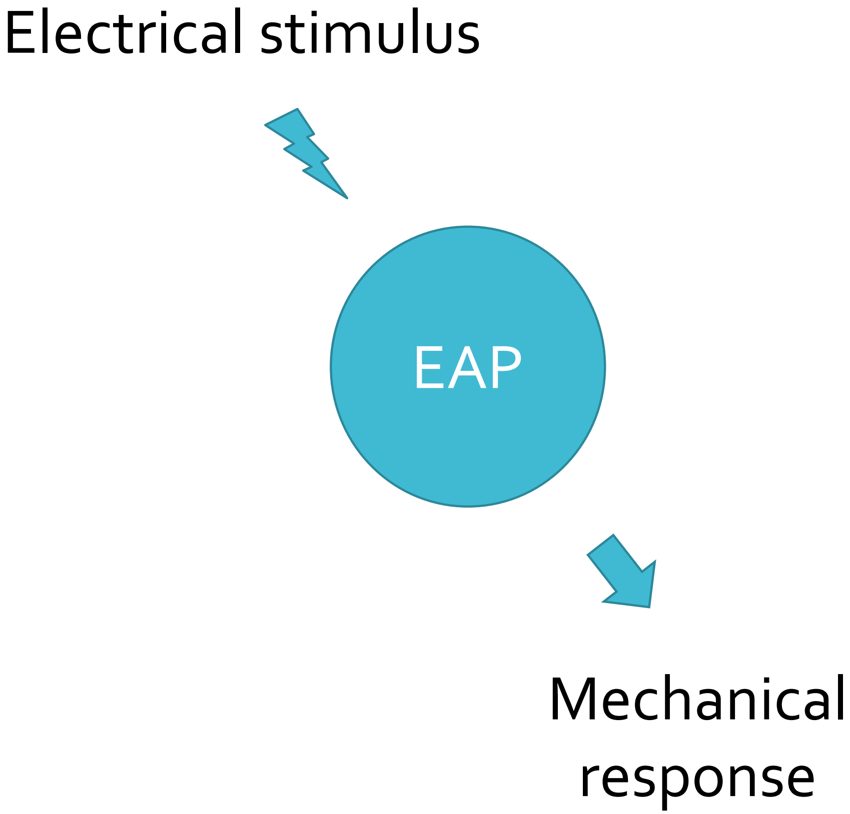


External stimulus

SMART MATERIAL

Property(ies) change

Electroactive polymers

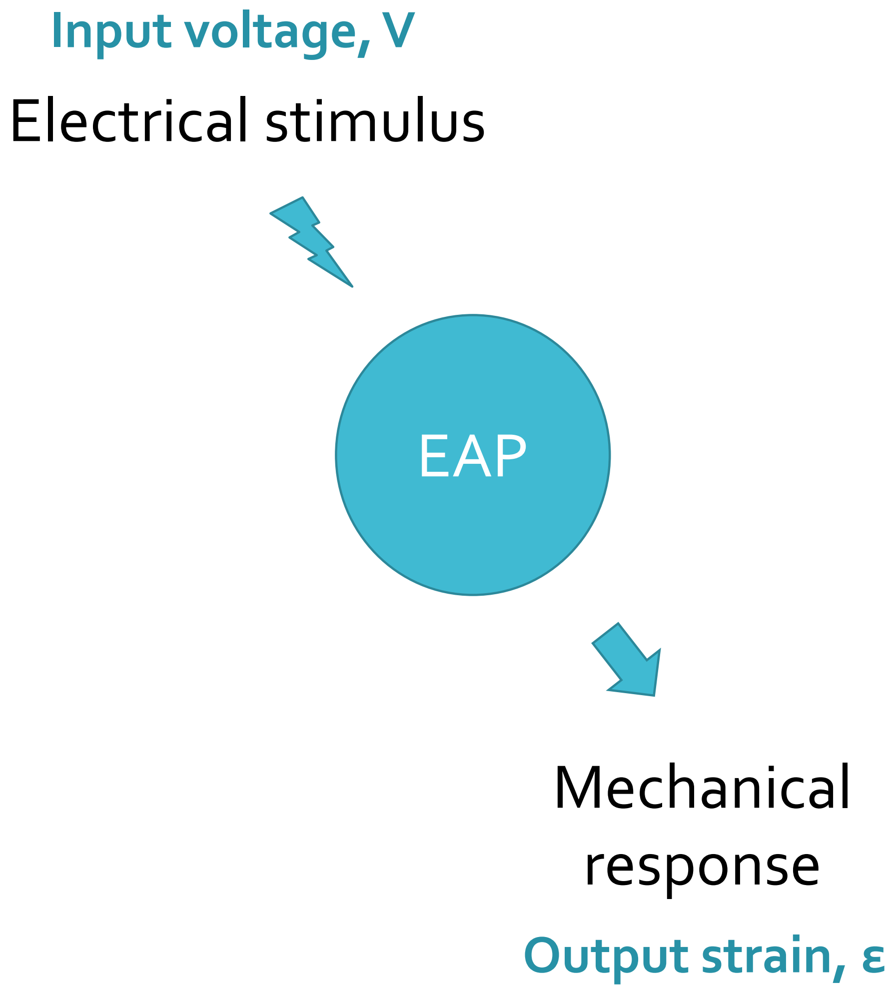


Electrical stimulus

EAP

Mechanical response

Electroactive polymers



Input voltage, V

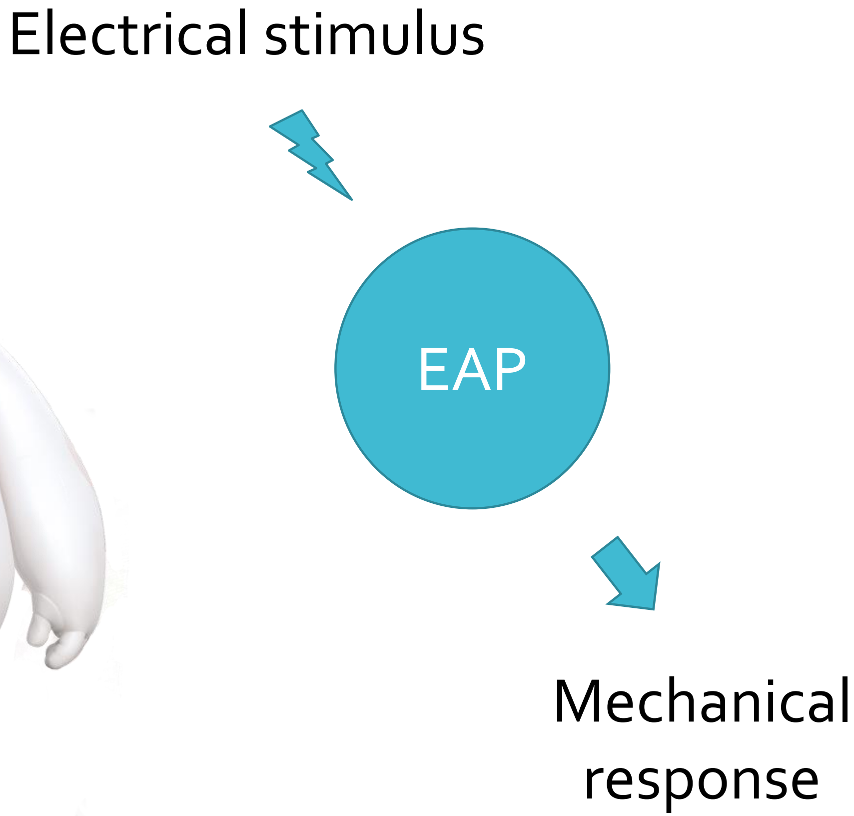
Electrical stimulus

EAP

Mechanical response

Output strain, ε

Why use them?

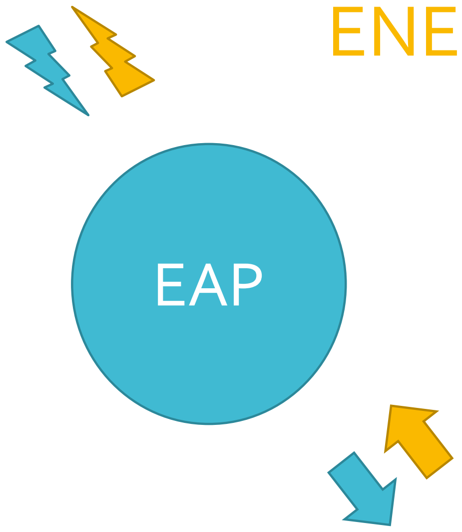

Electrical stimulus

EAP

Mechanical
response


SOFT
ACTUATORS

Why use them?



Electrical stimulus

EAP

Mechanical response

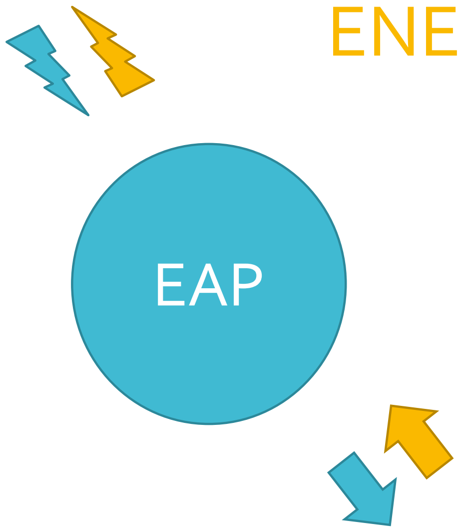
SENSORS AND ENERGY HARVERSTERS

SOFT ACTUATORS

Why use them?

- efficient energy output
- high strains
- high mechanical compliance
- shock resistance
- low mass density
- no acoustic noise
- ease of processing
- high scalability
- low cost

Electrical stimulus



Mechanical response

SENSORS AND ENERGY HARVESTERS

SOFT ACTUATORS → ARTIFICIAL MUSCLES

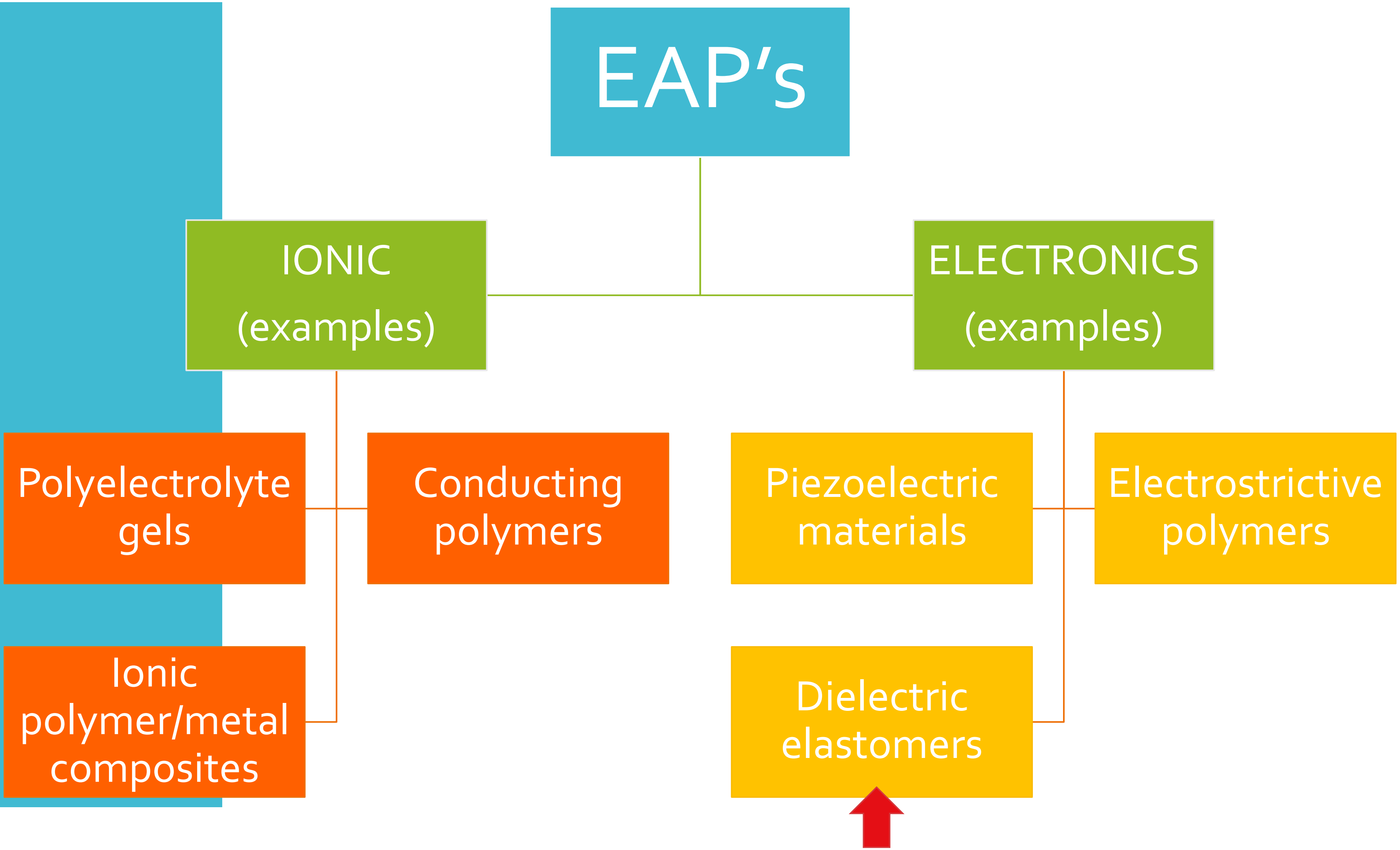
GENERAL APPLICATIONS 1

- compliant and light weight drive mechanisms
- intrinsically safe robots, anthropomorphic robots and humanoids
- **locomotion systems (https://www.youtube.com/watch?v=7Qxvyw5tUko)**
- **bioinspired and biomimetic systems** (https://www.youtube.com/watch?v=Y4Q16LBXC9c)
- **robotic hands/arms/legs/wings/fins**
- **grippers and manipulators (https://www.youtube.com/watch?v=DzX7BHYTTCE)**
- **haptic devices and tactile displays (https://www.youtube.com/watch?v=dWsVDKNOyY4)**

GENERAL APPLICATIONS 2

- variable stiffness devices and linkages and active vibration dampers
- minimally invasive interventional/diagnostic medical tools
- controlled drug delivery devices
- fluidic valves and pumps
- **tuneable optical and acoustic systems (https://www.youtube.com/watch?v=5K5KSDL1gXE)**
- systems to convert mechanical energy into electrical energy for mechanosensing and motion energy harvesting.

Ionic vs Electronic



EAP's

IONIC

(examples)

- Polyelectrolyte gels
- Conducting polymers
- Ionic polymer/metal composites

ELECTRONICS

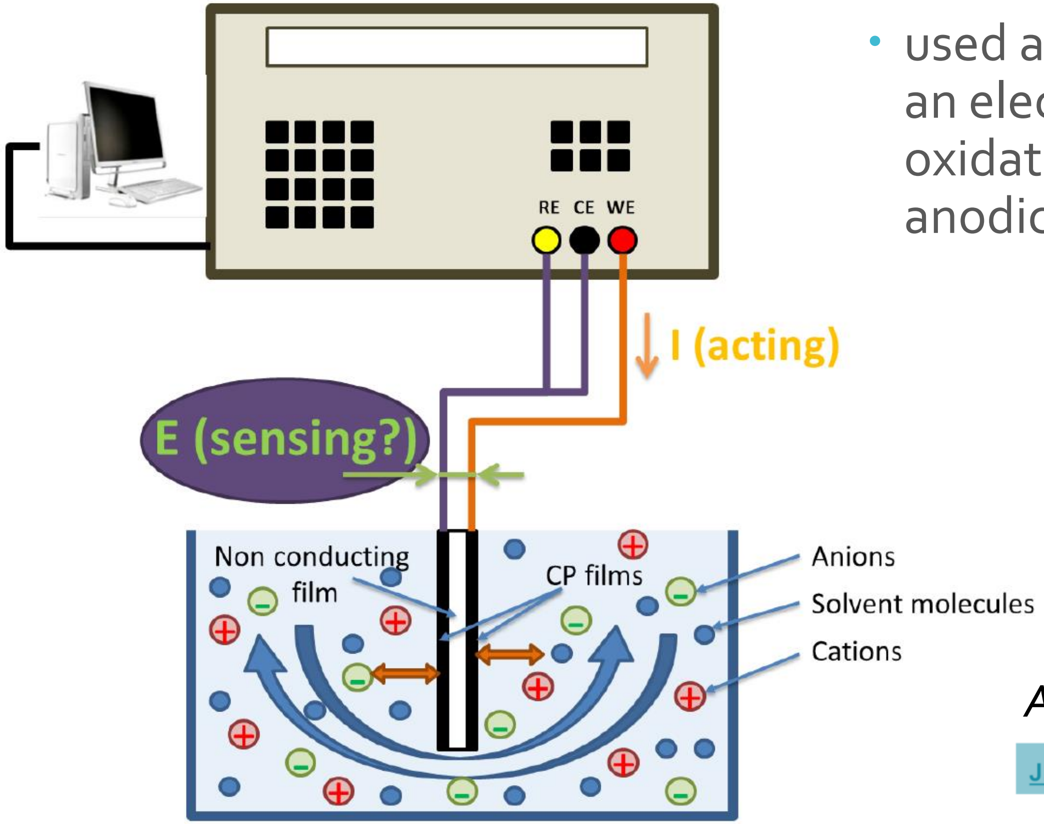
(examples)

- Piezoelectric materials
- Electrostrictive polymers
- Dielectric elastomers

IONIC EAP's

Activation occurs due to the migration of ions or charged molecules

$$\left(Pol^*\right)_s + n\left(A^-\right)_{sol} + m\left(S\right) \underset{Reduction}{\overset{Oxidation}{\rightleftarrows}} \left[\left(Pol\right)^{n+}\left(A^-\right)_n\left(S\right)_m\right]_{gel} + ne^-$$

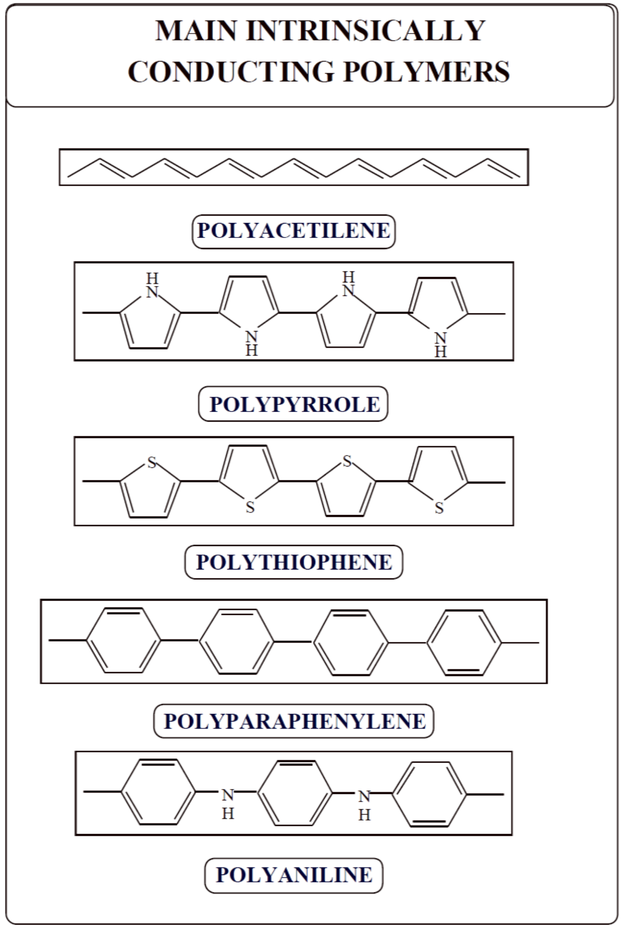


- used as working electrode inside an electrolyte follow reversible oxidation/reduction by flow of anodic/cathodic currents

Adapted from Toribio et al.

J. Electroanal. Chem., 341, 369-375, (1992)

IONIC EAP’s



Example of a family of Ionic EAPs

- ✓ require low voltages
- ✓ produce large bending displacements Requires low voltage
- ✗ apart from CPs and NTs, ionic EAPs do not hold strain under DC voltage
- ✗ slow response (fraction of a second)
- ✗ bending EAPs induce a relatively low actuation force
- ✗ low electromechanical coupling efficiency

IONIC EAP’s

https://www.youtube.com/watch?v=QhoX_TiH1C4 Classic example

https://www.youtube.com/watch?v=TYrh3MgB-8Q Insect-like

https://www.youtube.com/watch?v=vtXXl7sEvA8 Textiles

ELECTRONIC EAPs

Activation occurs by applied electric fields and Coulomb forces

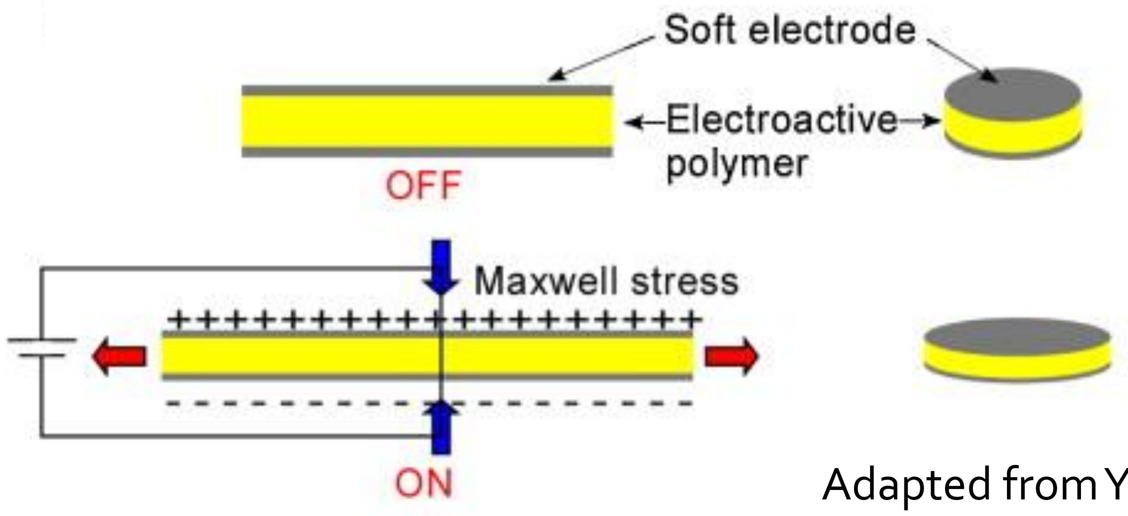
✓ can operate in room condition for a long time

✓ rapid response (msec level)

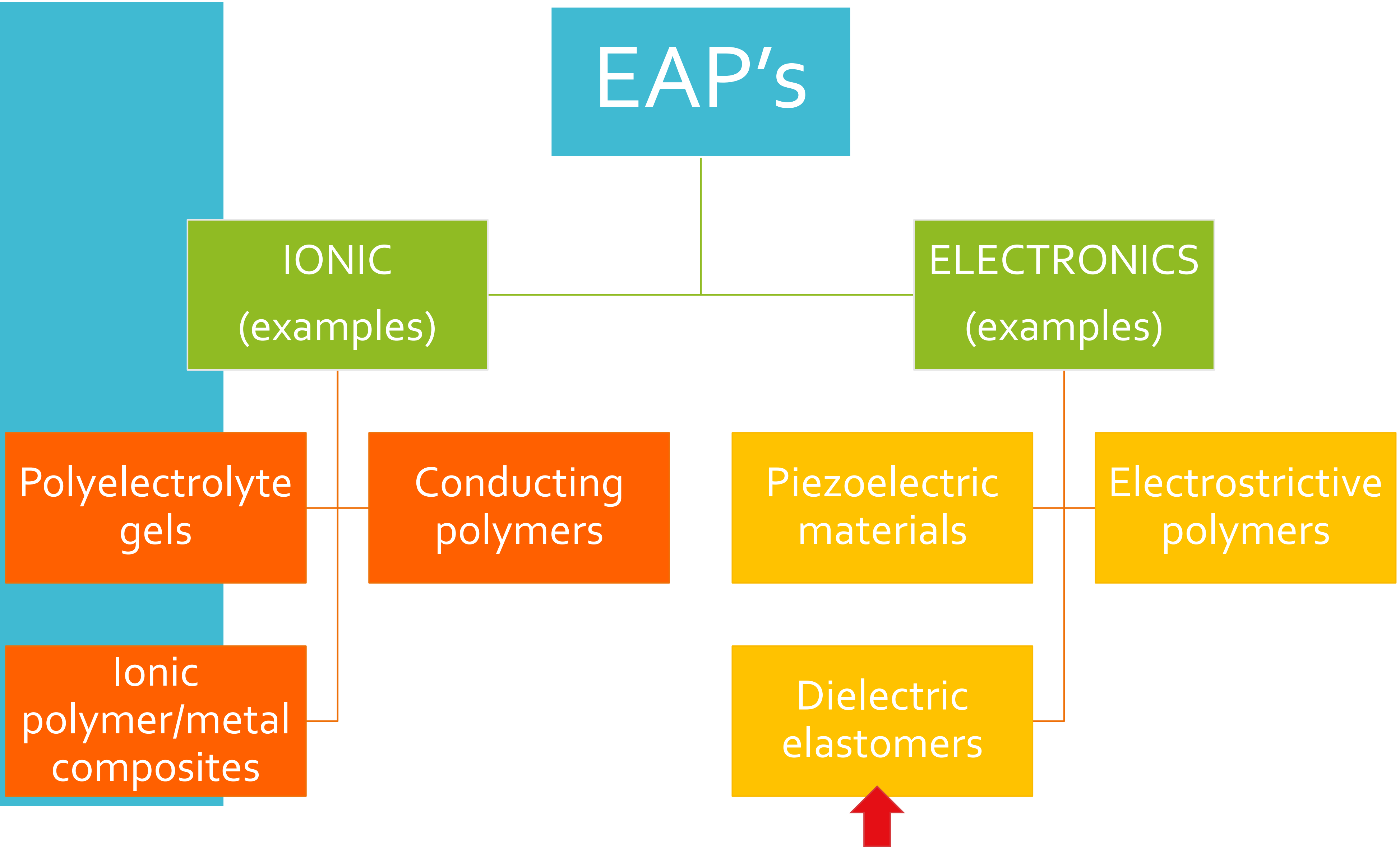
✓ can hold strain under DC activation Induces relatively large actuation force

× require High Voltage on the order of 150 MV/m Compromise between strain and stress

× glass transition temperature is inadequate for low-temperature actuation task



Adapted from Yo et al, 2013
https://doi.org/10.1016/j.snb.2013.04.025



EAP’s

IONIC

(examples)

Polyelectrolyte gels

Conducting polymers

Ionic polymer/metal composites

ELECTRONICS

(examples)

Piezoelectric materials

Electrostrictive polymers

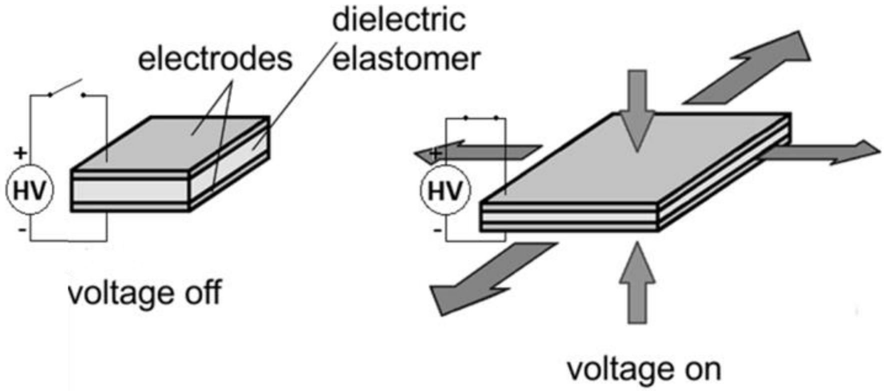
Dielectric elastomers

Dielectric Elastomers Actuators (DEA)

When a voltage V is applied, the electric charging results in an electrostatic compression of the elastomer due mainly to Columbian forces. The effective electromechanical pressure p, also known as Maxwell stress, that compresses the elastomer film is given by the following equation:

$$\boxed{p = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r (\frac{V}{d})^2}$$

where εo is the permittivity of vacuum, εr is the dielectric constant of the elastomer, E is the applied electric field and d is the initial thickness of the elastomer film.



Structure and principle of operation of the basic configuration of a DEA

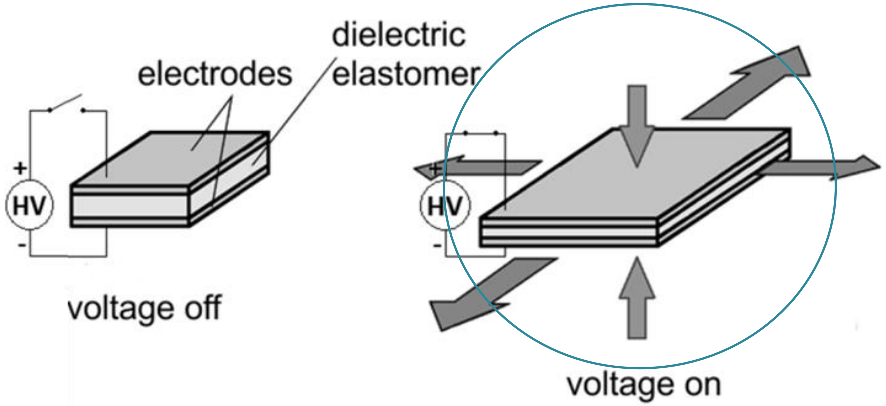
Dielectric Elastomers Actuators (DEA)

$$p = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r \left(\frac{V}{d}\right)^2$$

DEA is an **INCOMPRESSIBLE** material

⬇

Thickness is reduced so the area expands



Structure and principle of operation of the basic configuration of a DEA

Requirements for a DEA

DE film

Electrodes

HV source

$$p = \varepsilon_0 \varepsilon_r (\frac{V}{d})^2$$

Requirements for a DEA

DE film

- low stiffness
- high dielectric constant
- high electrical breakdown strength

Electrodes

HV source

NOTE: Pre-stretching the DE film reduces electromechanical instabilities and increases performance in terms of strains achieved

Most widely used DE:

- Polyurethanes
- Acrylics
- Silicones

$$p = \varepsilon_0 \varepsilon_r \left(\frac{V}{d}\right)^2$$

DE film

Requirements for a DEA

Silicone elastomers have a flexible silicon-oxygen backbone that contributes to low elastic modulus. When compared with acrylics, silicones have much **lower viscoelasticity**, showing a **faster electromechanical response** with **lower mechanical losses**, and show a more stable mechanical behavior over a wide temperature range. On the other hand, they exhibit relatively low dielectric constant and **modest electromechanical actuation strain**, thus their use is typically restricted to applications where displacement lower than 10% are required.

DE film

Requirements for a DEA

Acrylic elastomers are made of aliphatic acrylate mixtures, which have vinyl groups as the main structure with a carboxylic acid terminal group, but there has not been a detailed report on their composition. VHB films from 3M™ are widely used acrylate elastomers, since they **present low elastic modulus, low price** and **good compliance**. Such properties give VHB high-level actuating capabilities: thickness strains up to 60-70% at 400 V/µm, area strains up to 200% at 200 V/µm and corresponding stresses of some MPa have been reported. They have although a predominant **viscoelastic behavior**.

Requirements for a DEA

DE film

- low stiffness
- high dielectric constant
- high electrical breakdown strength

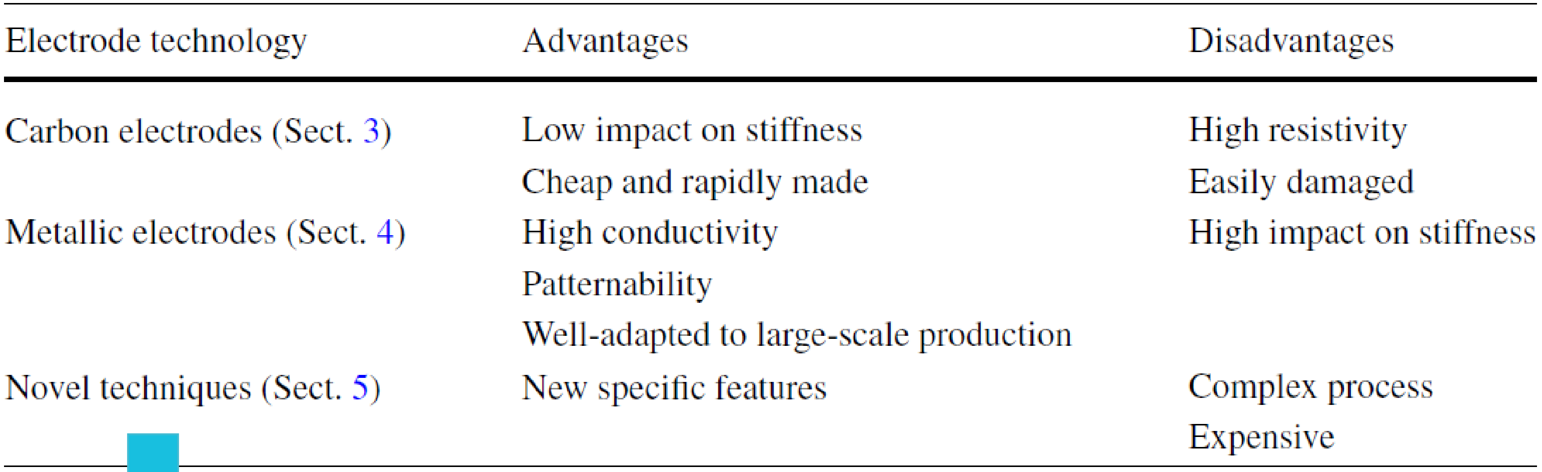
Electrodes

- highly compliant
- highly conductive
- negligible contribution to stiffness

HV source

Requirements for a DEA

Electrodes



Electrode technology	Advantages	Disadvantages
Carbon electrodes (Sect. 3)	Low impact on stiffness Cheap and rapidly made	High resistivity Easily damaged
Metallic electrodes (Sect. 4)	High conductivity Patternability Well-adapted to large-scale production	High impact on stiffness
Novel techniques (Sect. 5)	New specific features	Complex process Expensive

Photopatternable electrodes

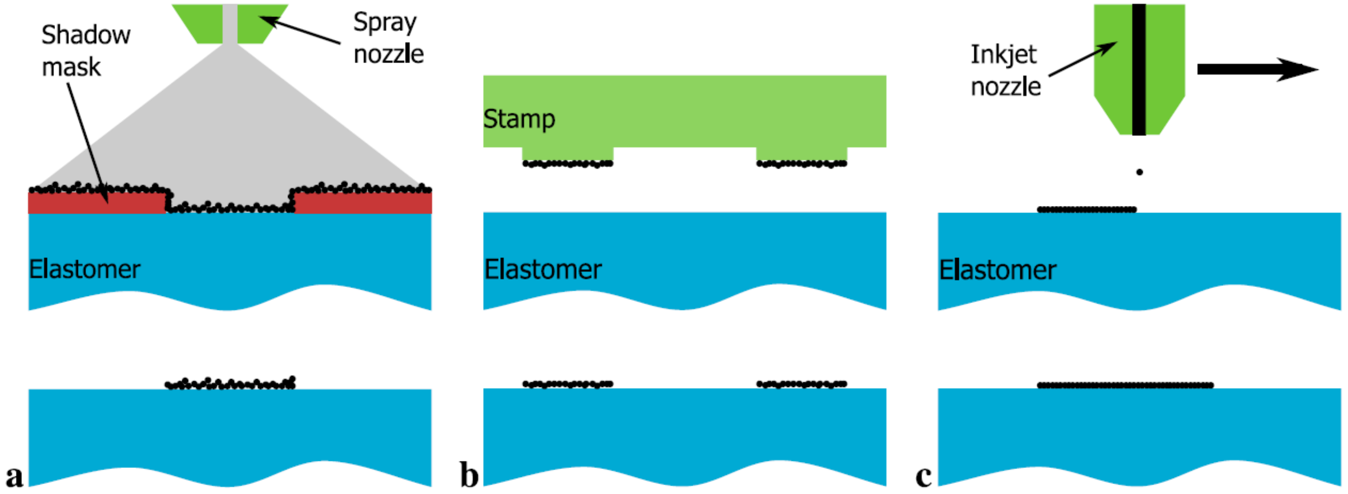
Transparent electrodes

Adapted from Rosset et al 2012
DOI 10.1007/s00339-012-7402-8

Electrodes

Requirements for a DEA

Electrode technology	Advantages	Disadvantages
Carbon electrodes (Sect. 3)	Low impact on stiffness Cheap and rapidly made	High resistivity Easily damaged



Different ways to pattern carbon electrodes. (a) Using a shadow mask to selectively protect part of the elastomeric membrane. (**b**) Using a patterned elastomeric stamp to pick-up the electrode material and apply it on the elastomeric membrane. (**c**) Using standard printing techniques, such as drop-on-demand inkjet printing

Adapted from Rosset et al 2012
DOI 10.1007/s00339-012-7402-8

Requirements for a DEA

- DE film
  - low stiffness
  - high dielectric constant
  - high electrical breakdown strength
- Electrodes
  - highly compliant
  - highly conductive
  - negligible contribution to stiffness
- HV source

Requirements for a DEA

The challenge is to reduce their main drawback: the need for high voltages. How?

$$\boxed{p = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r \left(\frac{\overset{\downarrow}{V}}{d \leftarrow}\right)^2}$$

- Using high permittivity elastomers
  - Composites
  - Blends
  - New synthetic polymers

- Reducing the film thickness

Examples of DEAs

https://www.youtube.com/watch?v=YDsG2wpwUow Blimp

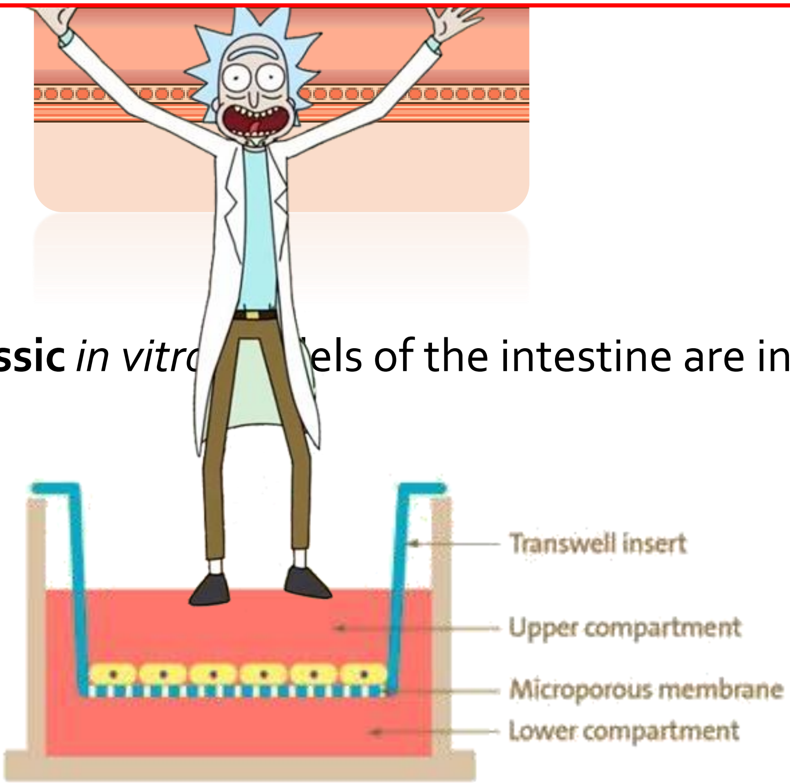
- https://www.youtube.com/watch?v=Pi2T7rE0NkE Caterpilar
- https://www.youtube.com/watch?v=-JDFEmqXRDU Haptics

Case of study: a bioreactor for the mechanical stimulation of cells

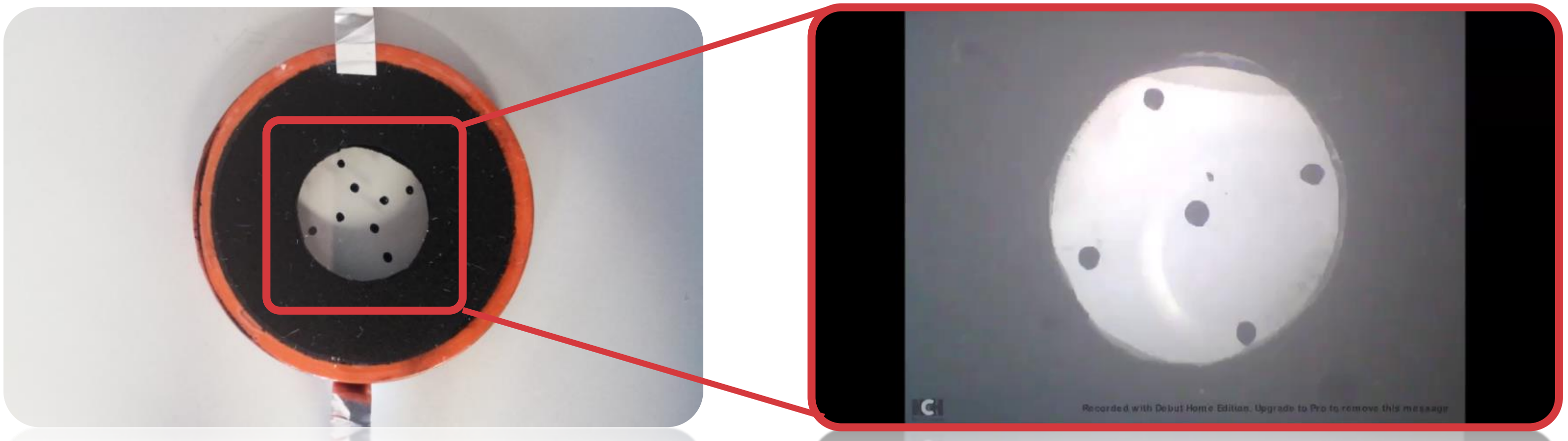
In the **intestine**, the **3D** architecture, the **flow** of nutrients and the **motility**, influence cell behaviour and also the absorption of substances.

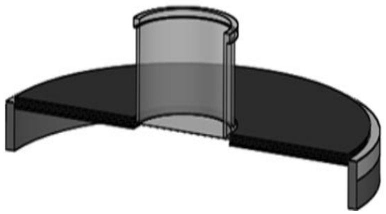
Physiologically relevant *in vitro* models need mechanical cues!

However, the **classic** *in vitr* els of the intestine are in **2D** and **static**



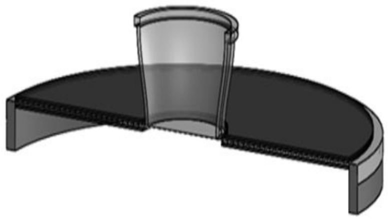
Case of study: a bioreactor for the mechanical stimulation of cells





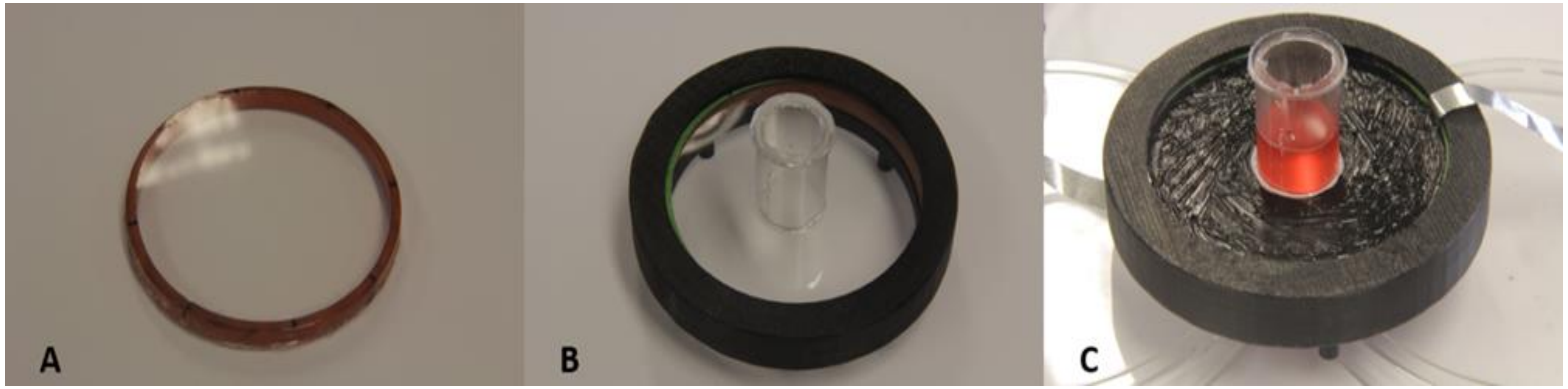
Culture of Caco-2 cells on a EAP

Voltage ON

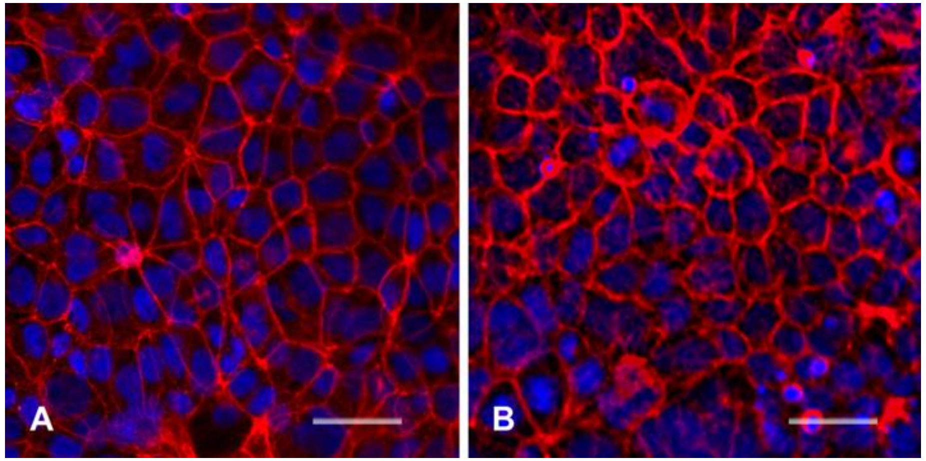


The actuation of the device provides mechanical deformation of the cells

Case of study: a bioreactor for the mechanical stimulation of cells



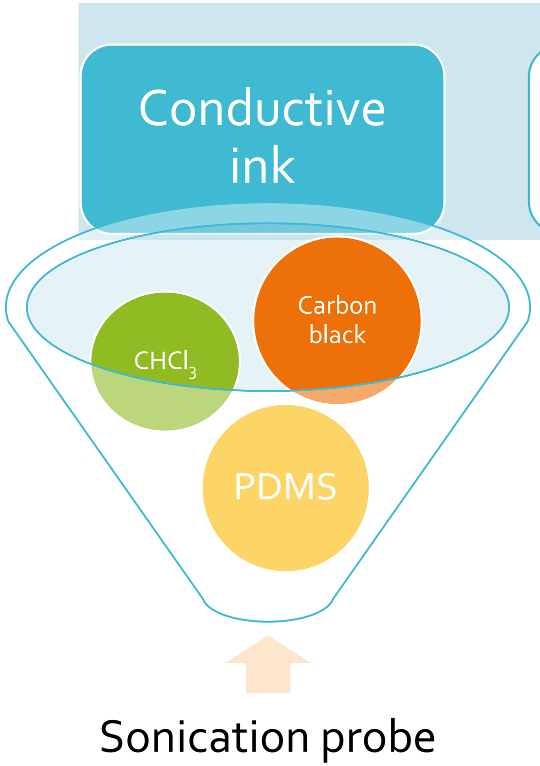
The bioreactor at various stages of fabrication: A) the membrane, B) the flexible central well, C) the complete bioreactor mounted within its case, containing the cultured cells and1 mL of medium within the well and equipped with the carbon grease electrodes.

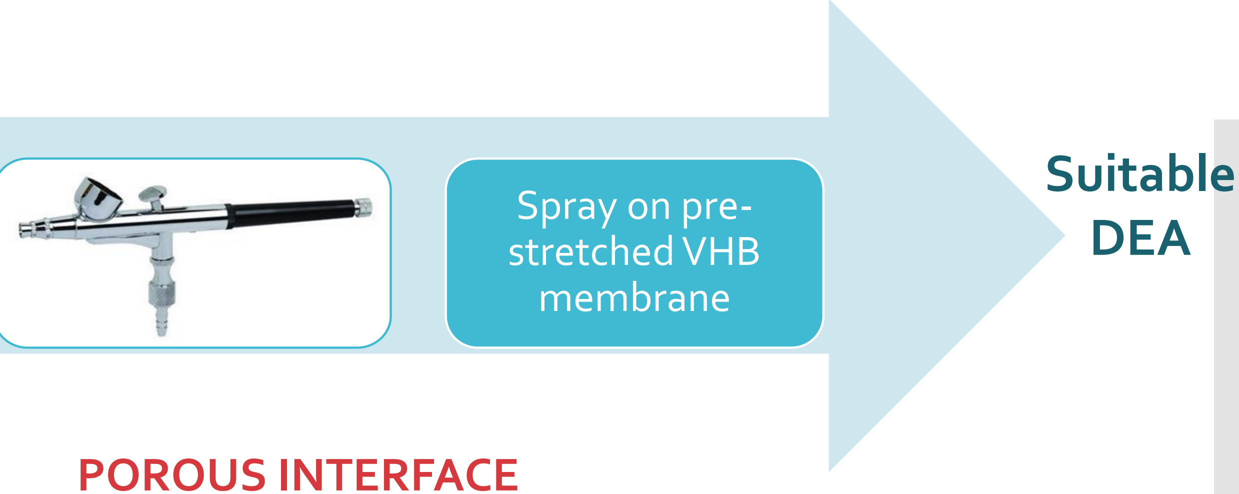


Fluorescence images of Caco-2 cells stained with DAPI (blue nuclear stain) and phalloidin (red, actin fibers) after 21 days of culture on the DEA membrane: A) not actuated sample; B) actuated sample after 4 hours of cyclic actuation at 0.15 Hz in an incubator at 37°C and 95% humidity. Scale bar=50 μm.

Cei et al 2016
https://doi.org/10.1088/1748-3190/12/1/016001

Case of study: a bioreactor for the mechanical stimulation of cells





NEW ELECTRODES

Conductive ink

Spray on pre-stretched VHB membrane

Suitable DEA

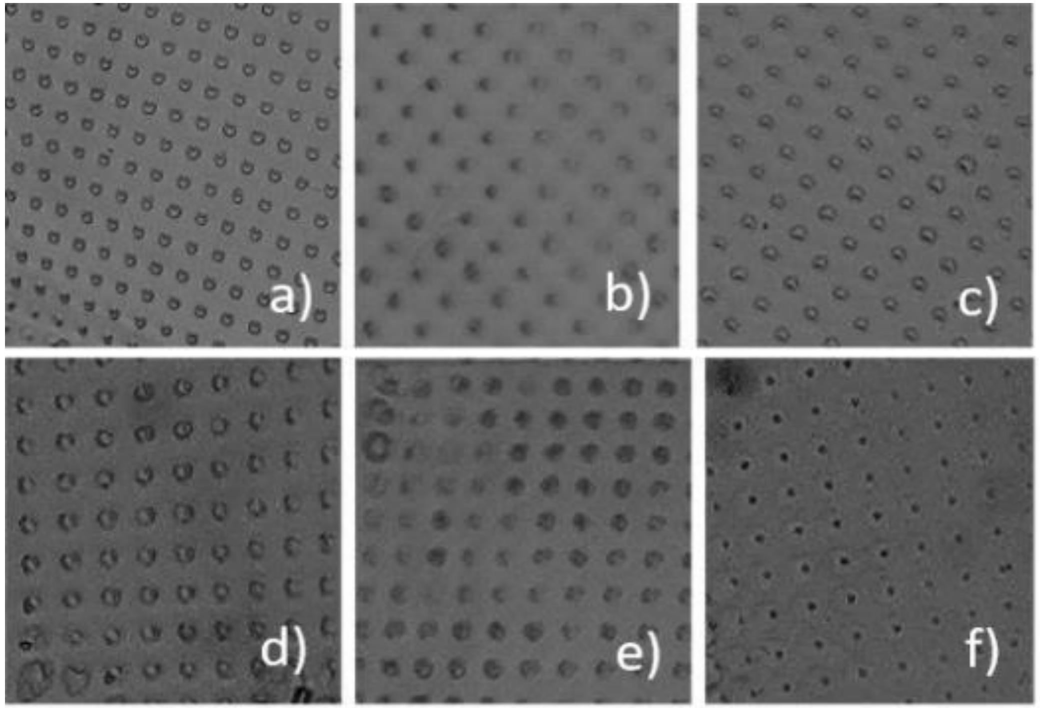
$CHCl_3$

Carbon black

PDMS

Sonication probe

POROUS INTERFACE

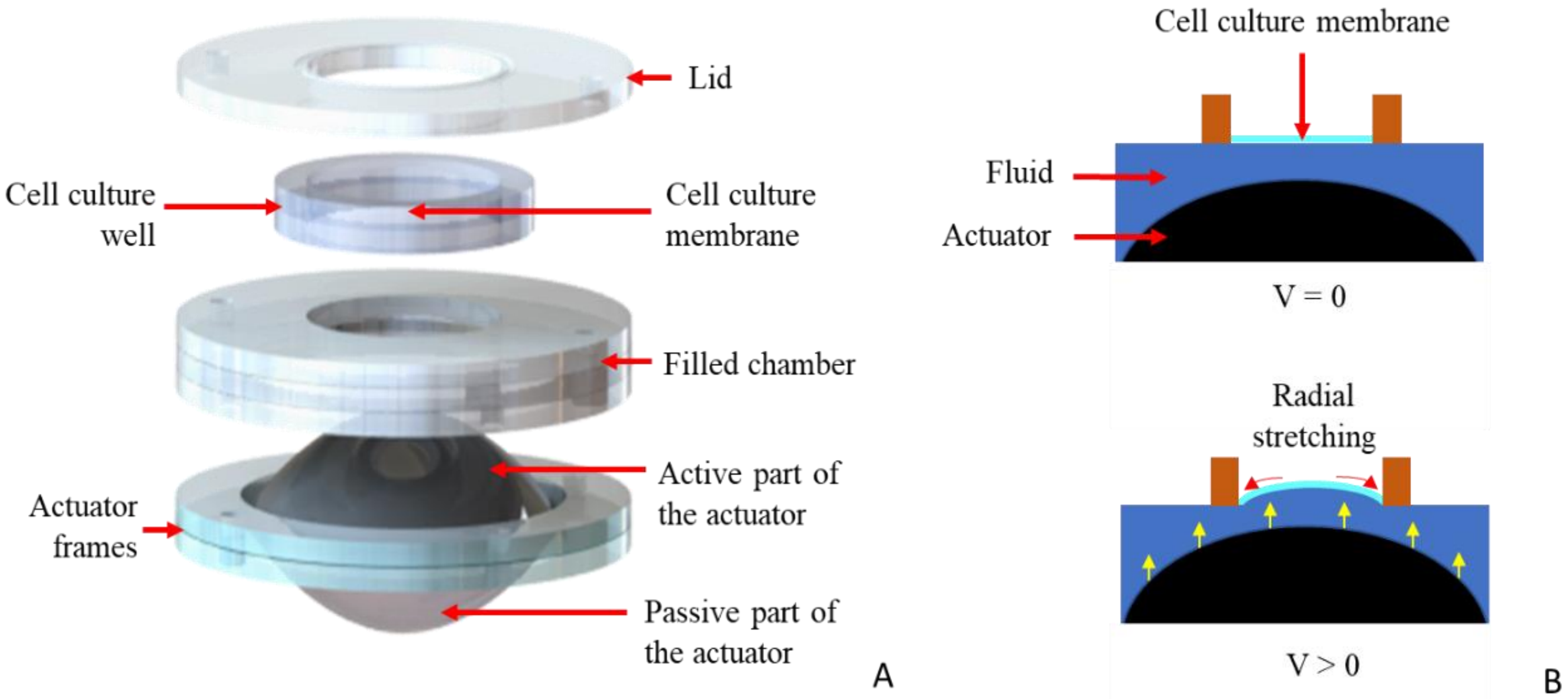


Imaging from the optical microscope (magnification 10x) tested with different temperatures (a) RT; (b) 50° C; (c) frozen; different testing time (d) 15min; e) 180 min; f) overnight).

From "A bioreactor using a porous EAP actuator as a physiological-like interface for cell culture studies", EuroEAP 2017
Joana Costa, Marta Feula, Daniele Cei, Arti Ahluwalia

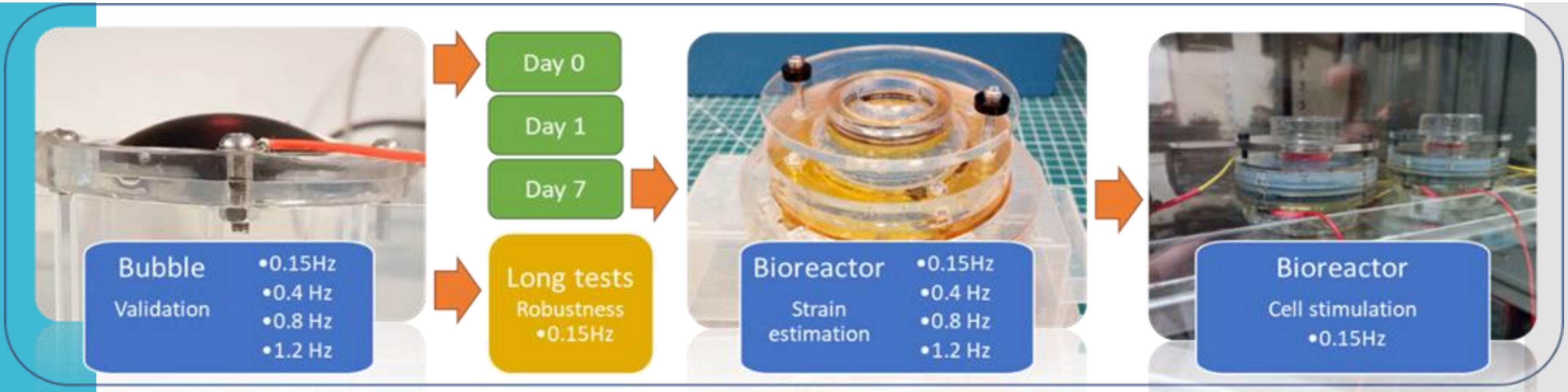
Case of study: a bioreactor for the mechanical stimulation of cells

Most recent prototype based on a Bubble DE Actuator



Representation of the bubble actuator bioreactor. A. Elements that constitute the bioreactor. B. When voltage is applied, the deformation of the active part of the bubble will displace the fluid inside the chamber against the flexible cell culture membrane that will buckle and radially stretch the cells adhered on it.

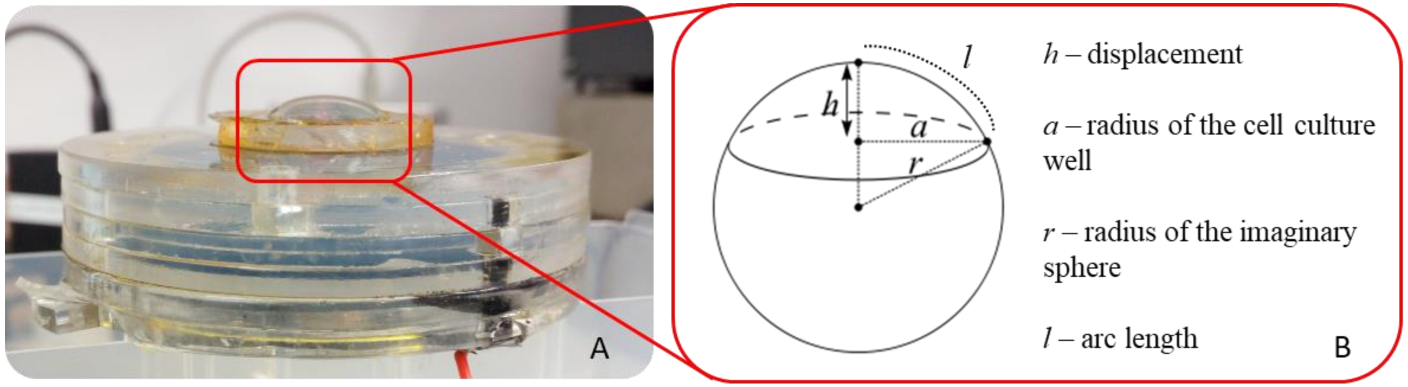
Case of study: a bioreactor for the mechanical stimulation of cells



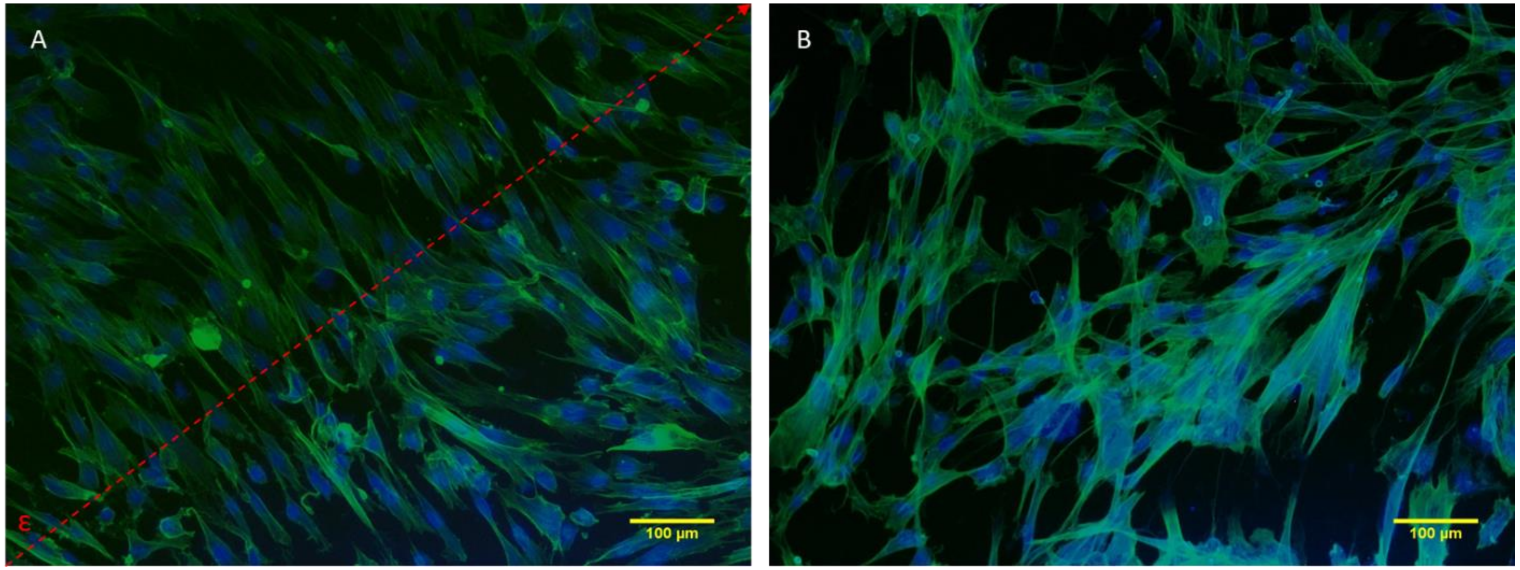
Scheme of the methodology used to validate the prototype

Bubble actuator being stimulated with 4.5 kV at different frequencies

Case of study: a bioreactor for the mechanical stimulation of cells



Approximation of the membrane buckling to a spherical cap. A. Chamber filled with Transil 40, when bubble is actuated. B. Geometric parameters of a spherical cap. The value h is determined by the measurement of the displacement upon actuation; a is determined by the cell culture unit in use; r and l can be calculated knowing the previous values.



Fluorescence microscopy imaging of HFFF2 fibroblasts cultured in the stretching bioreactor for 2 days and stained with DAPI (blue nuclear stain) and phalloidin (green, actin fibers); magnification of 10x. A. Cells subjected to an estimated radial strain of ~5% for 8h . B. Control cells, not subjected to mechanical stimulation.

THE END

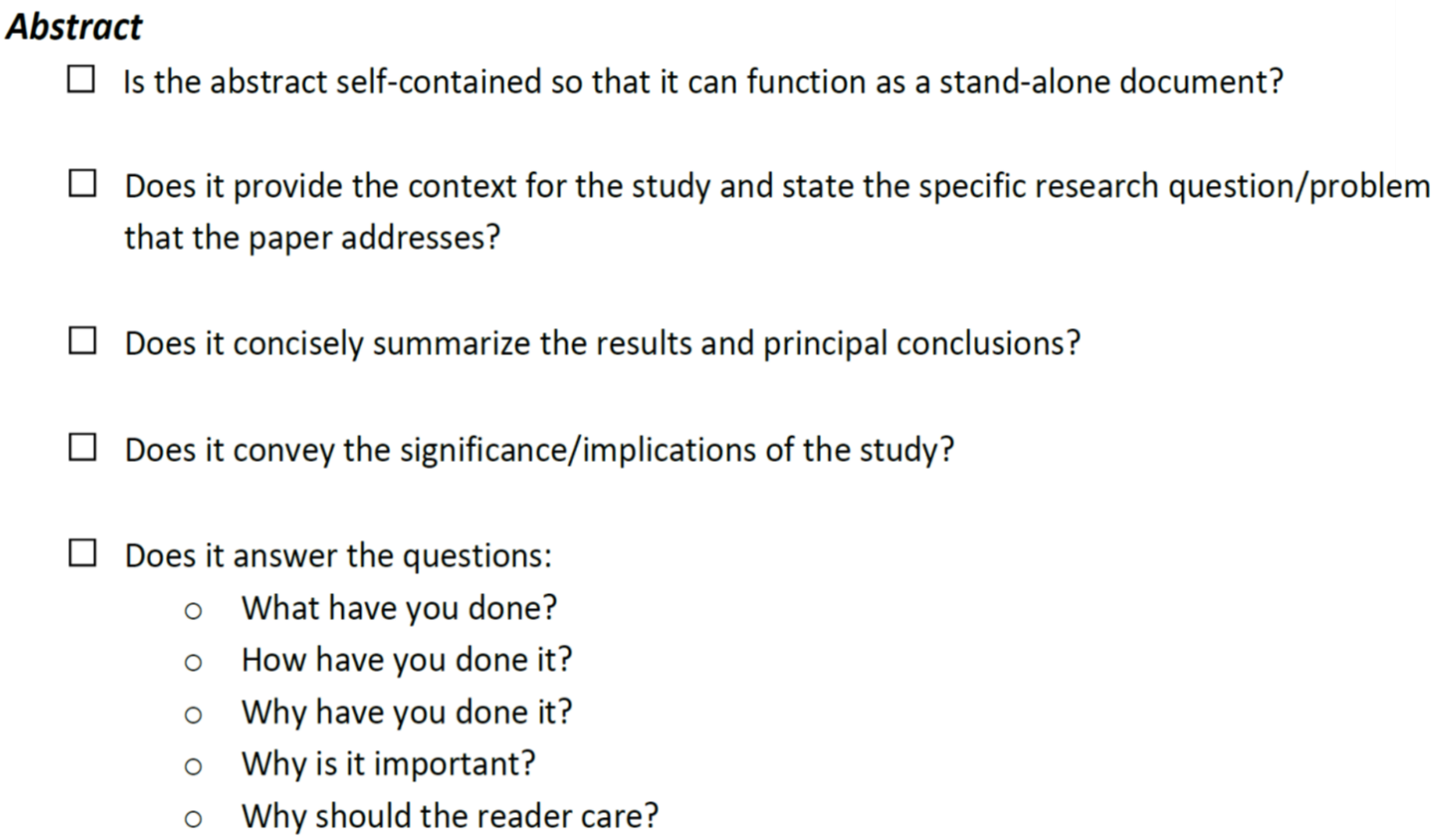
SOFT SKILLS GYM

How to write a scientific abstract

Writing an abstract

- https://www.youtube.com/watch?v=P5108sbWlwk

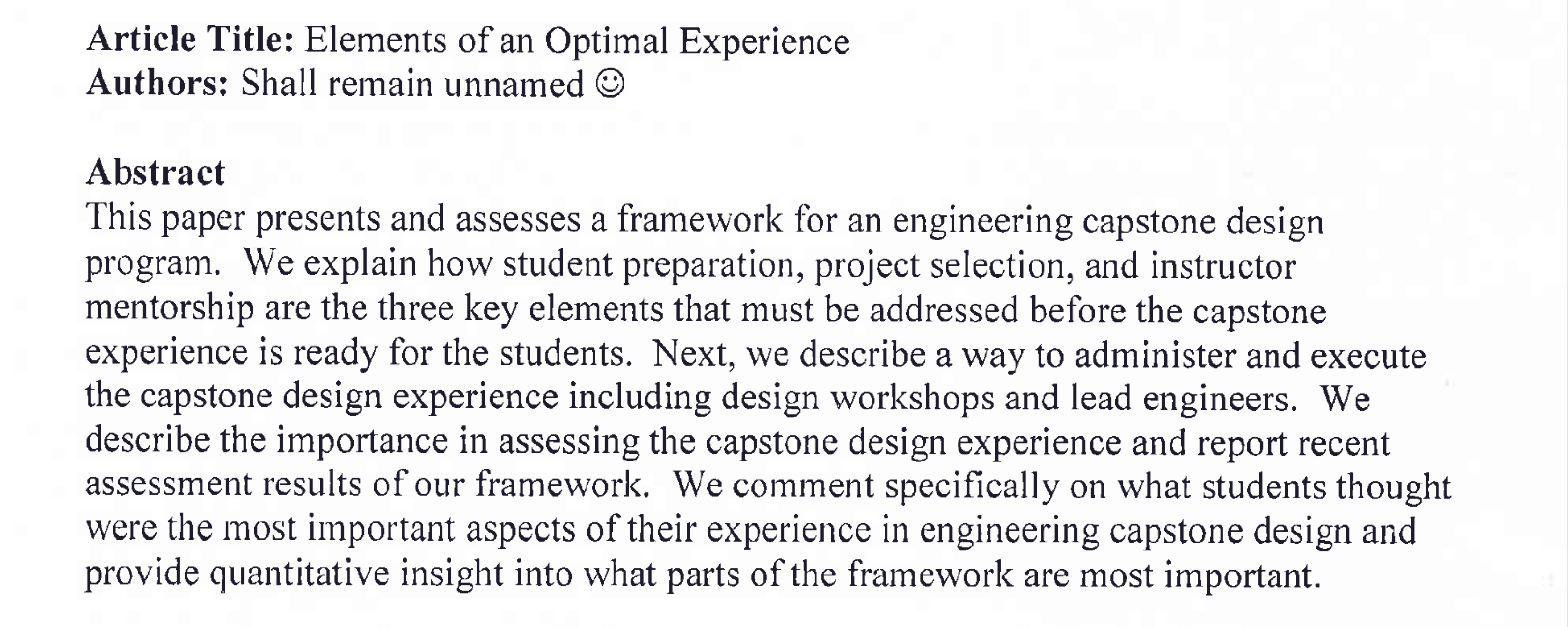
Abstract checklist



Abstract

- ☐ Is the abstract self-contained so that it can function as a stand-alone document?
- ☐ Does it provide the context for the study and state the specific research question/problem that the paper addresses?
- ☐ Does it concisely summarize the results and principal conclusions?
- ☐ Does it convey the significance/implications of the study?
- ☐ Does it answer the questions:
  - ○ What have you done?
  - ○ How have you done it?
  - ○ Why have you done it?
  - ○ Why is it important?
  - ○ Why should the reader care?

An example… what's wrong?



Article Title: Elements of an Optimal Experience
Authors: Shall remain unnamed ☺

Abstract

This paper presents and assesses a framework for an engineering capstone design program. We explain how student preparation, project selection, and instructor mentorship are the three key elements that must be addressed before the capstone experience is ready for the students. Next, we describe a way to administer and execute the capstone design experience including design workshops and lead engineers. We describe the importance in assessing the capstone design experience and report recent assessment results of our framework. We comment specifically on what students thought were the most important aspects of their experience in engineering capstone design and provide quantitative insight into what parts of the framework are most important.

- This abstract begins well with a concise statement of the objectives of the paper, but then wanders from good technical writing style from there.
- The abstract is written in the first person (e.g. "We explain...", "We discuss...", “’We comment...", etc.),
- No results are presented. This abstract describes only the organization of the paper.