M. Sc. Bionics Engineering

Università di Pisa — Sant'Anna Scuola Universitaria Superiore Pisa — IMT Scuola Alti Studi Lucca

Advanced Materials for Bionics

Lecture 1: Introduction

Prof. Francesco Greco

AY 2024-25

L1 - 27.09.2024

Teacher: Francesco Greco

Education & Experiences

2004 **M. Sc.** Materials Science, University of Pisa (Italy)
2009 **Ph.D.** Chemical Sciences, University of Pisa (Italy)

2009 - 2013 **Postdoc Junior/Senior** CMBR IIT, Pontedera (Italy)
2013 - 2017 **Team Leader**, CMBR IIT, Pontedera (Italy)

2016 - 2017 **Associate Professor**, Waseda University, Tokyo (Japan)
2018,2020 – **Invited Guest Lecturer**, Waseda University, Tokyo (Japan)

2017 – **Assistant Professor**, Inst. Solid State Physics, TU Graz (Austria)

Sep 2021 – **Associate Professor**, Biorobotics Institute, SSSA, Pisa (Italy)

TEACHER: FRANCESCO GRECO

Current Positions

- **Associate Professor** - Biorobotics Institute SSSA, Pisa (Italy)
- **Ass. Prof.** –Inst. Solid State Physics TUGraz (Austria)
- **Head of LAMPSE** (Lab of Applied Materials for Printed and Soft Electronics) https://lampselab.com/

CONTACT: francesco.greco@santannapisa.it

Research Interests

Polymer, nanocomposite functional and stimuli-responsive materials with applications in **organic (bio)electronics**, **soft robotics** and **biomedicine**.

3 main areas:

1.SMART MATERIALS – SOFT ACTUATORS & SENSORS -

2.SOFT & TATTOO electronics

3.BIOINSPIRED SURFACES & BIOINTERFACES

LAMPSe Laboratory of Applied Materials for Printed and Soft electronics

ISTITUTO DI BIOROBOTICA
Sant'Anna Scuola Universitaria Superiore Pisa

Sant'Anna Scuola Universitaria Superiore Pisa

LAMPSe

Anna Chiara Bressi
PhD student

Yulia Steksova
PhD student

Alexander Dallinger
PhD student

Sofia Papa
PhD student

Sreenadh Thaikkattu
PhD student

Kirill Keller
Fellow

TU Graz
Graz University of Technology

Marina Galliani
Post-Doc

Laura Ferrari
Assistant Professor

BRIEF

Hilda Gómez Bernal
Technician

Aliria Poliziani
Technologist

LAMPSe @IF - TUGRAZ

Graz University of Technology

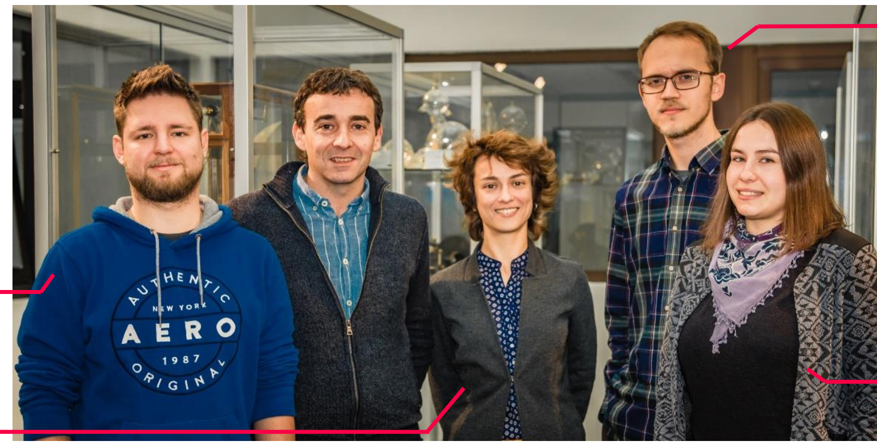
Institut für Festkörper Physik - Institute of Solid State Physics, TUGraz

Laboratory of **A**pplied **M**aterials for **P**rinted and **S**oft **E**lectronics

LAMPSe

Alexander Dallinger

Alexandra Serebrennikova



Kirill Keller

Hana Hampel

Felix Steinwender

our Website

lampselab.com

Stella Drewes

Bachelor students

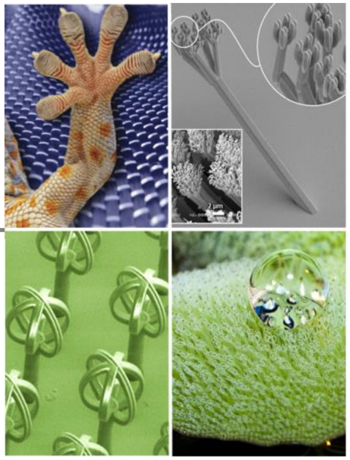
- David Gritzner
- Fabian Gasser
- Matthias Gritzner
- Benedikt Kraxberger
- Michael Gobald
- ...

Research Focus Outline

Research Focus | SOFT INTELLIGENT MATERIALS & INTERFACES for BIOROBOTICS

1 Smart Materials/Soft Robotics

2 Soft & Tattoo Electronics



3 Bioinspiration & Biointerfaces

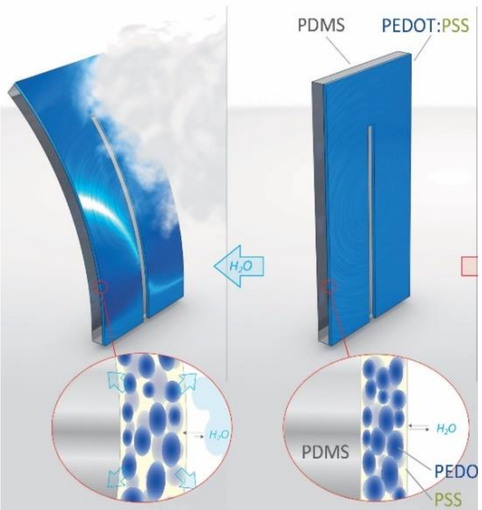
Highlight: Research Area 1

1 Smart Materials/Soft Robotics

ELECTRICAL/HYGROMORPHIC SOFT ACTIVE MATERIALS

Humidity response

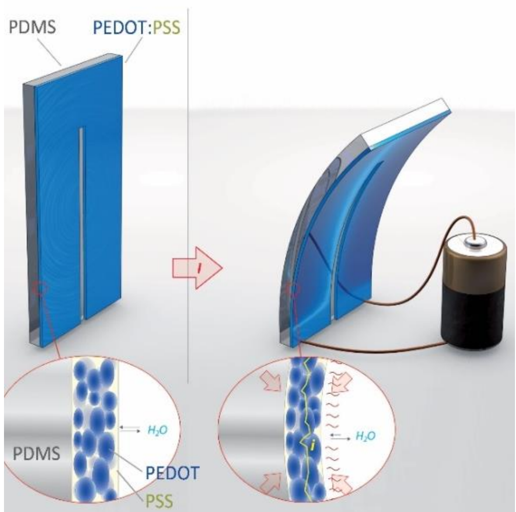
(no electric/electronic activation!)

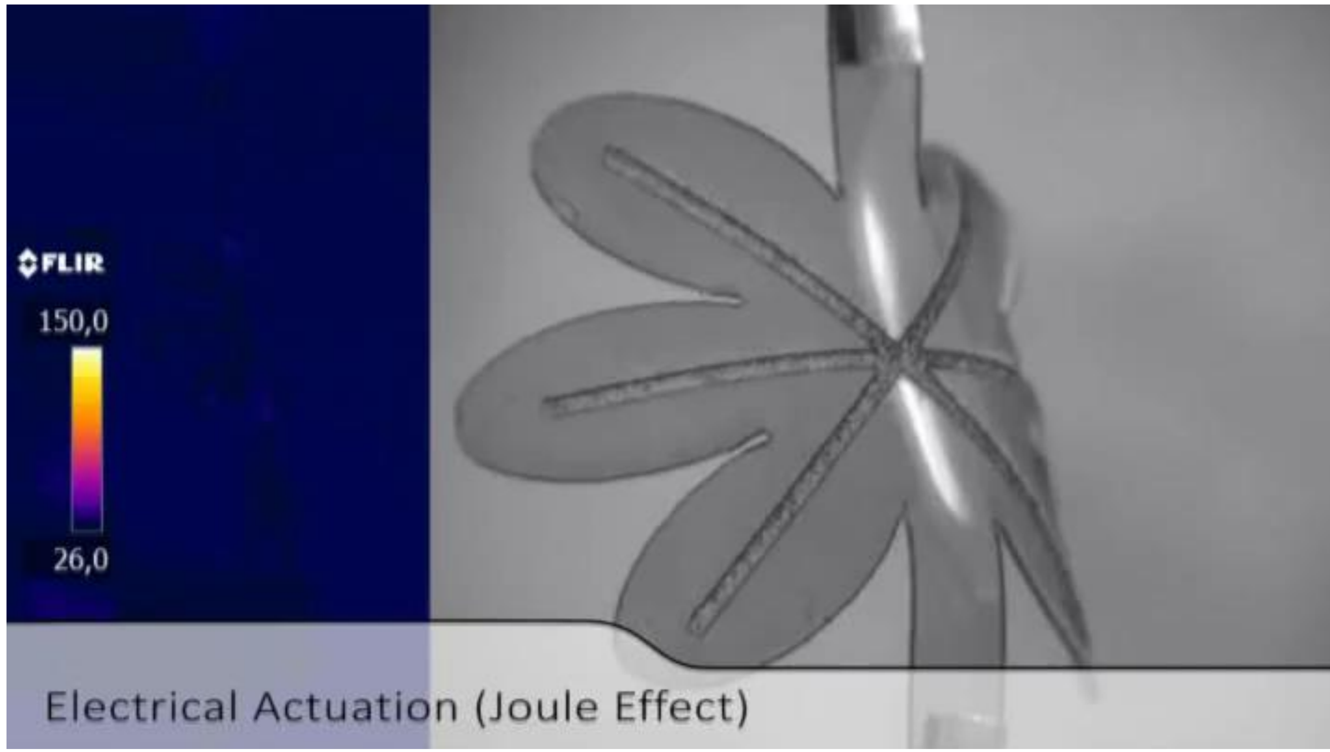


S. Taccola, *et al.*, *Advanced Materials* 27, 1668-75, **2015**

Electric activation

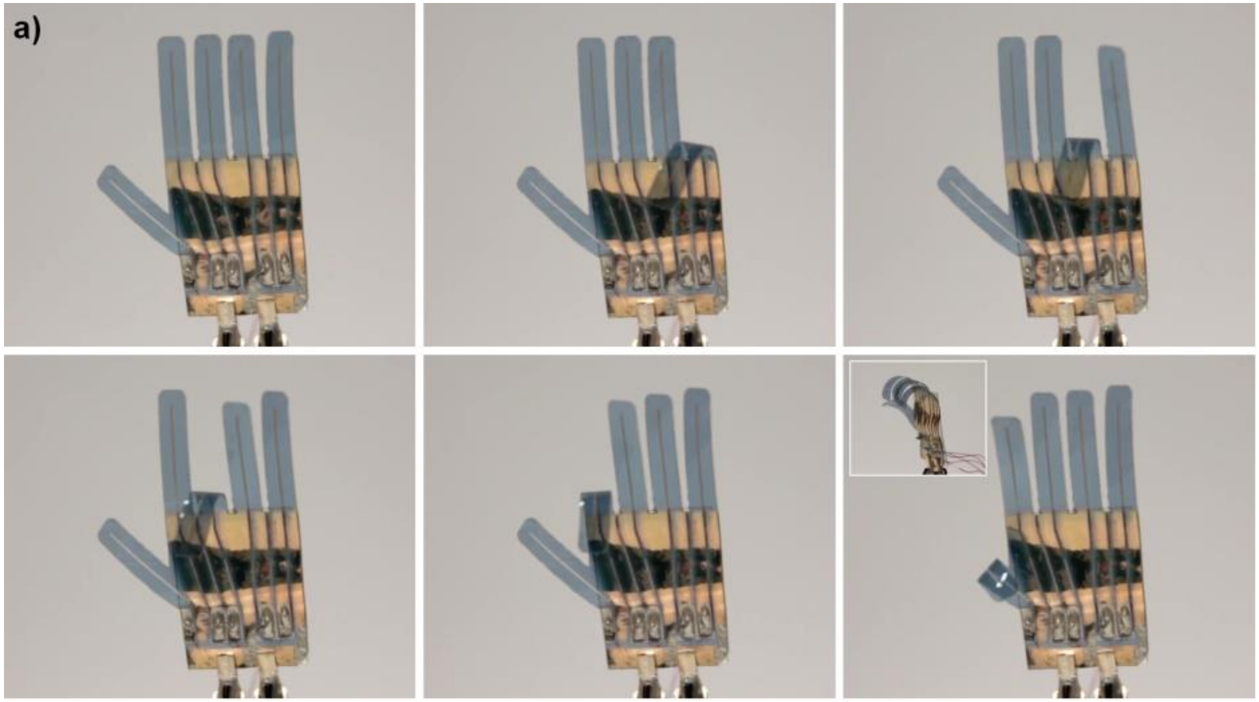
(T change by Joule heating)

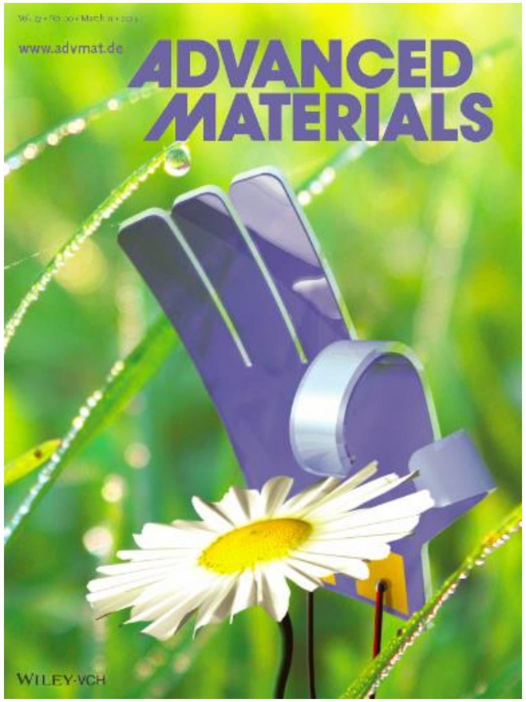




S. Taccola, *et al.*, *Advanced Materials* 27, 1668-75, **2015**

Electric trigger (Joule heating)





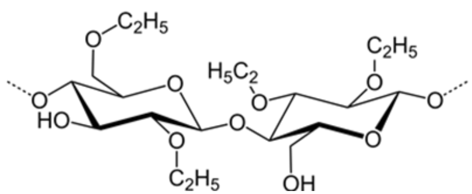
S. Taccola, *et al.*, *Advanced Materials* 27, 1668-75, **2015**

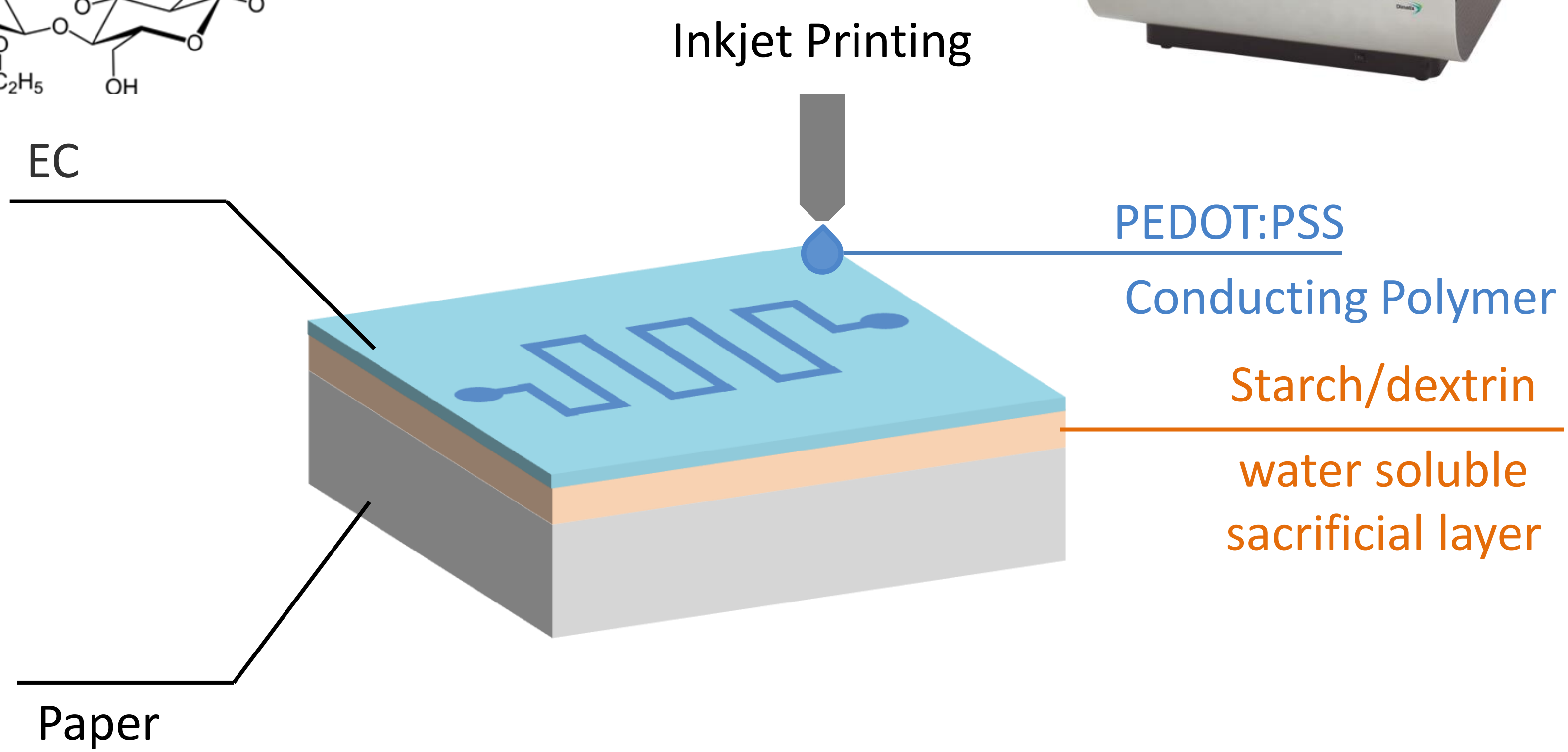
Research Area 2

2 Soft & Tattoo Electronics

CIRCUITS ON TATTOO

Ethylcellulose



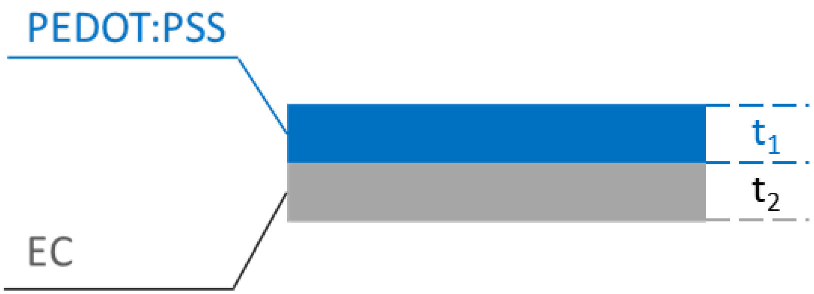


A. Zucca, *et al.*, *Advanced Healthcare Materials* 4, 983-90, **2015**

L. Ferrari, *et al.*, *Advanced Science* 5, 201700771, **2018**

L. Ferrari, *et al.*, *npj Nature Flexible Electronics* 4, 4 **2020**

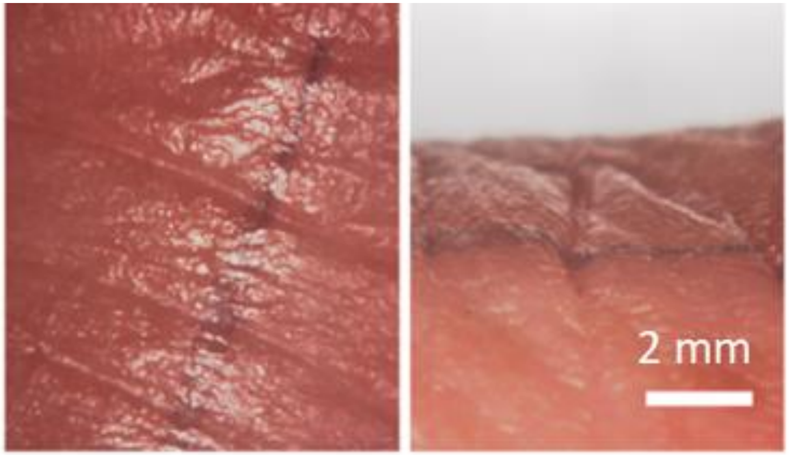
CIRCUITS ON TATTOO: PEDOT:PSS/EC

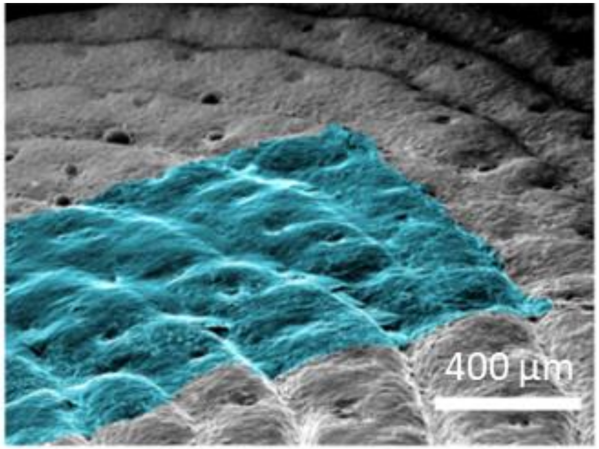


t_1 = 100 – 800 nm
$t_2 \approx$ 450 nm

thickness

Ultrathin, ultraconformable

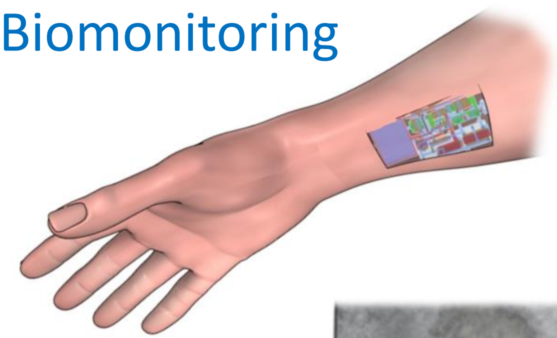




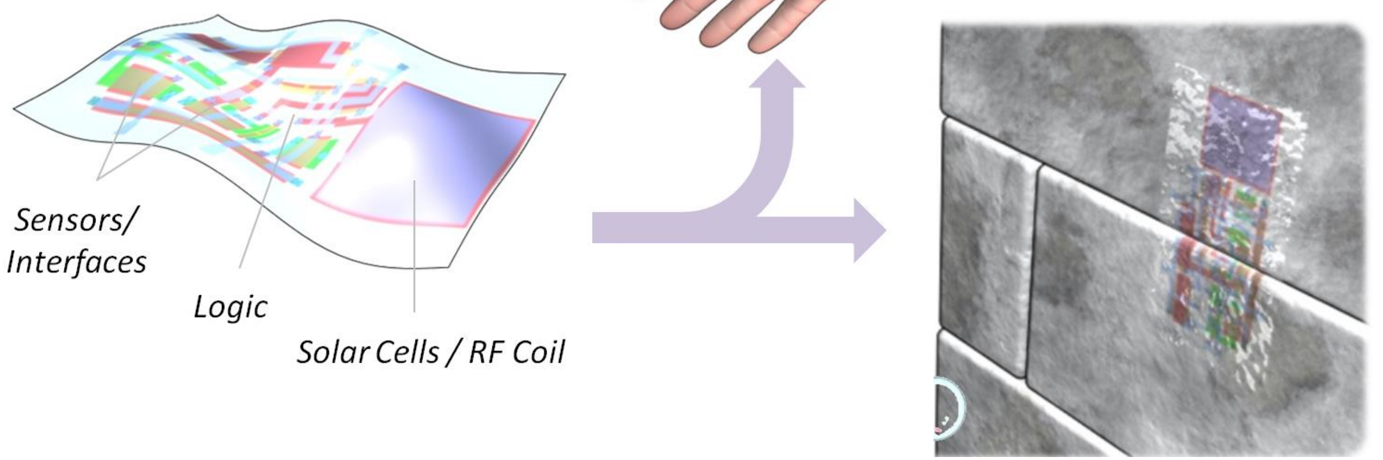
L. Ferrari, *et al.*, *Advanced Science* 5, 201700771, **2018**

ULTRA-CONFORMABLE ORGANIC (BIO)ELECTRONICS

Epidermal Devices
Biomonitoring

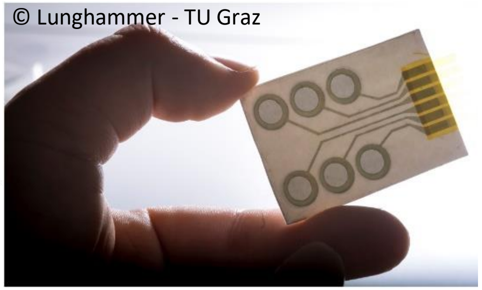


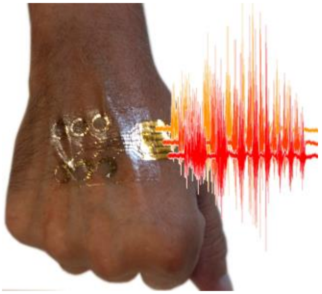
Printed Organic Electronics
on Tattoo



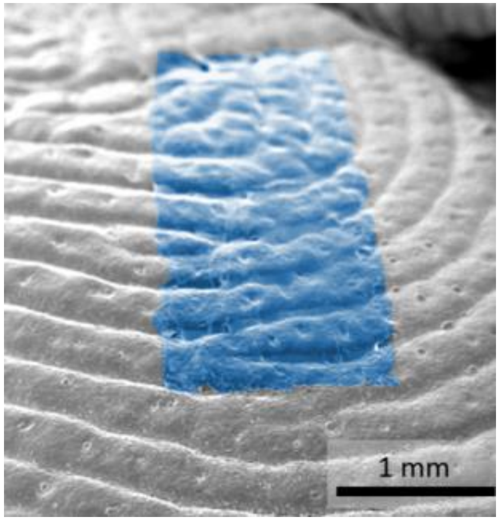
Transferrable Sensors

TATTOO APPLICATIONS IN ELECTROPHYSIOLOGY





Unperceivable skin-contact electrodes



Heart
ECG Electrocardiography

Muscles
EMG Electromyography

Brain
EEG Electroencephalography

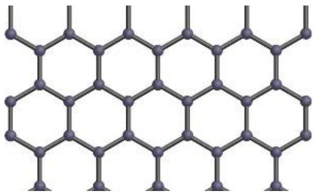
TTMEAs on Skin

Temporary Tattoo Multielectrode Arrays (TTMEAs)

L. Ferrari, *et al., Advanced Science* 5, 201700771, **2018**

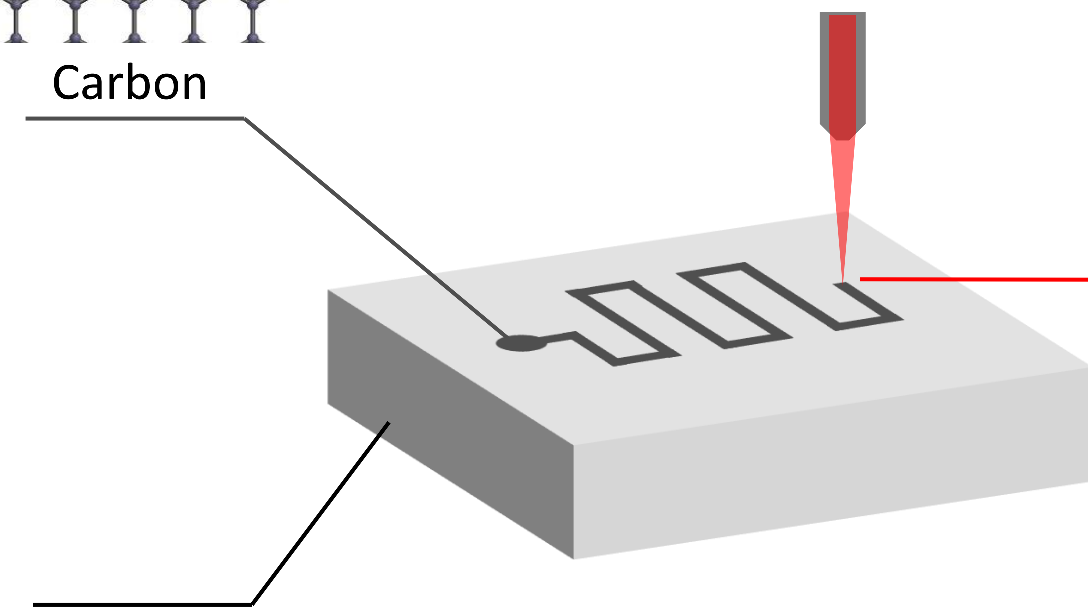
NEW APPROACH: LASER INDUCED GRAPHENE (LIG)

laser-scribing graphene conductors into polymer precursors



Carbon

CO_2 (Infrared) laser



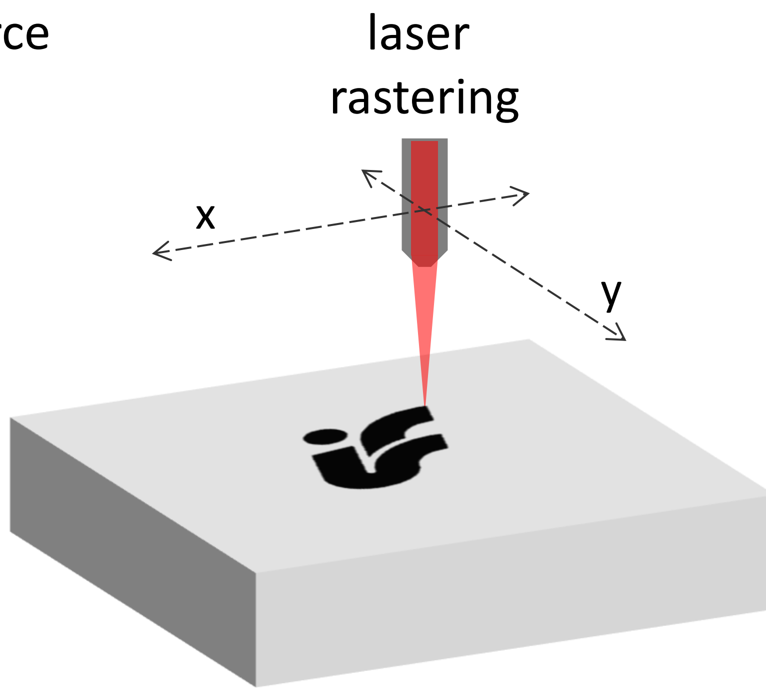
Laser Induced Pyrolysis

Laser Induced Graphene
LIG

J. Lin, J. M. Tour, *et al., Nature Commun.* 5, 5714 **2014**

NEW APPROACH: LASER INDUCED GRAPHENE (LIG)

CO_2 laser source
λ = 10.6 μm
P = 30W



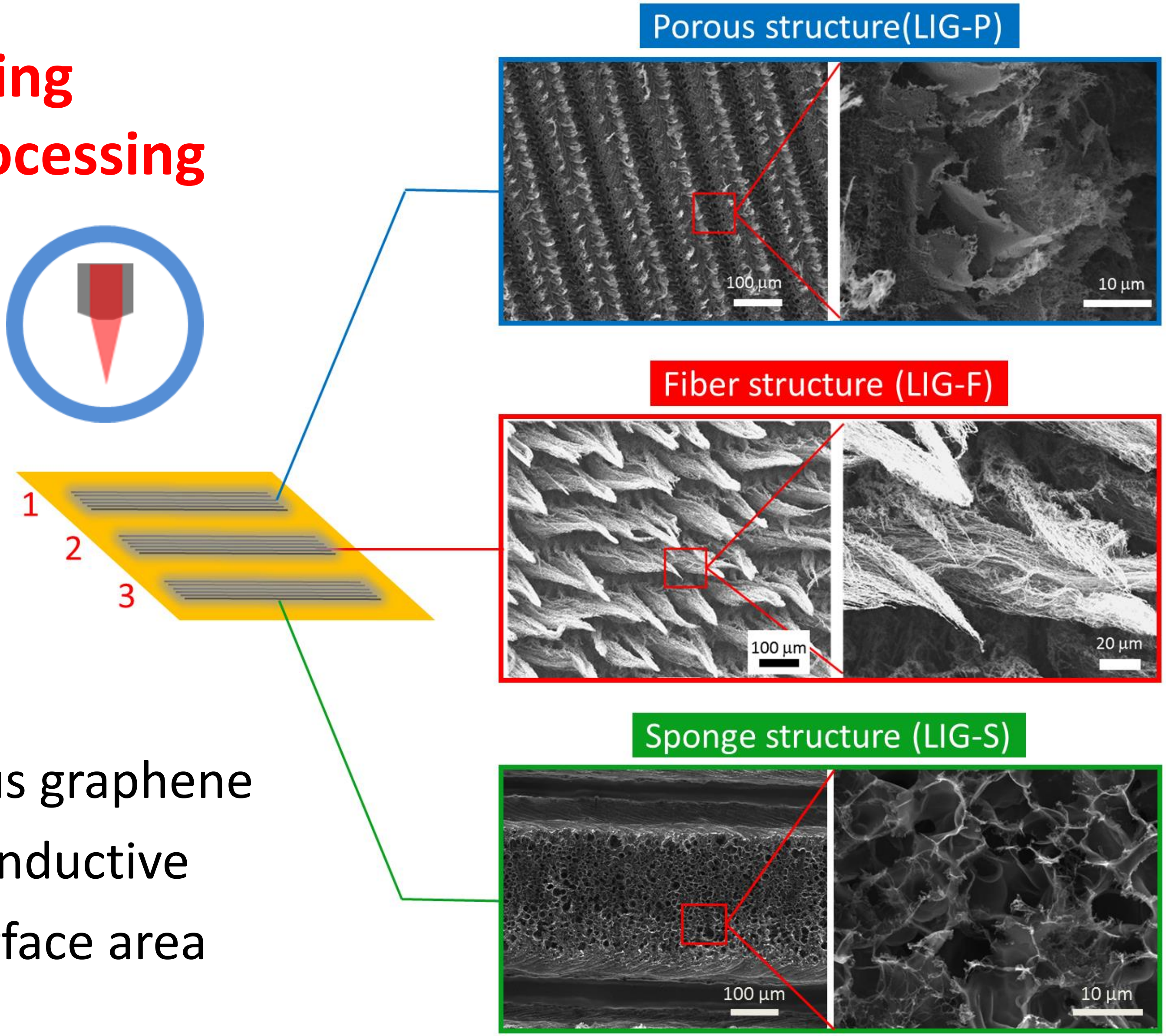
LIG on polyimide

2 mm

✓custom design
✓operation in air

Tuning Laser induced Graphene (LIG)

Tuning laser processing



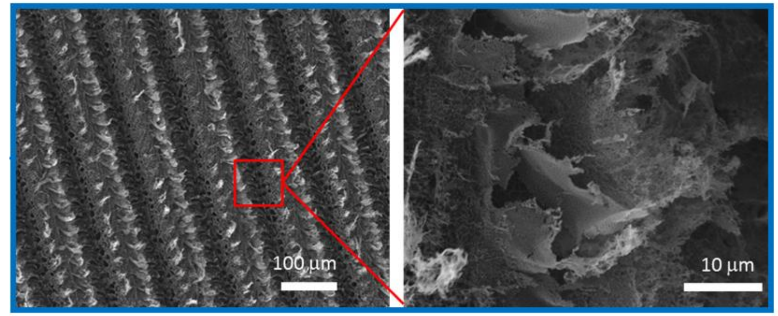
- 3D porous graphene
- highly conductive
- large surface area

A. Dallinger, K. Keller, H. Fitzek F. Greco *ACS Appl. Mater. Interfaces* **2020**, 12, 17, 19855-19865

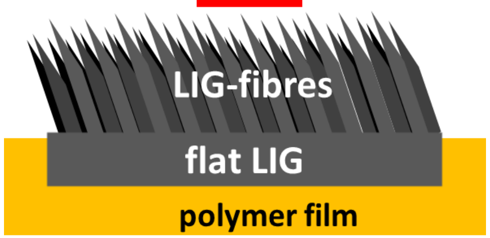
Tuning Laser induced Graphene (LIG)

LIG P

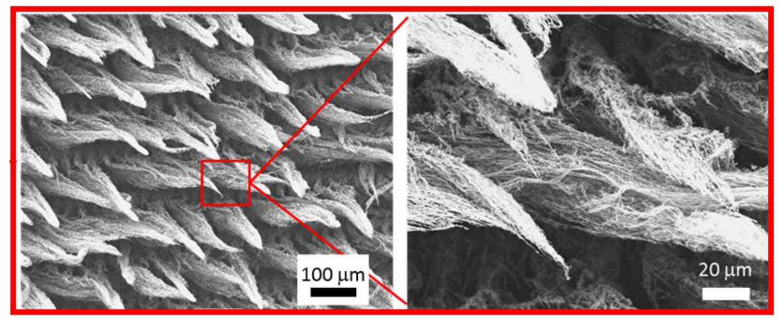
Porous structure(LIG-P)



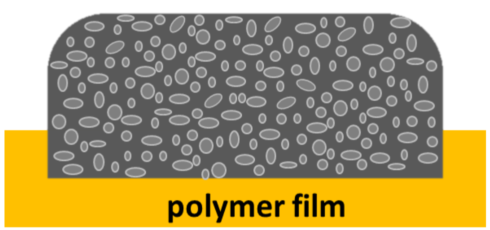
LIG F



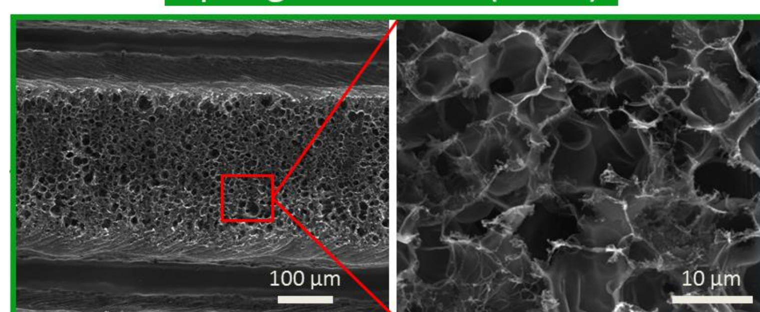
Fiber structure (LIG-F)



LIG S



Sponge structure (LIG-S)



A. Dallinger, K. Keller, H. Fitzek F. Greco *ACS Appl. Mater. Interfaces* **2020**, 12, 17, 19855-19865

ONGOING WORK : LIG MATERIALS

Graz University of Technology

LAMPSe

Activities

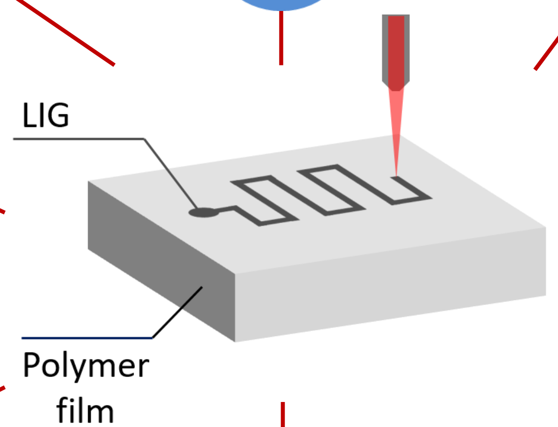
Basics/Fundamental — Applications

2. Precursors
renewable?
bio-derived?

3. Structure

4. Composition

1. Laser Processing
fluence model



5. Properties
electrical
mechanical
surface (wettability)

6. Stretchable conductors
composites

9. Supercap

7. Phys. Sensors
T, strain, pressure

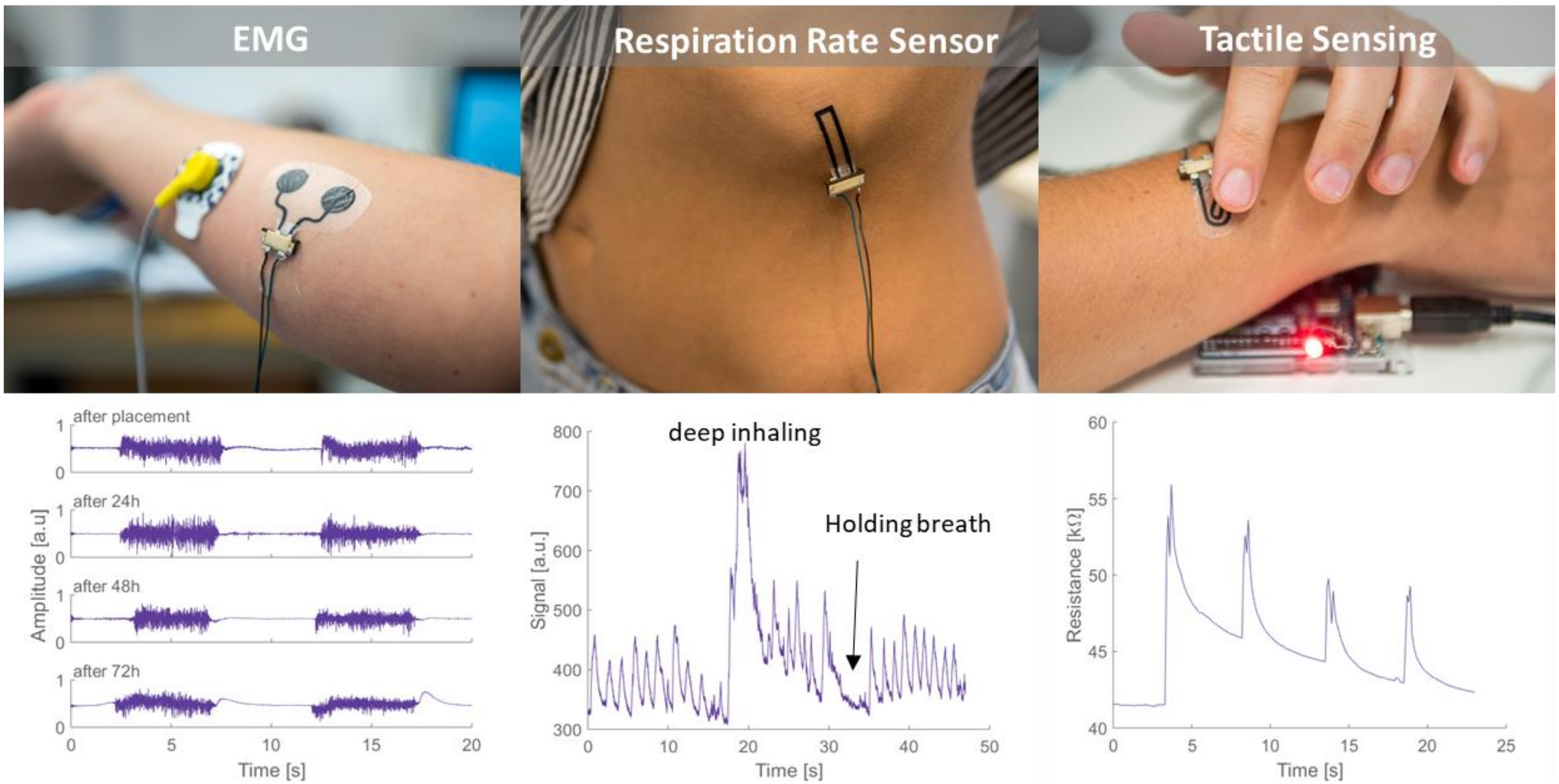
10. Biosensors/Epidermal
sweat, pH, urease, lactate,...

8. Actuators
+ stimuli responsive polymers

Wearable Biosensors

Embedding in Medical Polyurethane (MPU)

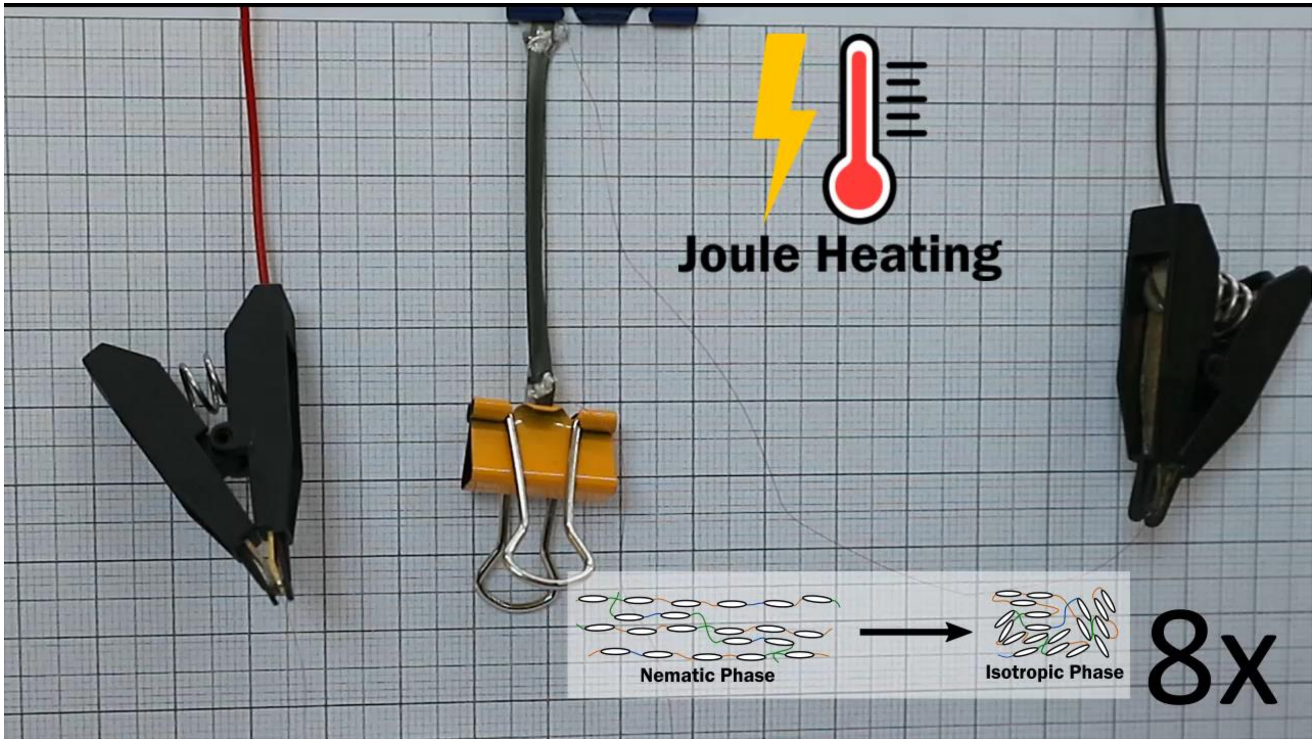
Conformable LIG/MPU Sensors worn on skin



A. Dallinger, K. Keller, H. Fitzek F. Greco *ACS Appl. Mater. Interfaces* **2020**, 12, 17, 19855-19865

SOFT ACTUATORS: LIG + LCE

Soft Actuators Based on Liquid Crystal Elastomer and LIG/MPU



Stella Drewes
Master Student
@LAMPSe TUGraz

LCE_Actuator – LAMPSe | Greco Group Graz (lampselab.com)

S. Drewes, *Master Thesis,* TUGraz **2023**

5D NANOPRINTING EU FET PROJECT

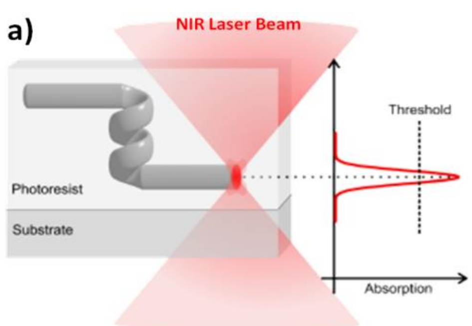
5D NANOPRINTING

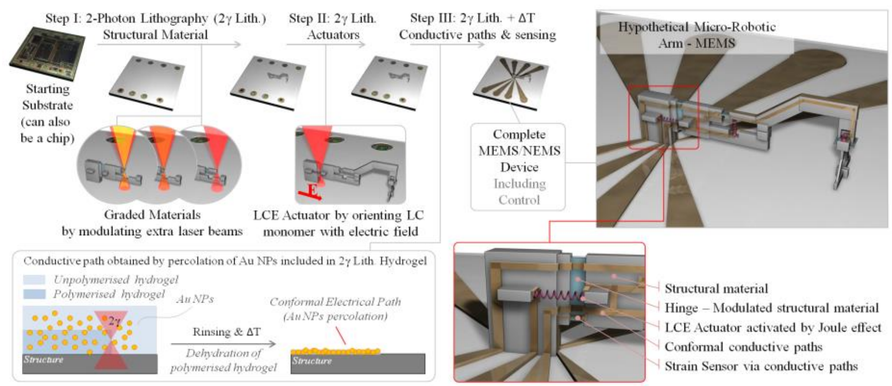
Sep 2020 – Sep 2024

Functional & Dynamic 3D Nano- MicroDevices (MEMS) by Direct Multi-Photon Lithography

LAMPSe role: **Micro-scale LIG scribing on 2PP materials**

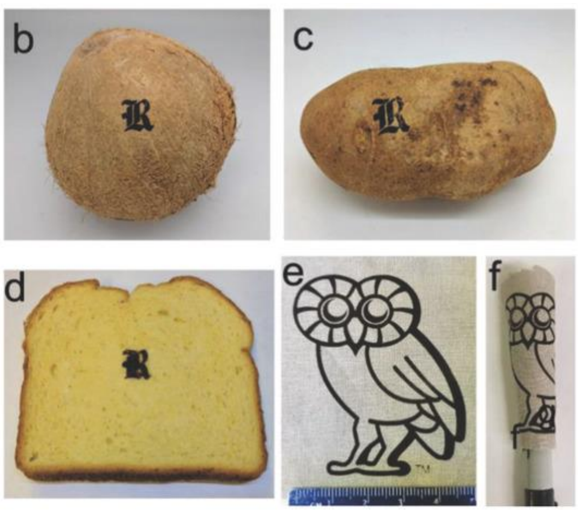
2-photon polymerisation: 2PP





LIG from Bio-Derived Materials

LIG from bio-based precursors: wood, cork, paper,…



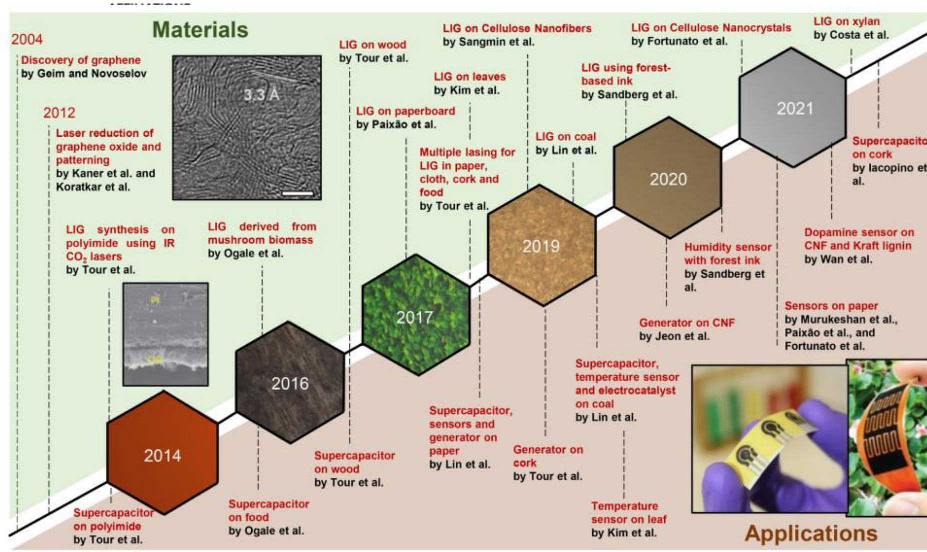
Y. Chyan, J. M. Tour, *et al. ACS Nano* **2018**, 2176

Applied Physics Reviews REVIEW scitation.org/journal/are

Sustainable carbon sources for green laser-induced graphene: A perspective on fundamental principles, applications, and challenges

Cite as: Appl. Phys. Rev. 9, 041305 (2022); doi: 10.1063/5.0100785
Submitted: 26 May 2022 · Accepted: 10 October 2022 ·
Published Online: 10 November 2022

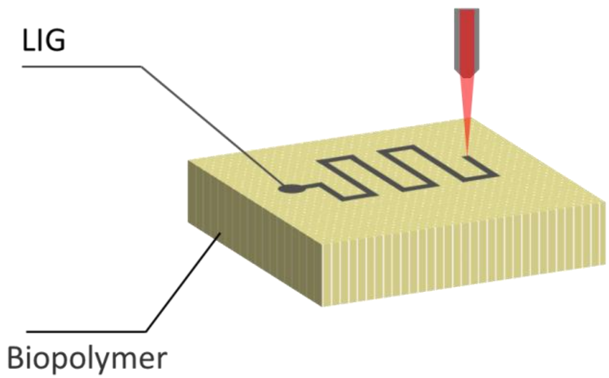
Pedro I. C. Claro,[1,2,a)] Tomás Pinheiro,[2] Sara L. Silvestre,[2] Ana C. Marques,[2] João Coelho,[2] José M. Marconcini,[3] Elvira Fortunato,[2] Luiz H. C. Mattoso,[3,b)] and Rodrigo Martins[2,c)]



Claro, Fortunato, Martins, *et al. Appl Phys Rev* 9, 041305 **2022**

LIG FROM RENEWABLE MATERIALS

Biologically derived polymer precursors for LIG



Raw Natural Materials:

- almond, hazelnut, pistachio **shells**
- wood, fibers…

RICH in **LIGNIN**

Thin films of **BIOPOLYMERS**:

- **algae-derived** high performance plastics
- **lignin** (discard from paper production)
- **starch-based** plastics

- **green electronics** manufacturing
- "transient electronics", low environmental footprint
- sustainability: **SDGs 9, 12**

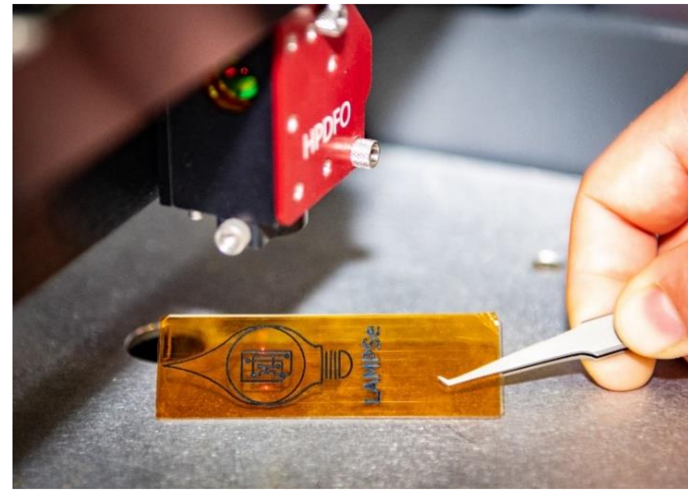
A video presentation by me (Starting Seminar at SSSA – Oct 27 2021) in italian!

https://youtu.be/xzop2LK7A1M

Graz University of Technology

Laboratory of **A**pplied **M**aterials for **P**rinted and **S**oft **E**lectronics

LAMPSe



More info, publications, videos available at

https://lampselab.com/

Classwork 1

Form: students' presentation

- questions about YOU
- email address for being added as member to the Teams Channel of the course

: 10 min

Classwork 1 AMB2024-25

https://forms.office.com/e/FkfsiRmc6V

L1.1

INTRODUCTORY NOTES ON THE COURSE

Advanced materials for bionics

Focus

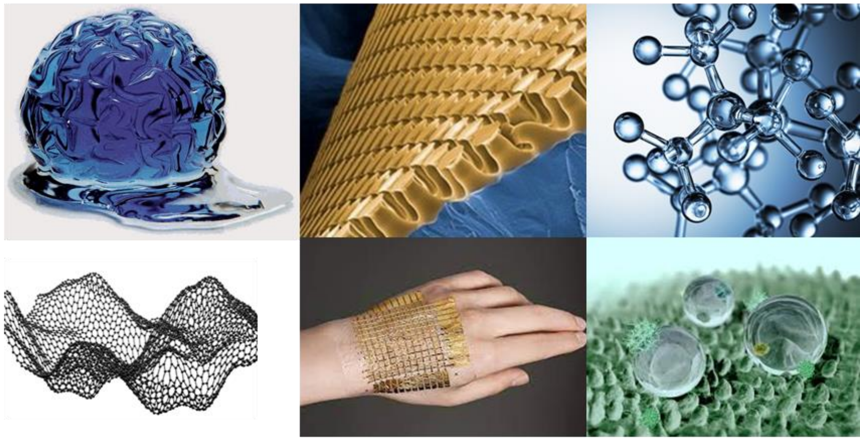
- Materials Science & Engineering: materials classes, structure, properties
- Advanced Concepts and applications of materials in Bionics

Learning Outcomes

- solid background in Materials Science & Engineering
- knowledge of uses of modern advanced materials in Bionics Engineering

Main Topics

- Basic traditional topics of Materials Science & Eng.
- Metals, Ceramics, Polymers, Composites
- Advanced Materials Concepts: Biocompatibility, complex Soft Matter, Nanotechnology & Nanostructures, Bioinspired & Stimuli Responsive Materials.
- Investigation & Fabrication Techniques
- Technology & Bionics Applications: materials for bionics, bioelectronics, sensors&actuators in robotics



https://www.bionicsengineering.it/edu/

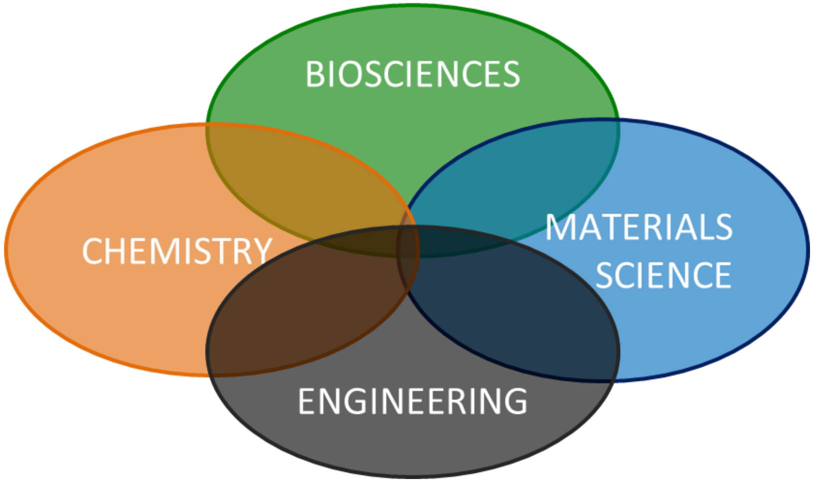
OBJECTIVES OF THE COURSE

To show:

- how **materials structure** (at several scales) is connected to **final materials properties**
- how synthetic, biological, bioinspired and smart materials can have **relevant technological applications in bionics**

To improve:

- **interdisciplinary cross-talk**



COURSE SECTIONS

Section 1:
Refresh of Basics Materials Science
(Lectures ≈ 2 - 10)

- Materials structure & properties
- Materials classes

Section 2:
Advanced Concepts
+ Technology &Bionics applications
(Lectures ≈11 - 18)

- Biological materials science
- Bioinspiration biomimetics
- Smart materials
- Nanotechnology
- Fab/patterning
- Robotics
- Bioelectronics
- Biomedicine

Course Structure

Lesson	Title	Section
1	INTRO	
2	Materials Structure 1 - Bonding	1 – Refresh of Basics Materials Science
3	Materials Structure 2: Crystal Structures	1
4	Mechanical Properties of Materials	1
5	Metals	1
6	Ceramics	1
7	Polymers 1	1
8	Polymers 2	1
9	Polymers 3	1
10	Composites	1
11	Soft Matter	2 - Advanced Concepts, Technology & Bionics Applications
12	Biological Materials 1	2
13	Biological Materials 2	2

COURSE STRUCTURE

Lesson	Day	Title	Section
14		Biological Materials 3	2
S1		Invited Seminar 1	2
S2		Invited Seminar 2	2
15		Stimuli Responsive Materials	2
S3		Invited Seminar 3	2
16		Additive Manufacturing	2
S4		Invited Seminar 4	2
17		Surface Energy & Wettability	2
18		Biomimetic surfaces	2
19		STUDENTS SEMINARS	1/2

Team work: Seminar on selected topics

- Students divided in **groups,** trying to include in each group students with **various backgrounds** in order to maximize an interdisciplinary approach.

- One selected topic per group
- **Assignment:**
  - perform a **bibliographic survey** on the topic
  - discuss among the group, divide tasks
  - find connections with topics discussed during the course
  - preparation & presentation of a 20 min **seminar**

ADVICE !!!
Start soon to work with group!!!

Seminar:
- held on **last day of lectures (?)** in front of class
- each person in the group should be involved in presentation **(no spokesperson)**

To help me in forming groups I will use today's classworks

SEMINAR TOPICS 1

SEMINAR TOPIC 1	AUXETIC Materials&Structures in BIOMEDICINE
SEMINAR TOPIC 2	Underwater adhesion in natural/bioinspired structures
SEMINAR TOPIC 3	Metal-based NEURAL INTERFACES
SEMINAR TOPIC 4	Responsive materials for Microrobots
SEMINAR TOPIC 5	3D printing of metals and its applications in Bionics
SEMINAR TOPIC 6	Sustainable materials for Electronics/Robotics
SEMINAR TOPIC 7	SMA or shape memory polymers in Bionics
SEMINAR TOPIC 8	Materials in Epidermal Electronics
SEMINAR TOPIC 9	Silicon Carbide applications in Biomedicine and Bionics
SEMINAR TOPIC 10	Zirconia and Alumina ceramics in Biomedicine/Bionics

SEMINAR TOPICS 2

SEMINAR TOPIC 11	LIQUID METALS for Stretchable Electronics and Bionics
SEMINAR TOPIC 12	Conjugated Polymers in Bionics
SEMINAR TOPIC 13	Reconfigurable materials for haptic devices
SEMINAR TOPIC 14	Tough biocompatible and/or bioinspired adhesives
SEMINAR TOPIC 15	Nanomaterial-based drug delivery strategies
SEMINAR TOPIC 16	Hydrogels in Bionics
SEMINAR TOPIC 17	Biomimetic Surface wetting/Fog basking
SEMINAR TOPIC 18	Self-Healing Materials and Materials Structures
SEMINAR TOPIC 19	Bioinspired materials approaches for camouflage
SEMINAR TOPIC 20	Liquid Crystal Elastomers: 3D Printing and applications

SEMINAR TOPICS 3

SEMINAR TOPIC 21	Bioderived/Bioinspired Elastomers and uses
SEMINAR TOPIC 22	Oleophobic, Omniphobic Surfaces: inspiration and uses
SEMINAR TOPIC 23	Optically responsive materials in bionics
SEMINAR TOPIC 24	Lipid based nanocarriers
SEMINAR TOPIC 25	Self-Assembling strategies in bioinspired materials
SEMINAR TOPIC 26	Materials strategies for Energy Harvesting devices
SEMINAR TOPIC 27	Origami/Kirigami Materials structures and uses
SEMINAR TOPIC 28	Low cost micro-nano patterning methods
SEMINAR TOPIC 29	4D Printing: principles and uses in bionics
SEMINAR TOPIC 30	Metallic glasses: current and potential uses

EVALUATION METHOD & MY FEEDBACK

- 10 aspects considered for evaluation

Biblio survey	Abstract	Graphic, Design, Style	Clarity of presentation	Contents	References	Engagement /Passion	Use of Multimedia (videos, online resources…)	Discussion	Duration

evaluation scores: + / -

+

- notes
- notes on oral presentation/speakers
- advice for improvement

Exams, Grades

Exam:

a) short written test/questions/exercises
b) oral interview

Grades*:

- grade (scale 0-30) assigned for the **seminar**
- grade (scale 0-30) assigned for the **exam**

* bonus points will be assigned for active class participations (e.g. for the «*cum laude*»)

Final Grade = Seminar Grade*0.3 + Exam Grade*0.7

How to study?

- **Slides of lessons** available as PDF files
- **Additional readings** (e.g. review papers) available

You are STRONGLY INVITED to read these as **homeworks** before attending the next lesson

- **Assignments** given in the form of **brief summary** or **questions** about lesson content and reading assignments.
- **Textbooks**
- For interested people who want to go further in depth in selected topics additional references, videos and reading materials will be available as «additions» to slides of lectures AND in a dedicated section of Teams

MICROSOFT TEAMS
«Advanced Materials for Bionics AY 2023/24»

Reference Textbooks

Section 1:

- W.D. Callister, D. Rethwisch, **Materials Science and Engineering** (any edition!)

Section 2 (parts):

- R. A. L.Jones, **Soft Condensed Matter**, Oxford Master Series 2002
- M.A. Meyers, P.Y. Chen, **Biological Materials Science**, Cambridge Univ. Press 2014

Other stuff on organization

- dates: ok for everyone?

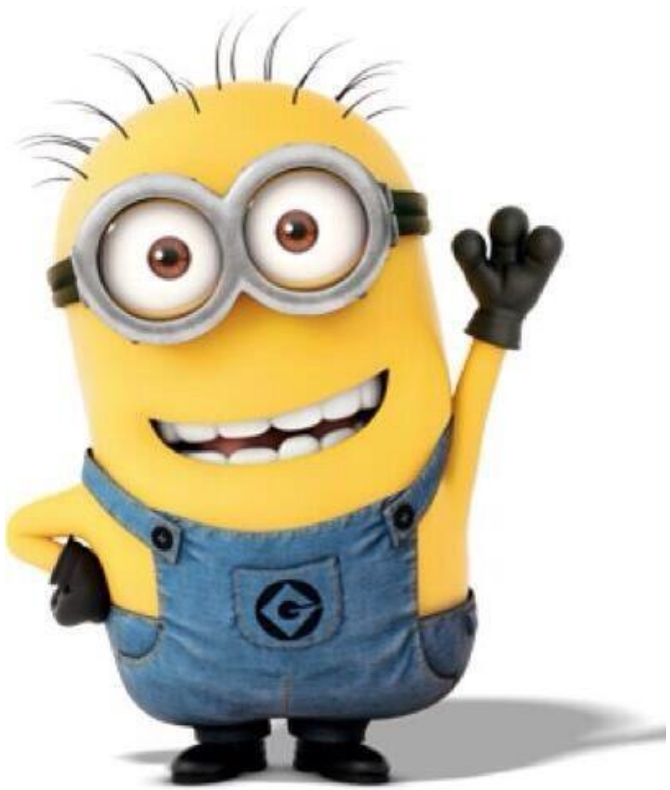
mon	fri
16.30 – 18.30	10.30 – 13.30
A23@Pisa Eng	R1@PSV

- joining MTeams workspace: UNIPI Teams?
- presence lectures
- invited seminars

REMARKS

VERY IMPORTANT! **If ANYTHING is not clear:**

KEEP
CALM
AND
RAISE
YOUR HAND



or email me at: francesco.greco@santannapisa.it

Classwork 2

Form: assessment of materials science background

<u>NO GRADE ASSIGNED!!!</u>

Answer **<u>very frankly</u>** to the questions: «I don't have any idea!» is an acceptable answer!

- no equations
- sketches, graphs/drawings welcome
- send sketches to: francesco.greco@santannapisa.it from your student email account

: 20 min

Classwork 2 AMB2024-25

https://forms.office.com/e/5CHBcjvG1b

CLASSWORK 2 QUESTIONS

1. what is a glass transition? describe it shortly and make **1 example** for a common polymer
2. make **1 example** of a crystalline material and name few of its properties (roughly quantitatively if possible)
3. why rubber is elastic? answer shortly
4. make **3 examples** of bio-macromolecules. can you sketch their rough chem structure?
5. sketch the chem structure of graphene. what is the difference btw.: I) a carbon nanotube, II) a fullerene, III) graphene, IV) graphite?
6. name **a few examples** of materials applied to biomedicine (any application!): e.g. Ti -> structural implants (hip replacement)
7. name a few additive manufacturing techniques
8. what is a composite?
9. why does water **wet** some **surfaces** but not others?
10. what is **photolithography** (briefly)? in which technological field is (mostly) used?

L1.2

Evolution of Materials Science & Engineering

HISTORICAL PERSPECTIVE

From natural materials to synthetic ones

Materials

2 million years ago - early hominids

stone

Prehistory

woods, bones, leather, pottery

8000 -5000 BCE Neolithic age

natural fibers (textiles)

glass

metals
(copper 6000 BCE)
(bronze, alloys 3000 BCE)
(iron 1200 BCE)

History

19th Century - Industrial Revolution

polymers
bakelite -first synthetic polymer 1907

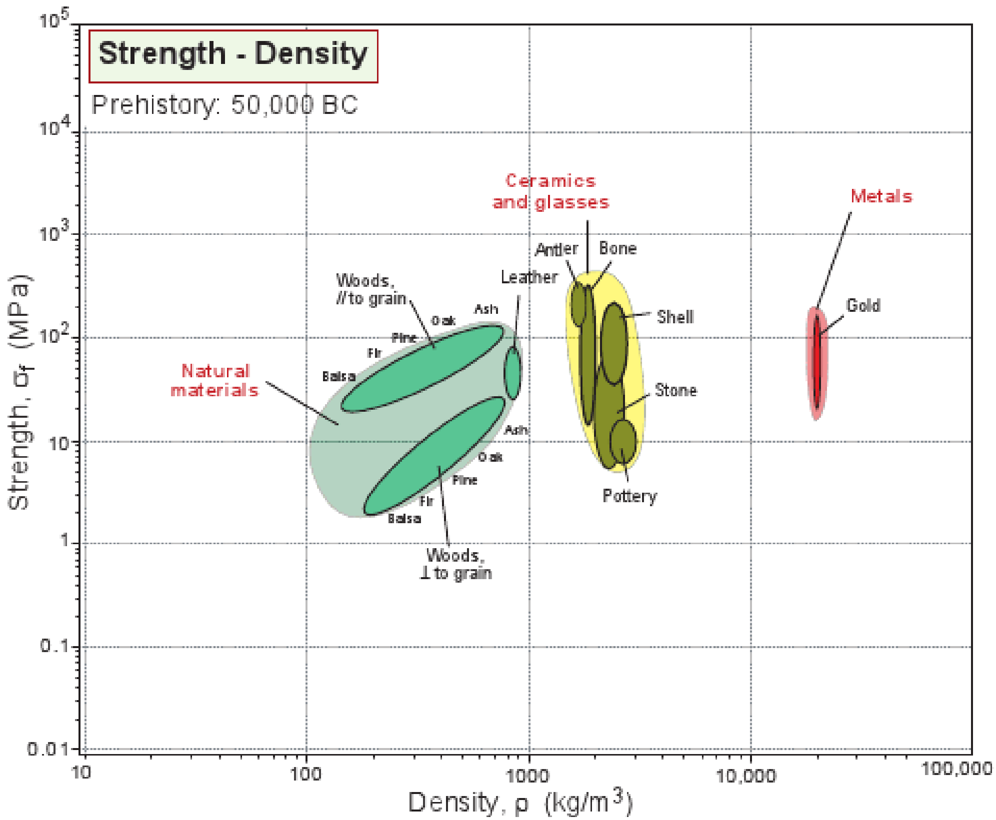
semiconductors, composites, nanomaterials, ...

today

EARLY MATERIALS

The first materials that men had at their disposal to fabricate their tools, houses, clothes were **natural** and **biological:** **stone, bones, antler, wood, skins, shells**

Strength vs. density Ashby plot of pre-historic synthetic materials



Some of early «synthetic» materials (ceramics, glasses and metals) are also shown on the plot: they provided added strength

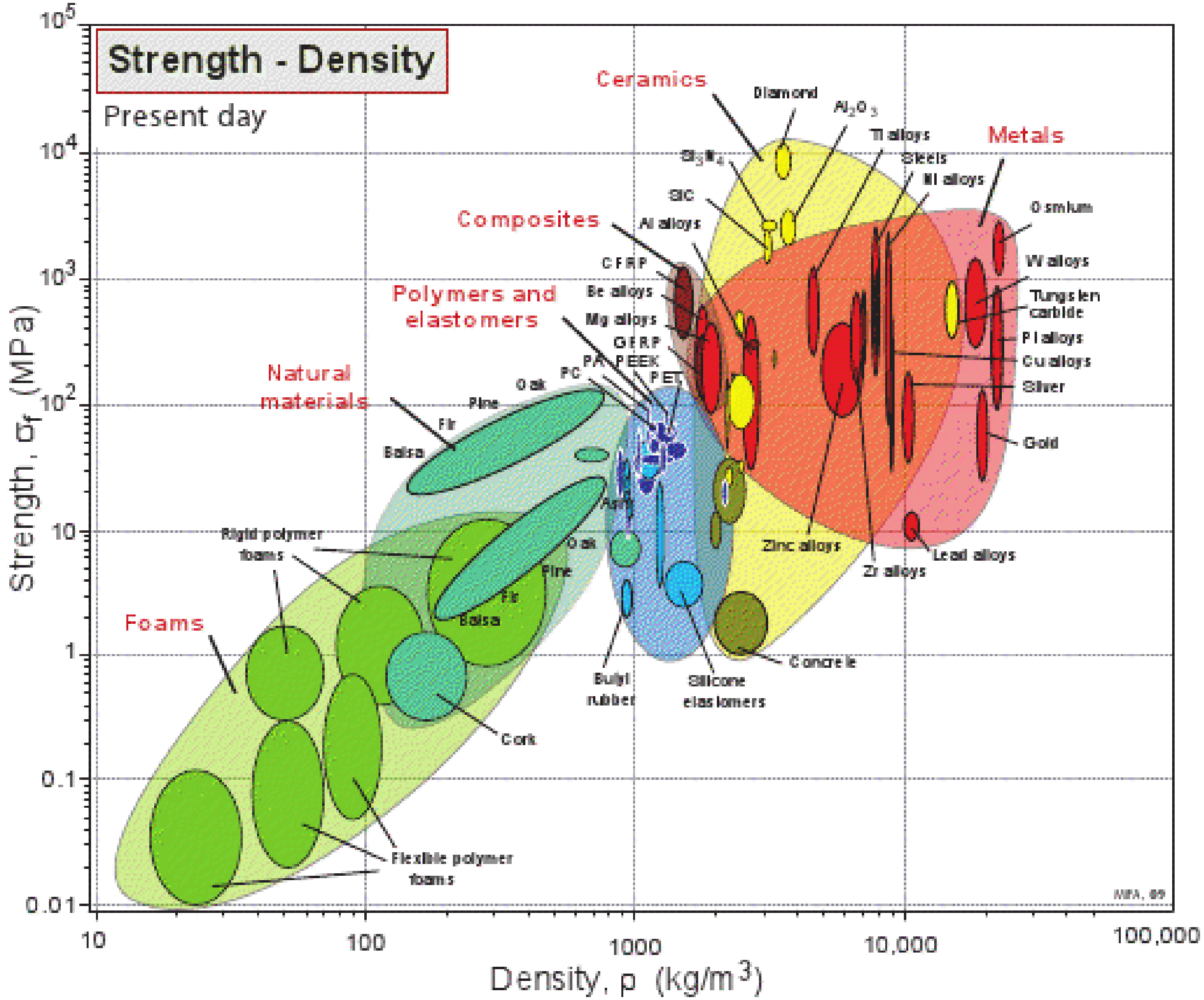
«SYNTHETIC» MATERIALS

Synthetic materials expanded the range of choices and significantly improved the performance of tools throughout 10,000 years of creative effort and technological development

CONTEMPORARY SYNTHETIC MATERIALS

Great complexity and variety → **exploited to the maximum**

Strength vs. density Ashby plots of contemporary synthetic materials



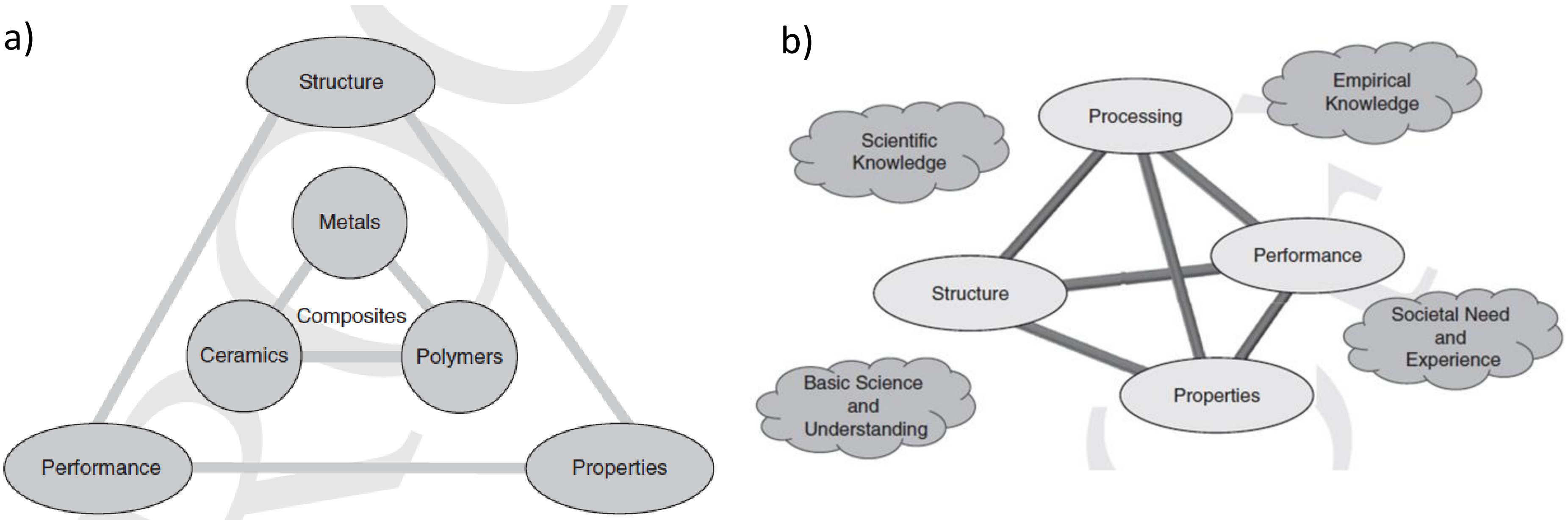
Materials Science and Engineering Revolution

Structure property paradigm

Unified approach to the study and utilization of metals, ceramics, polymers and their composites

a)

b)



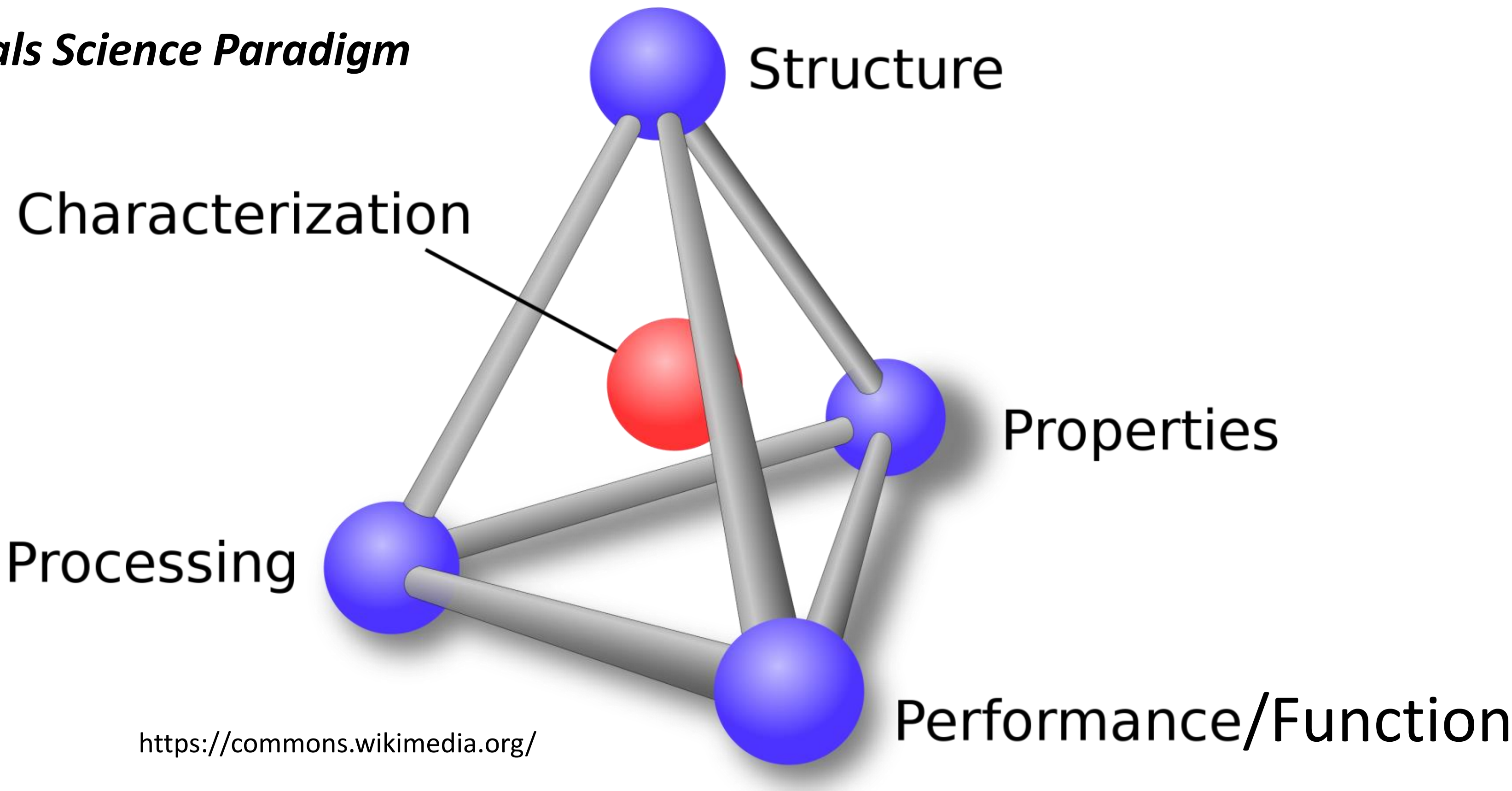
(a) The original Cohen structure–properties–performance triangle (1980)

(b) a modernized version.

MATERIALS SCIENCE & ENGINEERING TETRAHEDRON

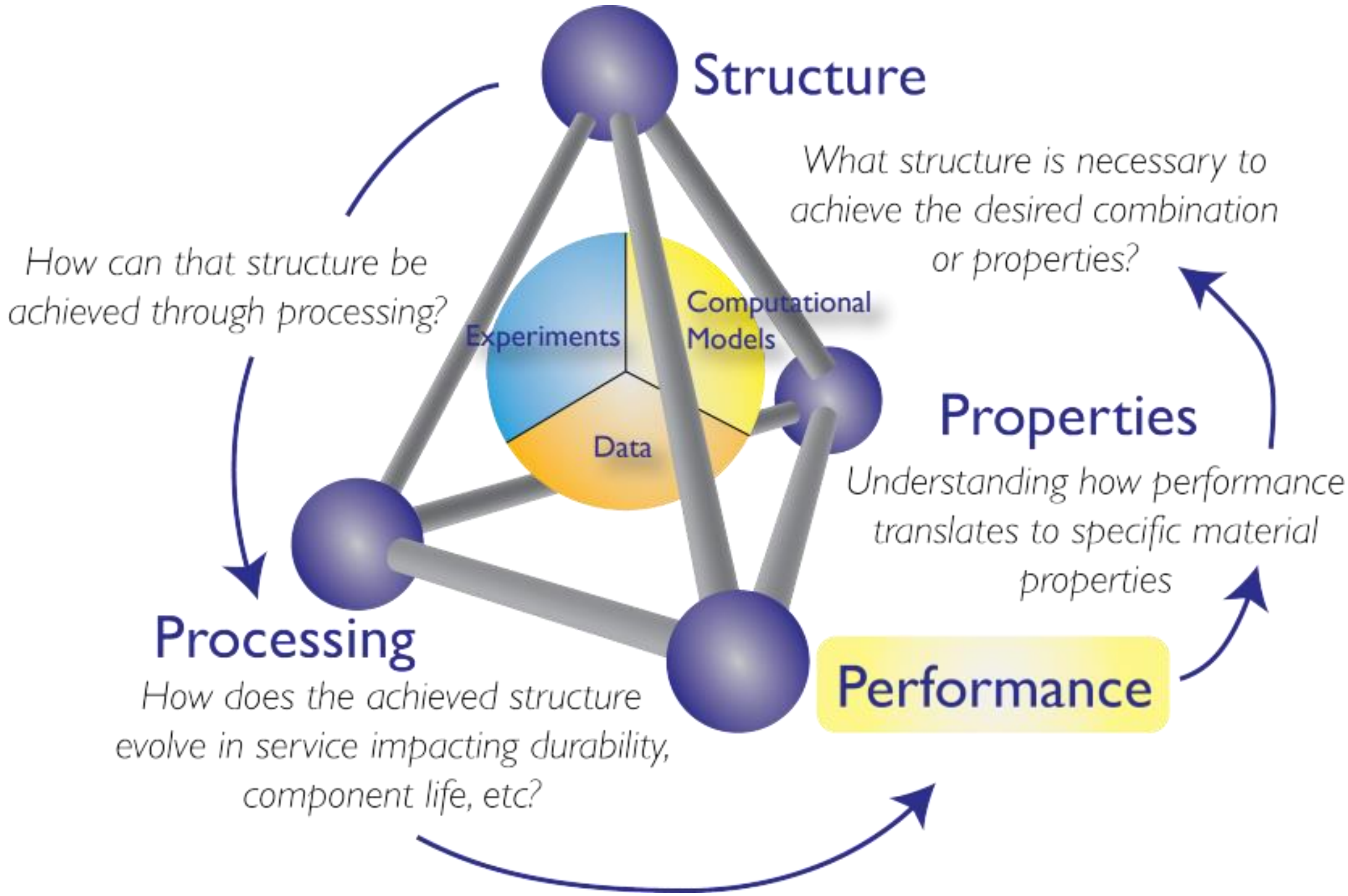
Since the 1990s much more emphasis and growing importance in Mat Sci & Eng has been given to **functional materials**, departing from the earlier focus in **structural materials**

Materials Science Paradigm



https://commons.wikimedia.org/

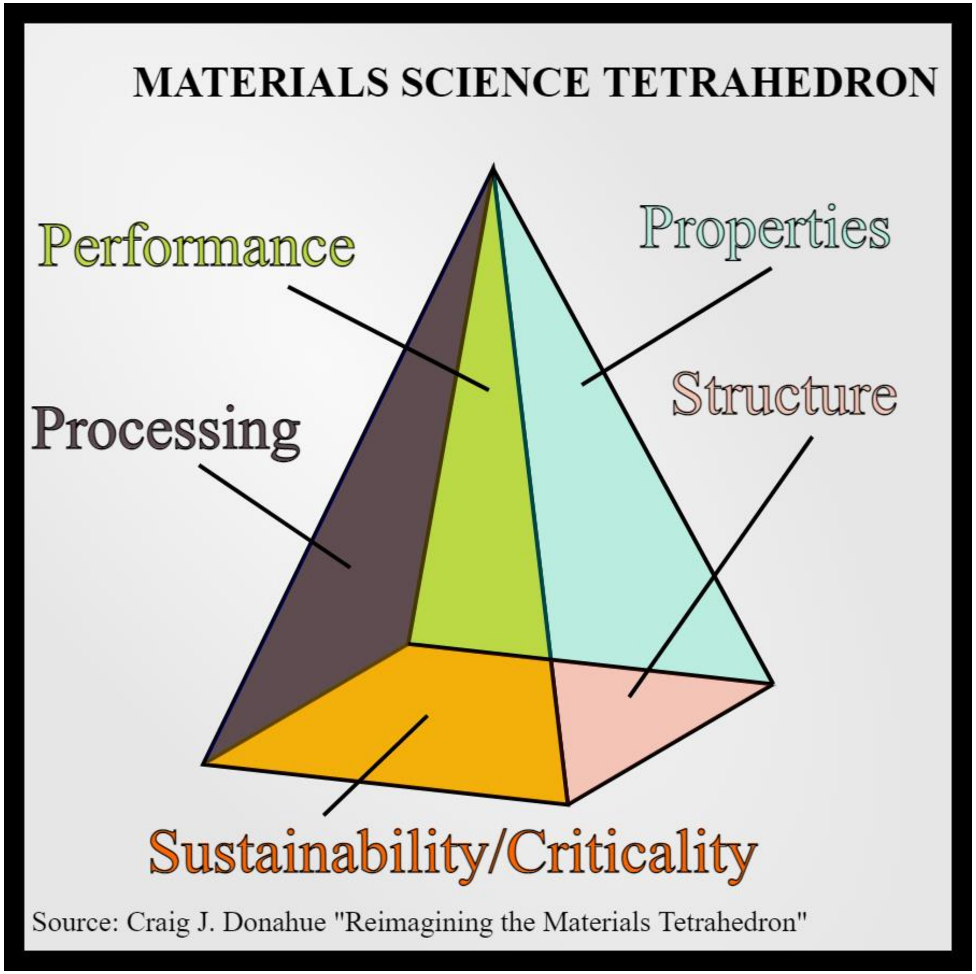
MATERIALS SCIENCE & ENGINEERING TETRAHEDRON



https://gems.matse.illinois.edu/educators/

MATERIALS SCIENCE & ENGINEERING TETRAHEDRON

- consideration for the ecological impact of the material

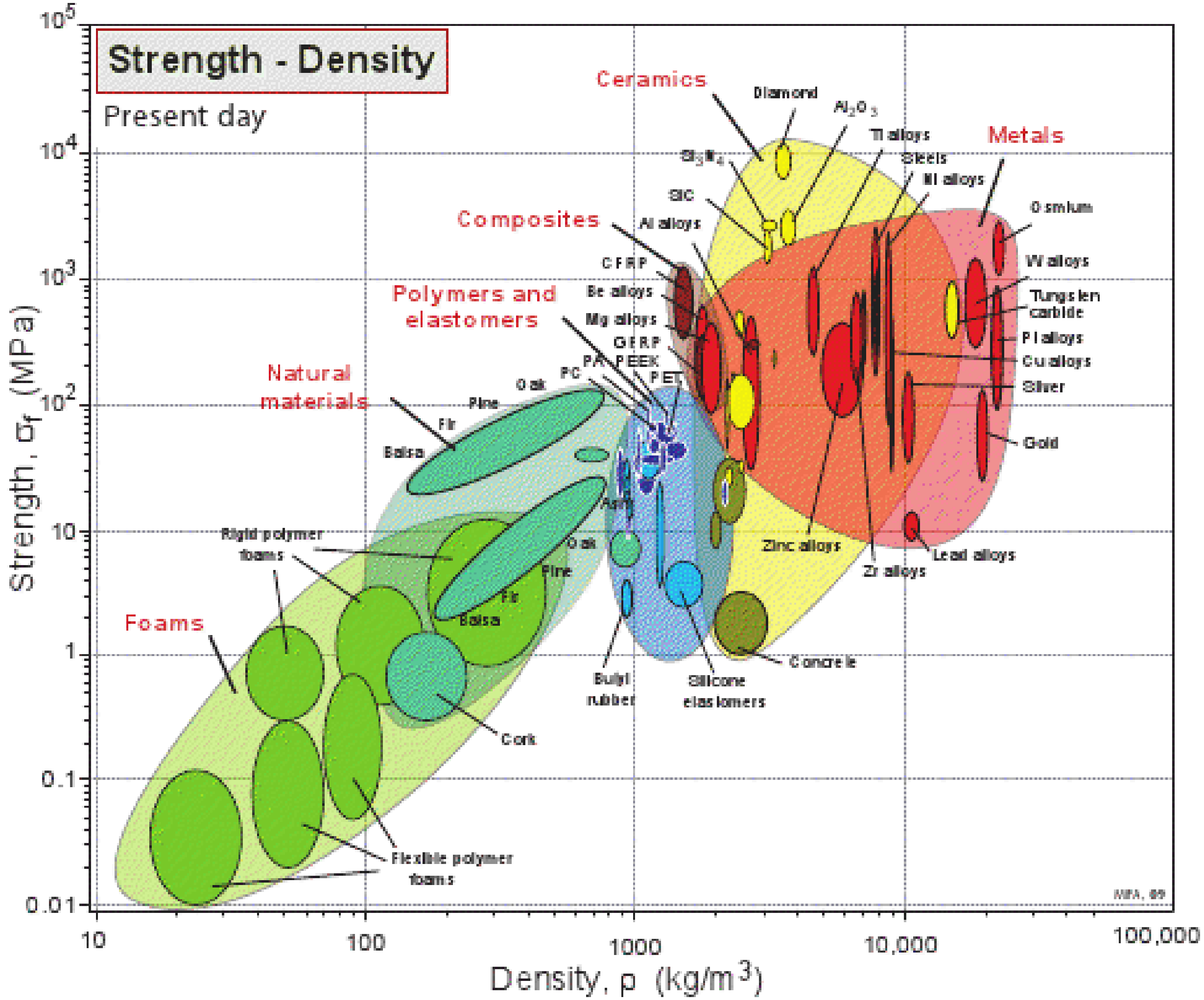


https://msestudent.com/

CONTEMPORARY SYNTHETIC MATERIALS

Great complexity and variety → **exploited to the maximum**

Strength vs. density Ashby plots of contemporary synthetic materials

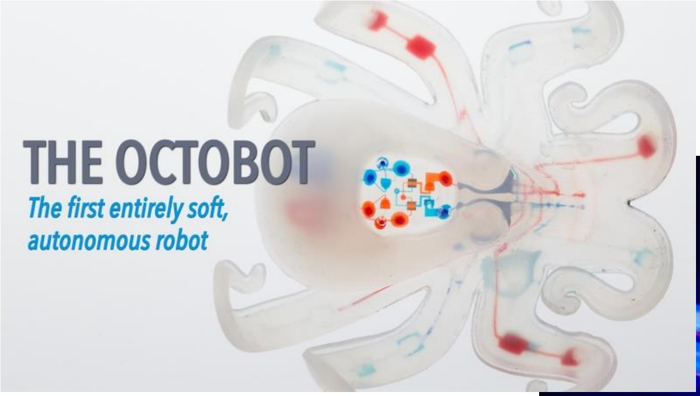


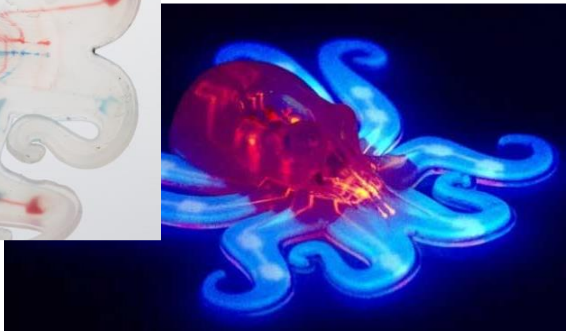
Today?

In the future?

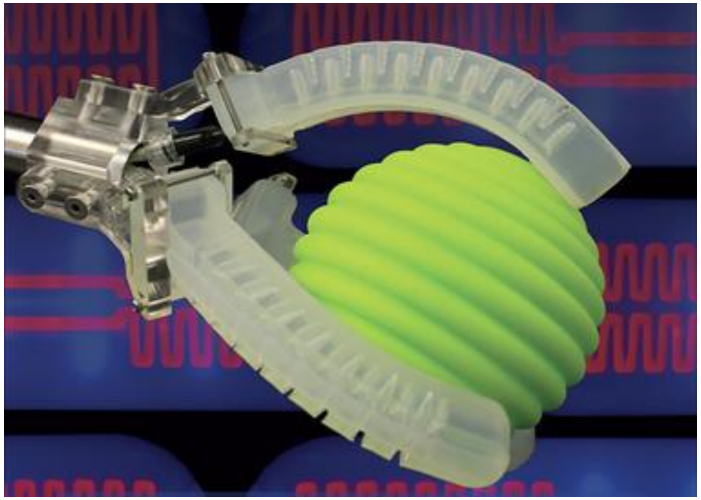
SOFT ROBOTICS

OCTOPUS,
The Biorobotics Institute - SSSA





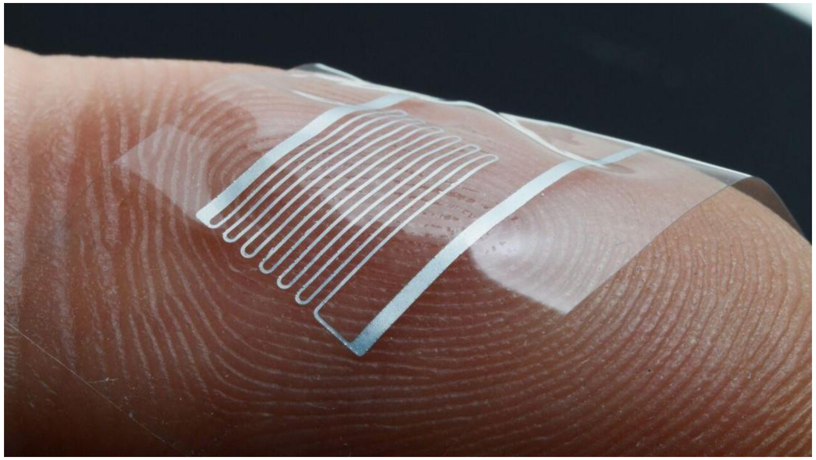
Octobot, Harvard Univ. (USA)



Soft Robot gripper, Harvard Univ. (USA)

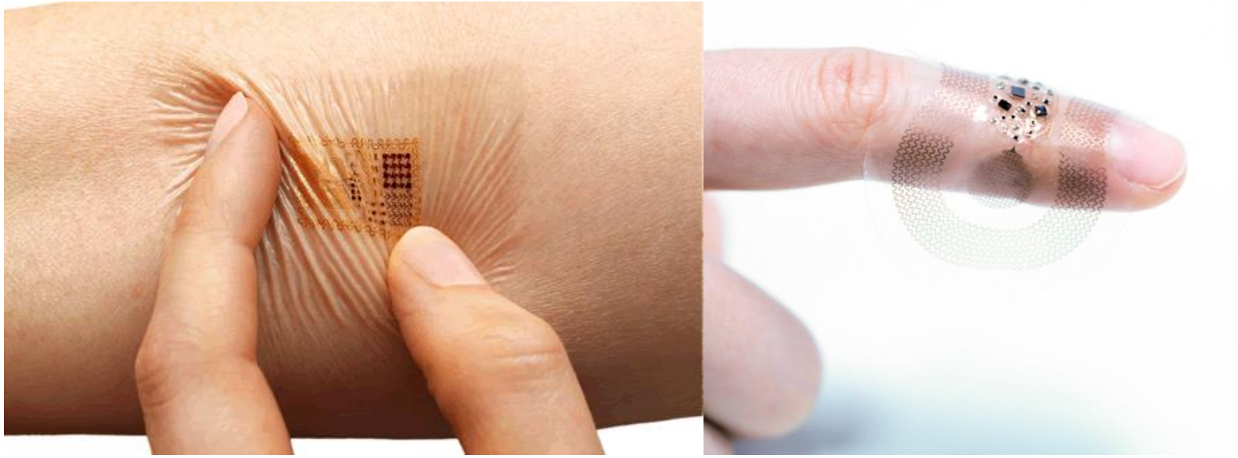
SOFT ELECTRONICS

Flexible/stretchable/conformable electronics & bioelectronics

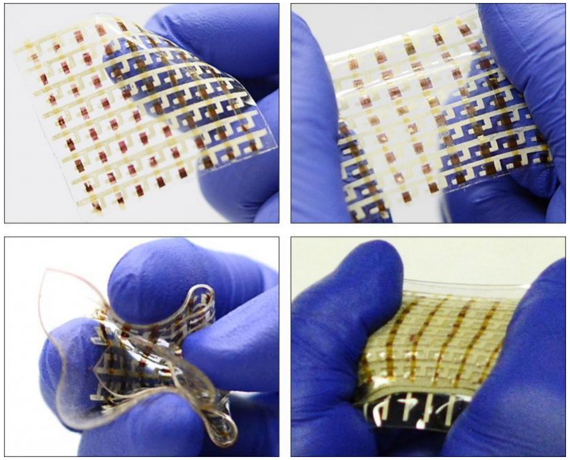


EPFL - Switzerland

Someya Group- Univ. Tokyo (Japan)



J. Rogers - Northwestern Univ (USA)



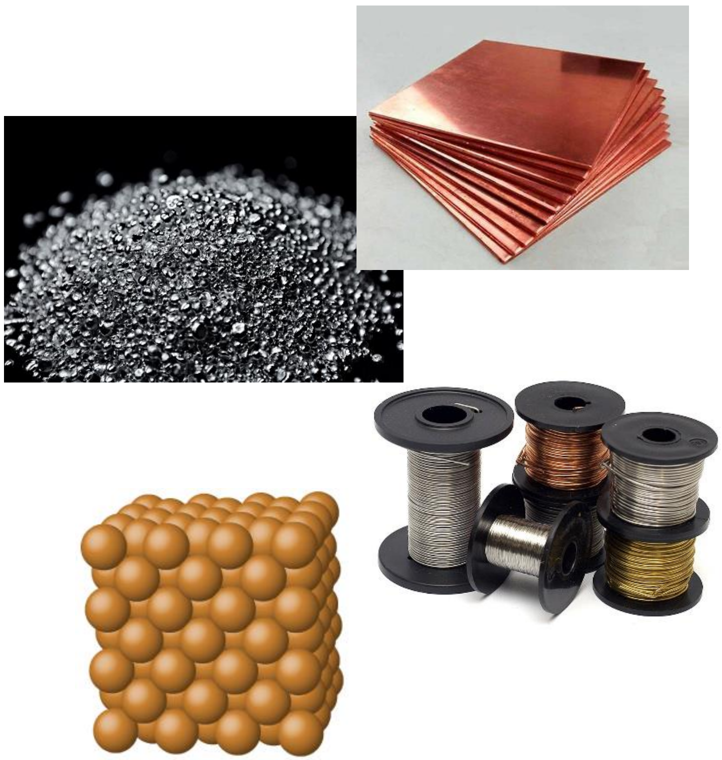
Houston Univ, USA

Sim et al., Sci. Adv. 2019; 5 5749

SOFT, FLEXIBLE, STRETCHABLE CONDUCTORS?

electrical properties

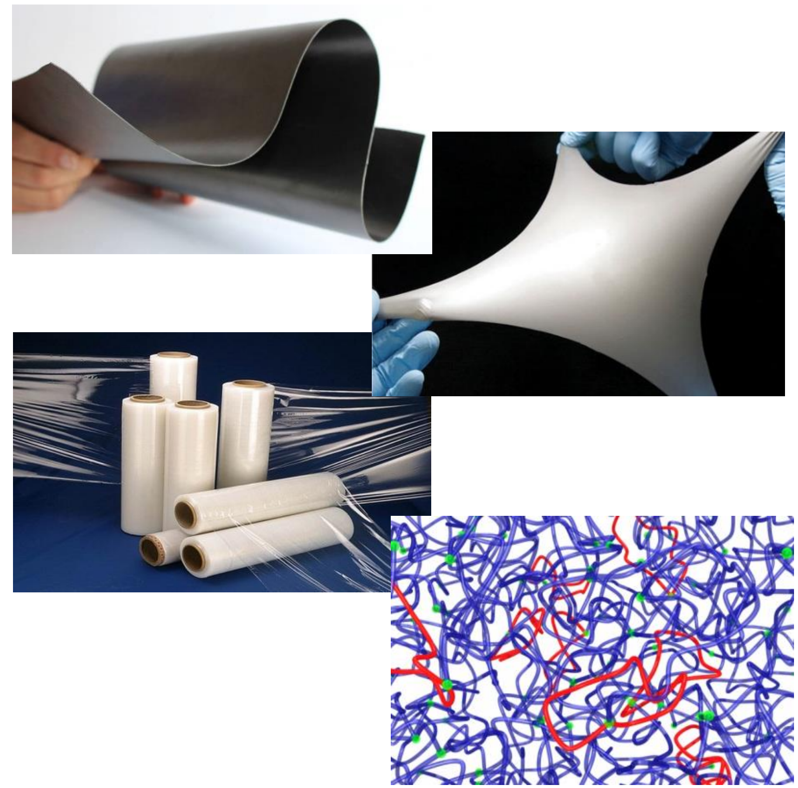
conductivity



metal conductors

mechanical properties

flexibility, stretchability



polymers

(thermoplastics, elastomers)

61

FUTURE MATERIALS?

- smart (responsive) materials
- resurgence of interest in natural (or biological) materials
- environmental concerns!
- «new» designs and concepts stolen from nature

Natural materials: often mechanically **weak** and/or with **poor functional properties**

BUT

combined in a very ingenious way to produce though components, robust designs, exceptional functional properties

BIOINSPIRATION AND BIOMIMETICS

Central idea: to produce materials using advanced technology along with bioinspired designs that have evolved in nature for million of years

L1.3

SHORT INTRO TO SMART MATERIALS

Intelligent (or Smart) Materials

DEFINITION

"…those materials that are multifunctional due to their unique molecular structure and respond to external stimuli by a characteristic behavior to the outside world."

M. Shahinpoor, H. J. Schneider,
Intelligent Materials, RSC Publishing, 2008.

INTELLIGENT?

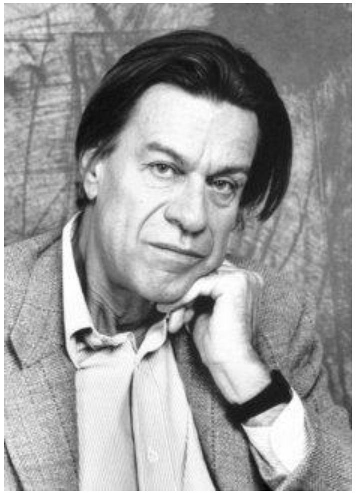
"Claiming to be intelligent is bold.

The materials [...] are actually somewhat less ambitious; they ***respond in an interesting way to an external stimulus****: a field, a change in pH, a pulse of light, a temperature jump, etc.*

I would tend to call them "sensitive" rather than "intelligent".

But…they have been invented, and improved, by highly intelligent scientists."

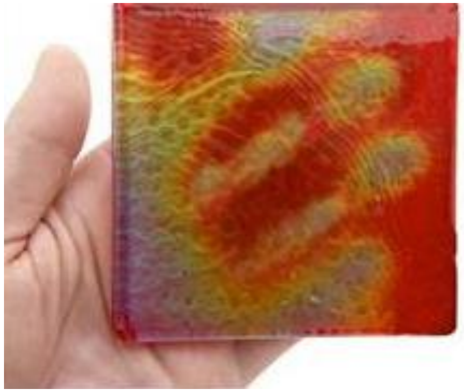
P.-G. de Gennes
Nobel Laureate in Physics 1991



www.nobelprize.org

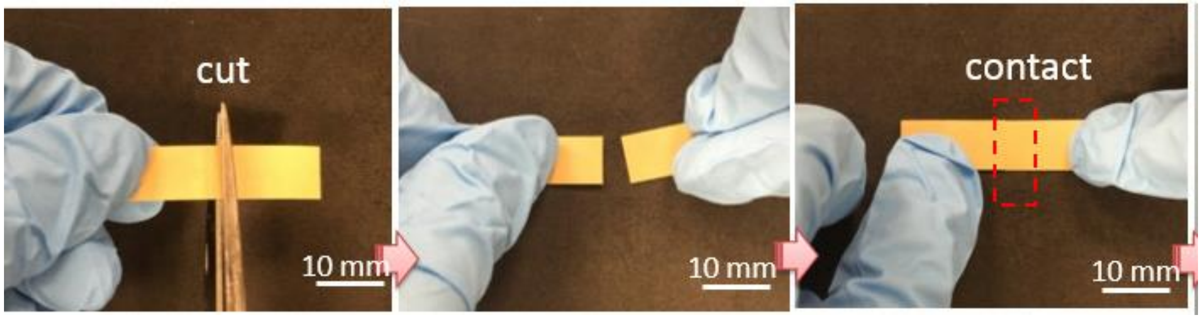
Stimuli → Responses

T → color



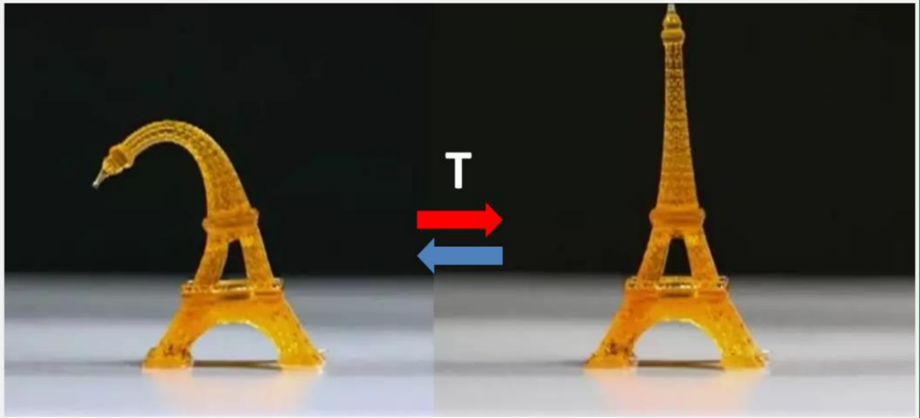
thermochromic polymer

damage → contact → self-healing



self-healing composite

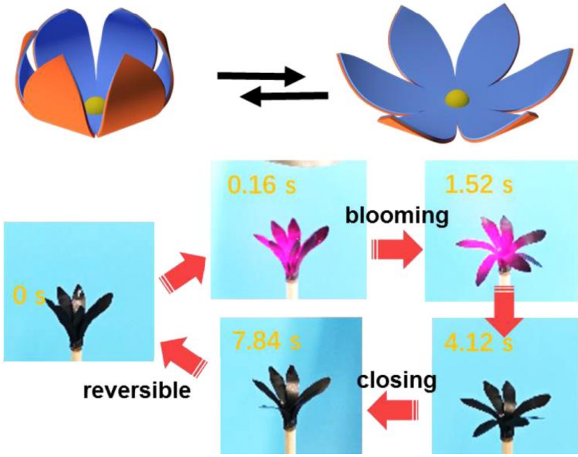
T → shape change



4D printed shape-memory polymer

Q. Ge *et al.* *Sci Rep.* 6 31110 (2016)

light (IR) → shape change



Y. Wang et al. *Nat. Commun.* 12, 1291 (2021)

STIMULI/RESPONSES IN SMART MATERIALS

EXTERNAL STIMULI:

- light (intensity or wavelength)
- temperature
- pressure, mechanical stress
- pH
- chemicals
- ionic force
- electric field
- magnetic field

…

RESPONSE (MODIFIED FUNCTIONS/PROPERTIES):

- shape
- volume
- mechanical properties (rigidity, viscosity,etc.)
- surface properties
- hydrophilicity/hydrophobicity
- color
- electric properties
- optical properties

…

Features of Smart Materials

Response to changes in the surrounding environment

Reversible response

Macroscopic response
depends on microscopic structure
Structure-property correlation

Speed of response to stimuli

Multifunctionality → Possible interaction of multiple stimuli

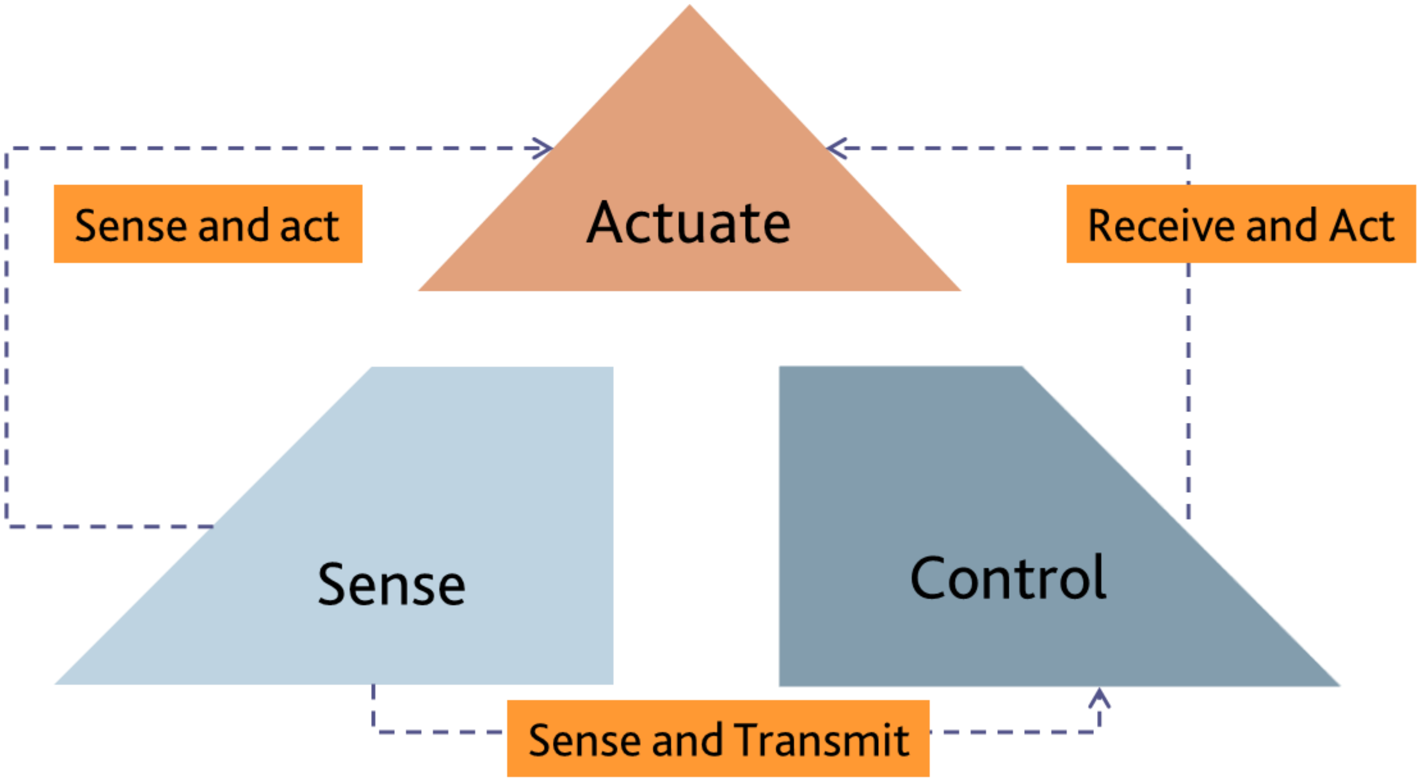
Technological Interest
e.g. simultaneous use for

Actuation

Sensing

68

COMBINATION OF FUNCTIONS IN SMART MATERIALS



INSPIRATION

TED talk David Gallo, oceanographer 2013 – available on YouTube

L1.4

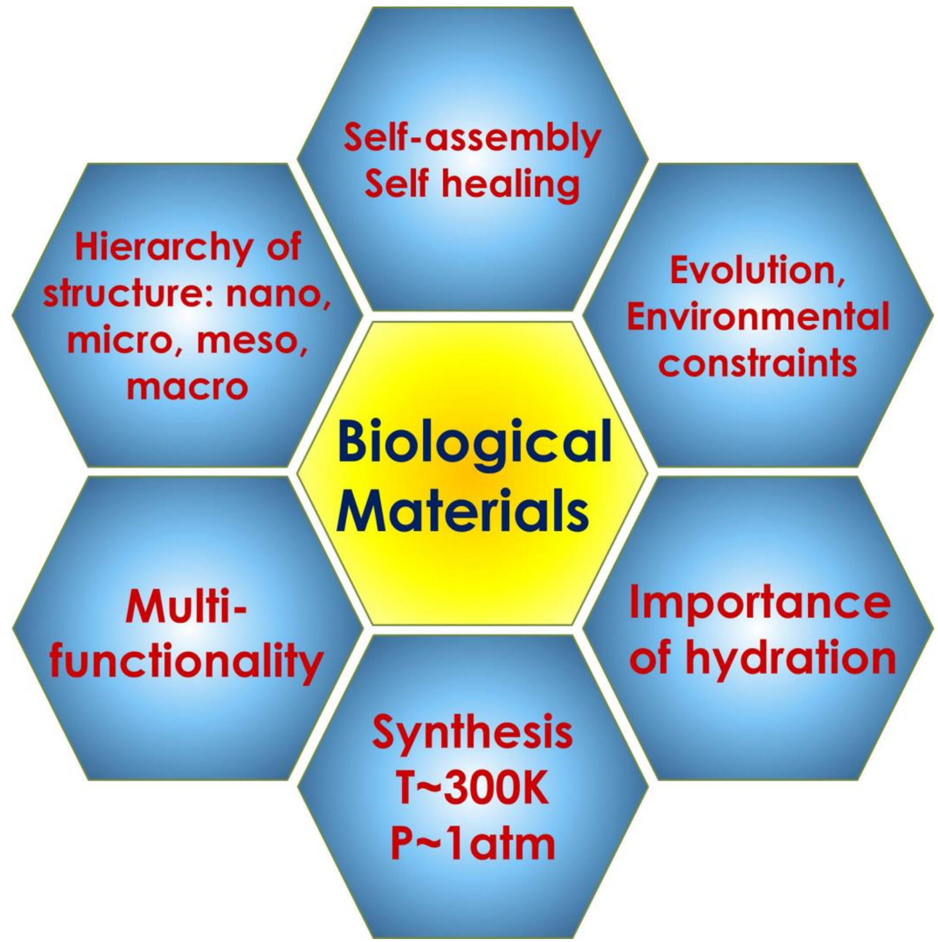
SHORT INTRO TO BIOLOGICAL MATERIALS

Biological and Bioinspired Materials

Distinguishing Features of Biological Materials

- **Hierarchical structure**
- **Multi-functionality**
- **Self-assembly/self-organization**
- **Synthesis under mild conditions**
- **Importance of hydration**

Hexahedron



Basic building blocks

Minerals

Calcium carbonate ($CaCO_3$)

Calcium phosphate

(hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$)

Silica (SiO_2)

Magnetite (Fe_3O_4)

Proteins

Collagen, keratin, elastin, resilin, abductin...

Polysaccharides

Chitin, chitosan, cellulose

DISTINGUISHING FEATURES OF BIOLOGICAL MATERIALS

Self-assembly: in contrast to many synthetic processes the structures are assembled from the **bottom up**, rather from the top down because of no availability of an overriding scaffold

Self-healing: synthetic materials undergo damage, failure in an irreversible manner; biological materials often have the capability to reverse the effects of damage by healing

Hierarchy: different organized scale levels (nano to macro-scale) that confer distinct and translatable properties form one level to the next

Hydration: the properties are highly dependent on the level of water in the structure

Functionality: multifunctional materials structures; many components serve more than one purpose

Examples:
Birds' feathers – flight, camouflage, thermal insulation
Bones – struct framework, growth red blood cells, protection to organs

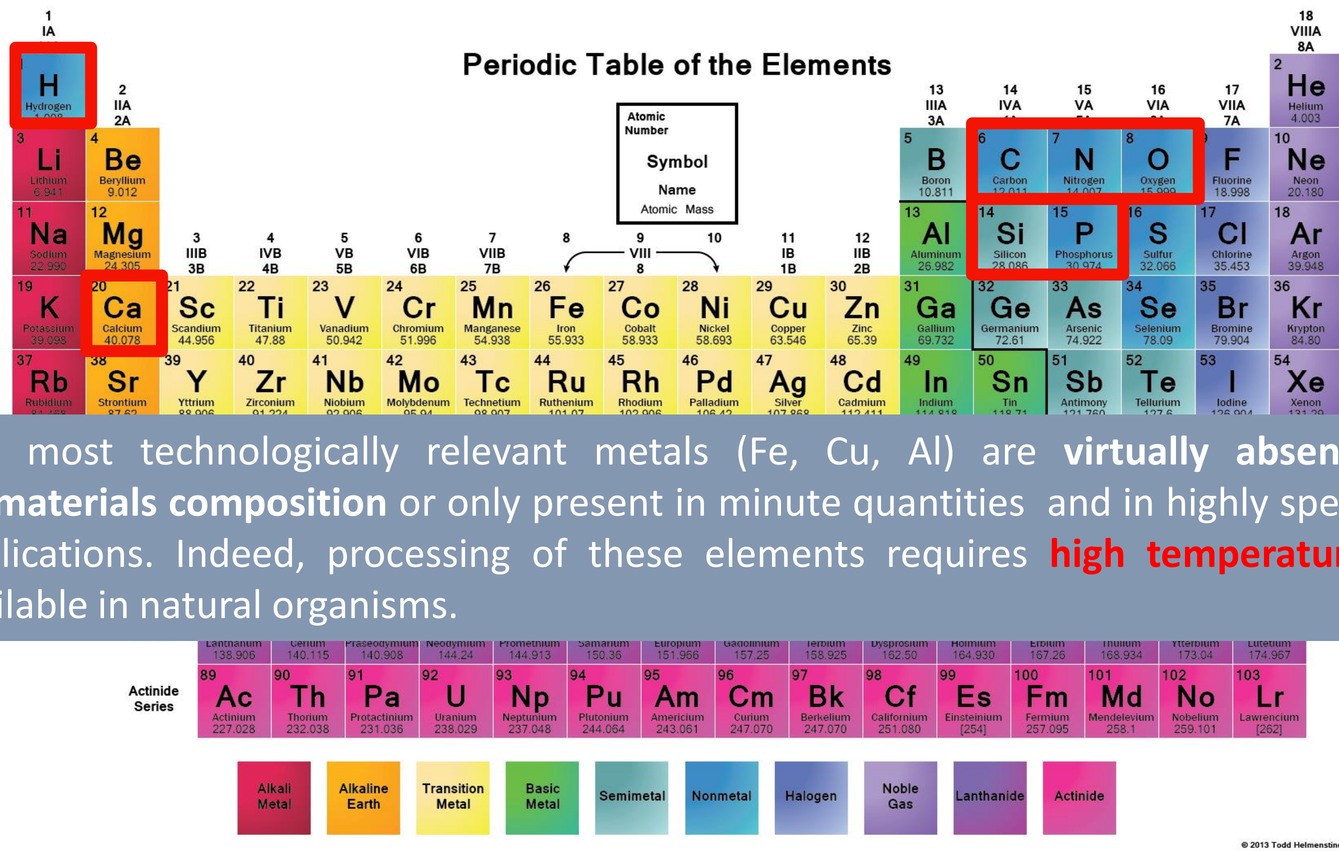
Mild synthesis conditions: the majority of biological materials are fabricated at ambient temperature and pressure and in an aqueous environment, a significant difference from synthetic materials

EVOLUTION AND ENVIRONMENTAL CONSTRAINTS

Few elements, myriads of materials and different properties

Evolution, environmental constraints, and the limited availability of materials dictate the morphology and properties

The principal elements available are very few: O, N, H, C, Ca, P, Si.



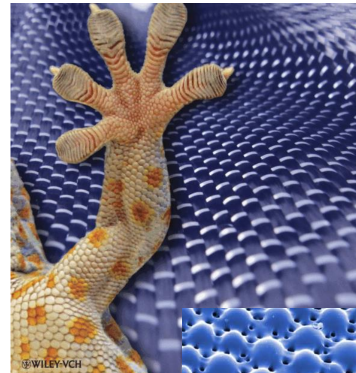
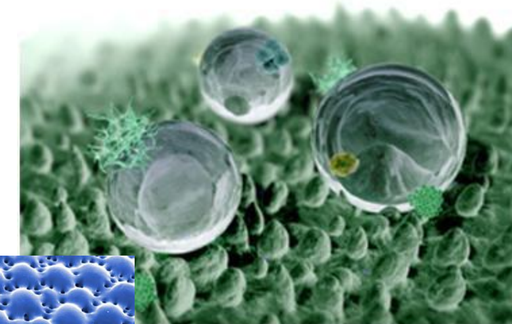
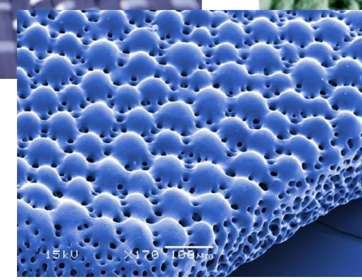
The most technologically relevant metals (Fe, Cu, Al) are **virtually absent from biomaterials composition** or only present in minute quantities and in highly specialized applications. Indeed, processing of these elements requires **high temperatures** not available in natural organisms.

EVOLUTION AND ENVIRONMENTAL CONSTRAINTS

Constraints: Not a weakness!

Despite these constraints

biological systems may have mechanical and functional properties far beyond those of synthetic materials!

Surprising fact:
basic polymers and minerals used in natural systems are intrinsically quite **weak**

BUT

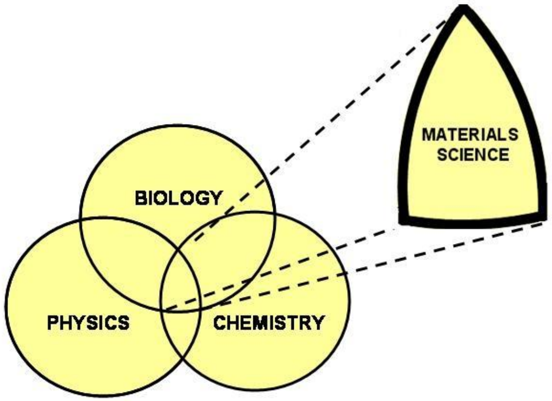
Biological organisms produce **composites**:

- organized in terms of composition and structure,
- containing **both inorganic and organic components**
- **complex hierarchical structures** (nano, micro, and meso levels).

Biological Materials Science

Study of biological materials and systems by materials scientists and engineers is recent!

New opportunities for materials scientists to solve complex multidisciplinary scientific problems



NOMENCLATURE

BIOLOGICAL MATERIALS: materials and systems encountered in nature.

BIOINSPIRED (OR BIOMIMICKED) MATERIALS: approaches to synthesizing materials inspired by biological systems

BIOMATERIALS: materials (e.g. Implants) specifically designed for optimum compatibility with biological systems

FUNCTIONAL BIOMATERIALS AND DEVICES

BIOLOGICAL MATERIALS SCIENCE

Study of biological materials and systems is intended:

1. to provide the tools for the development of biologically inspired materials.

BIOMIMETICS

2. to enhance our understanding of the interaction of synthetic materials and biological structures with the goal of enabling the introduction of new and complex systems in the human body, organ repairing, supplementation and substitution

BIOMATERIALS

SUMMARY L1

L1.1 • Intro, general info on the course and exam

L1.2 • Evolution of materials science & engineering

• Today and future?

• Novel approaches (and needs) in materials science

L1.3 • Smart materials

L1.4 • Bioinspiration and Biomimetics

• Biological Materials Science

Additional Resources, Readings

- going more in depth on some topics, for interested students

Additional Reference Books

- ***Handbook of Nanotechnology**,* B. Bushan, Springer 2017, ISBN 978-3-662-54357-3. Available online at: DOI: 10.1007/978-3-662-54357-3
- ***Stimuli-Responsive Materials: From Molecules to Nature Mimicking Materials Design**,* W. Urban, RCS 2016, ISBN: 978-1-84973-656-5.
- ***Organic Bionics**,* G. G. Wallace, S. E. Moulton, R. M.I. Kapsa, M. Higgins, Wiley 2012, ISBN: 978-3-527-32882-6.