

4D printing and Bio-printing: the “mass” is not yet over!

By J.C. André

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3D printing was first patented in Nancy in 1984 by adding voxel after voxel elements to a structure under construction. By modifying the environment, it is possible to modify the shape of the objects created in one or more potential fields. This defines the basic idea of 4D printing and Bio-printing, which is, to put it simply, 4D of living things. The conference will concern what these emerging technologies represent. It will show their current limits with some ways to break scientific barriers (complexity), teleology, epistemology and flexible organization in a context where results must be obtained as quickly as possible. We are at the end of “simple” ideas, like for 3D printing in 1984.

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J.C. André DR CNRS LRGP and INSIS

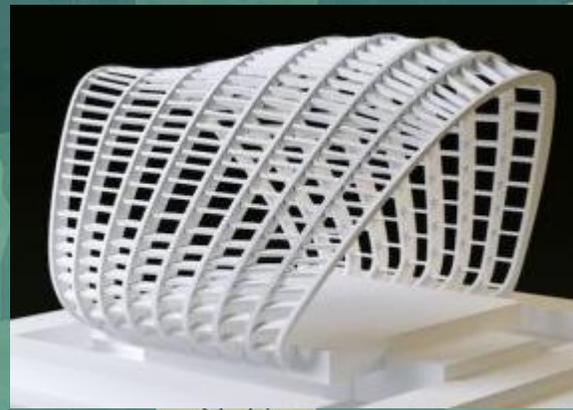
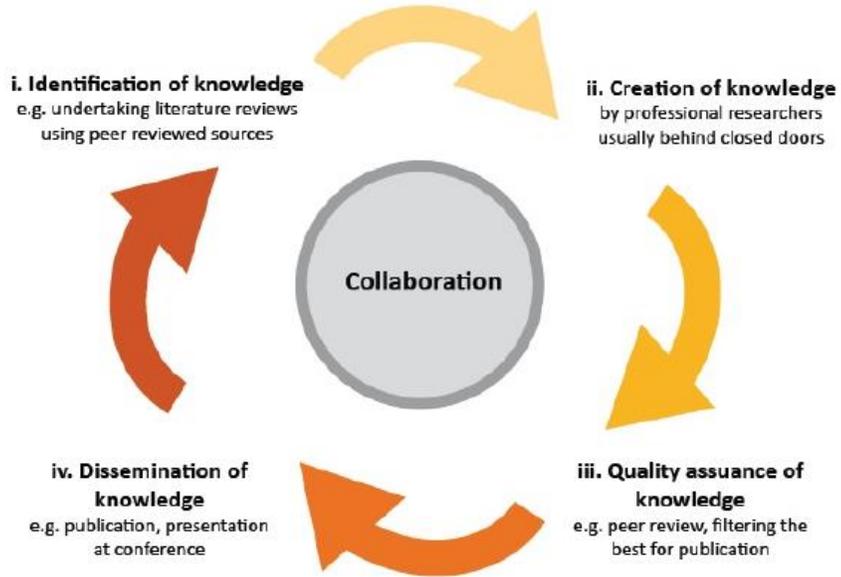


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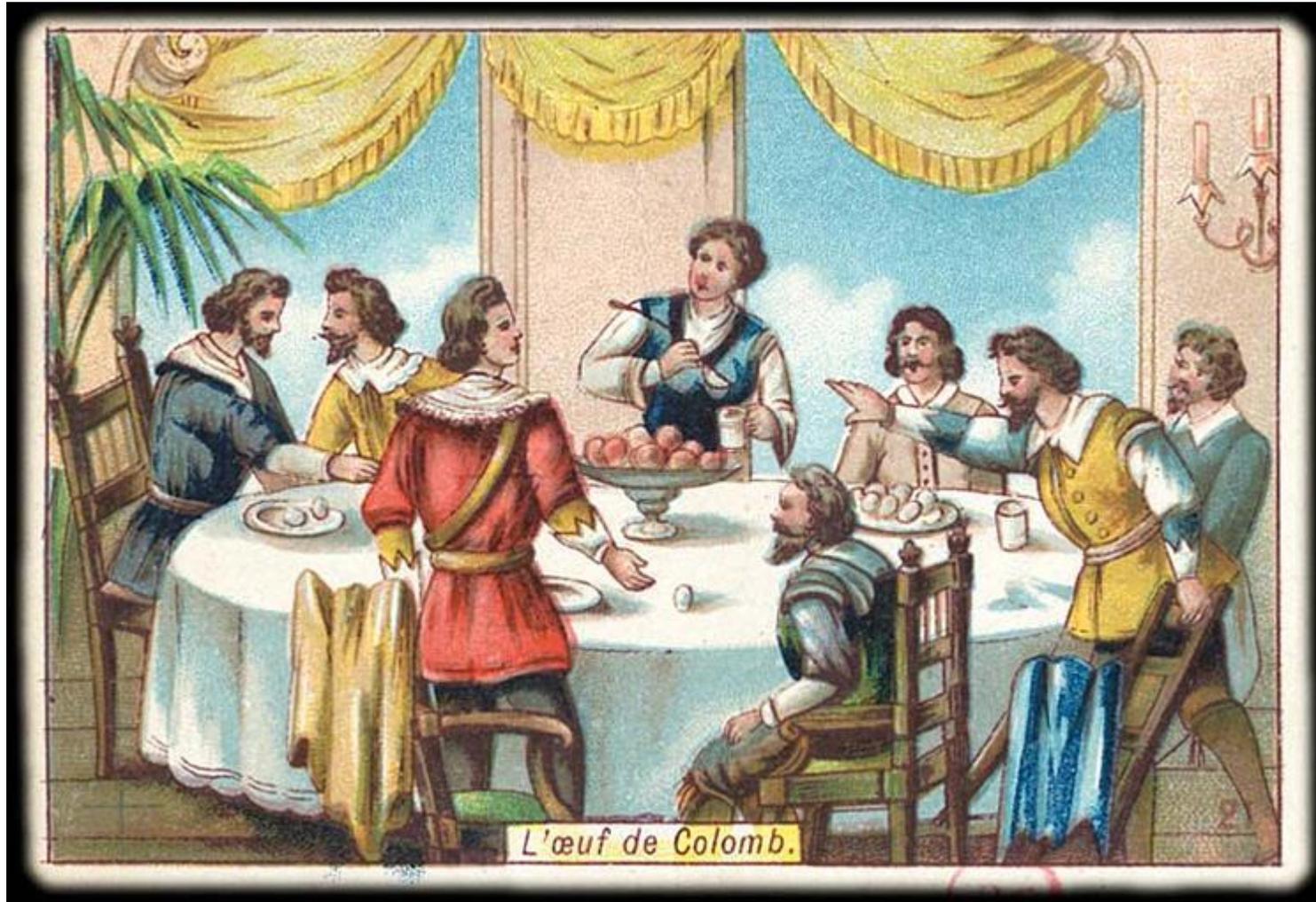
WARNING

The academic research cycle



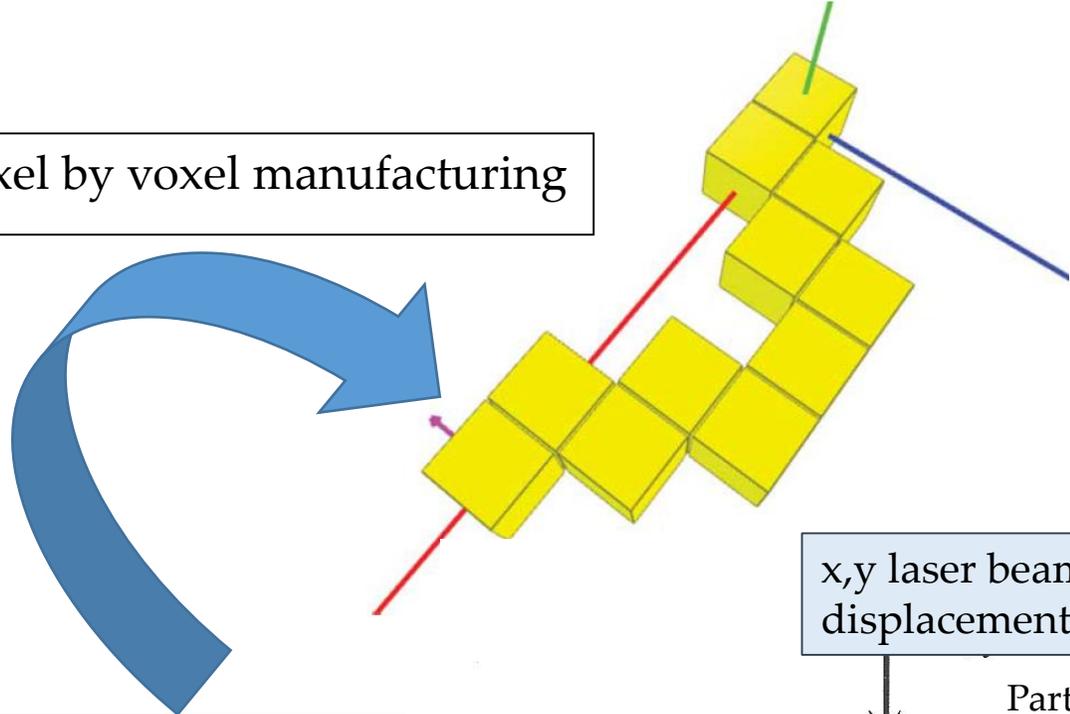
« *How To Make (Almost) Anything* »

1984 – 3D or the Columbus Egg?



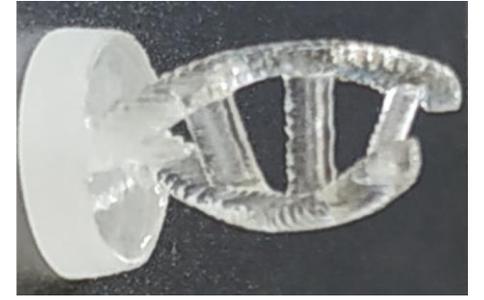
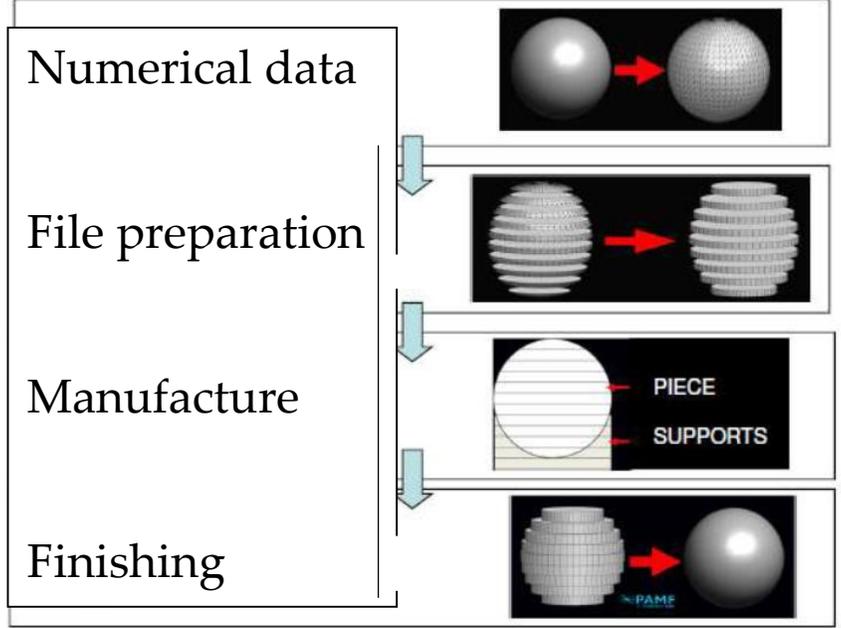
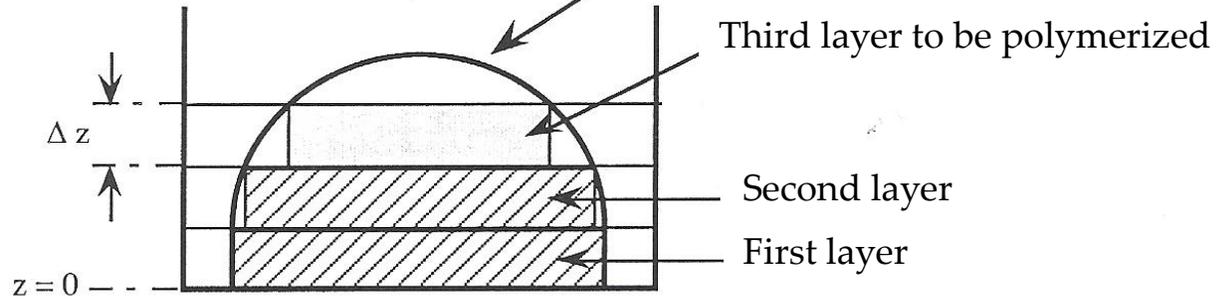
Basic idea

Voxel by voxel manufacturing



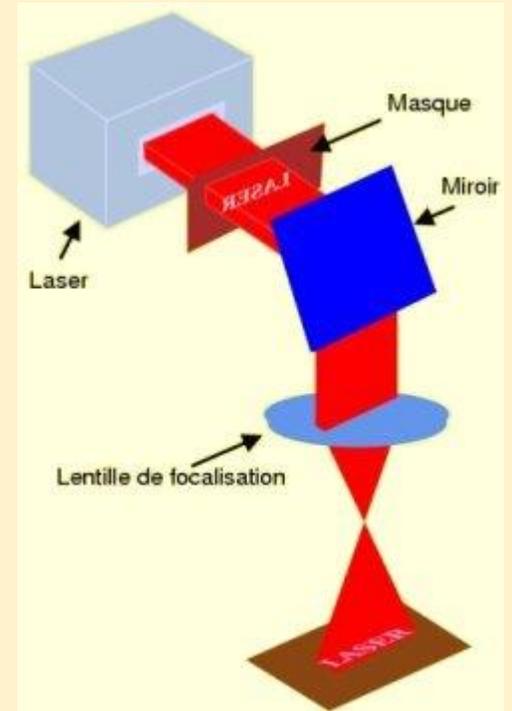
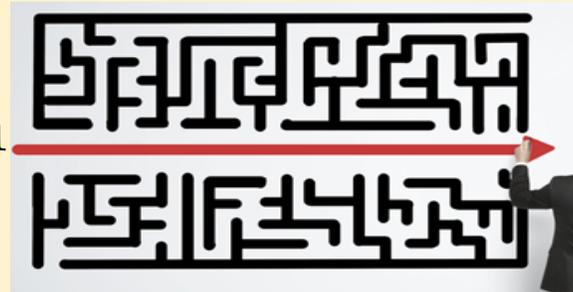
x,y laser beam displacement

Part to be manufactured



Existing elements (1984)

- Photo - polymers
- Chain Reaction Amplification
- Lasers
- CAD
- Numerical monitoring
- Galvanometric mirrors
- Dynamic masks
- Etc.



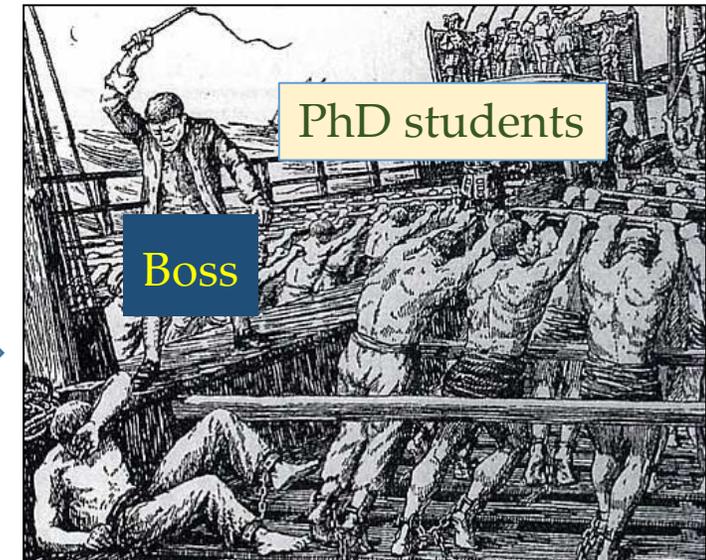
But, Hell is always in the detail...

- Supports,
- Volume shrinkage,
 - Viscosity,
 - Young modulus,
 - Deformations,
- Time of manufacture
 - Resolution
 - Etc.

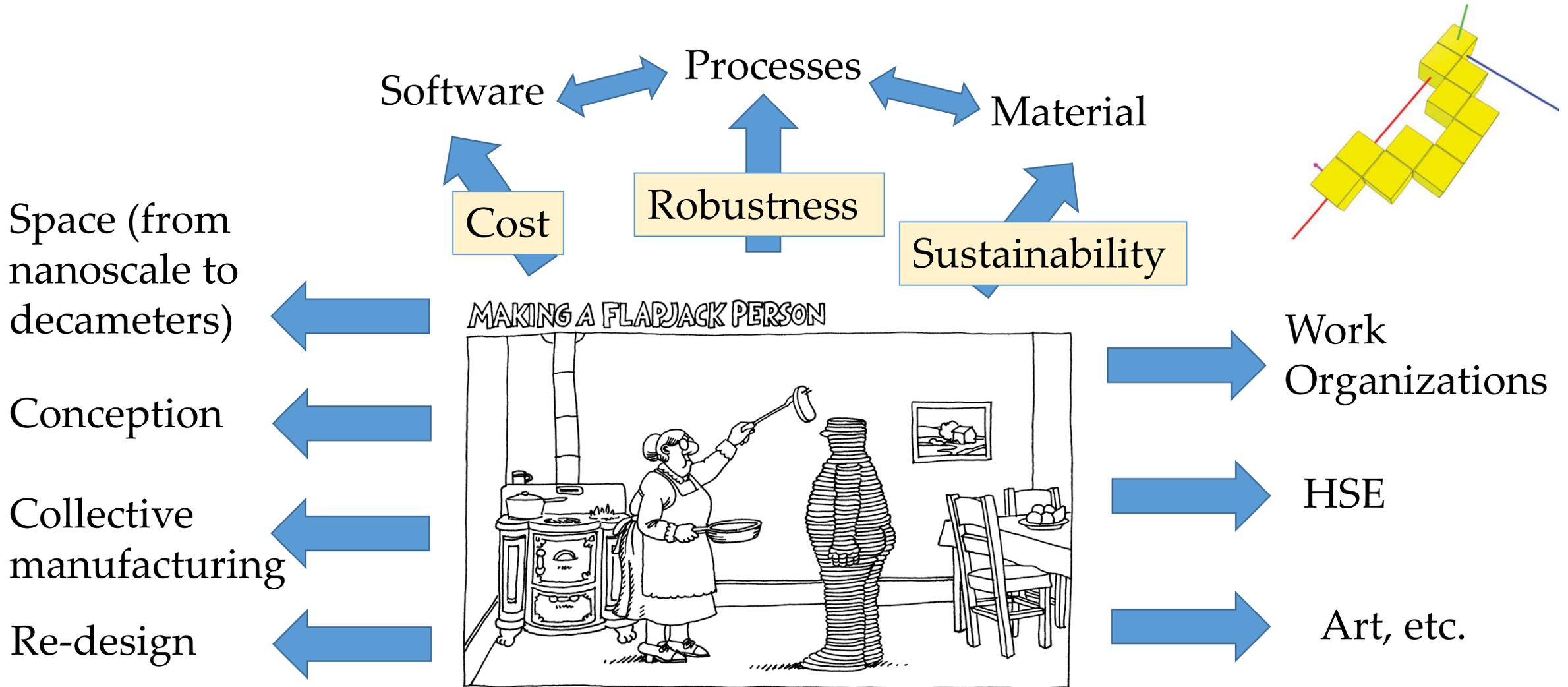


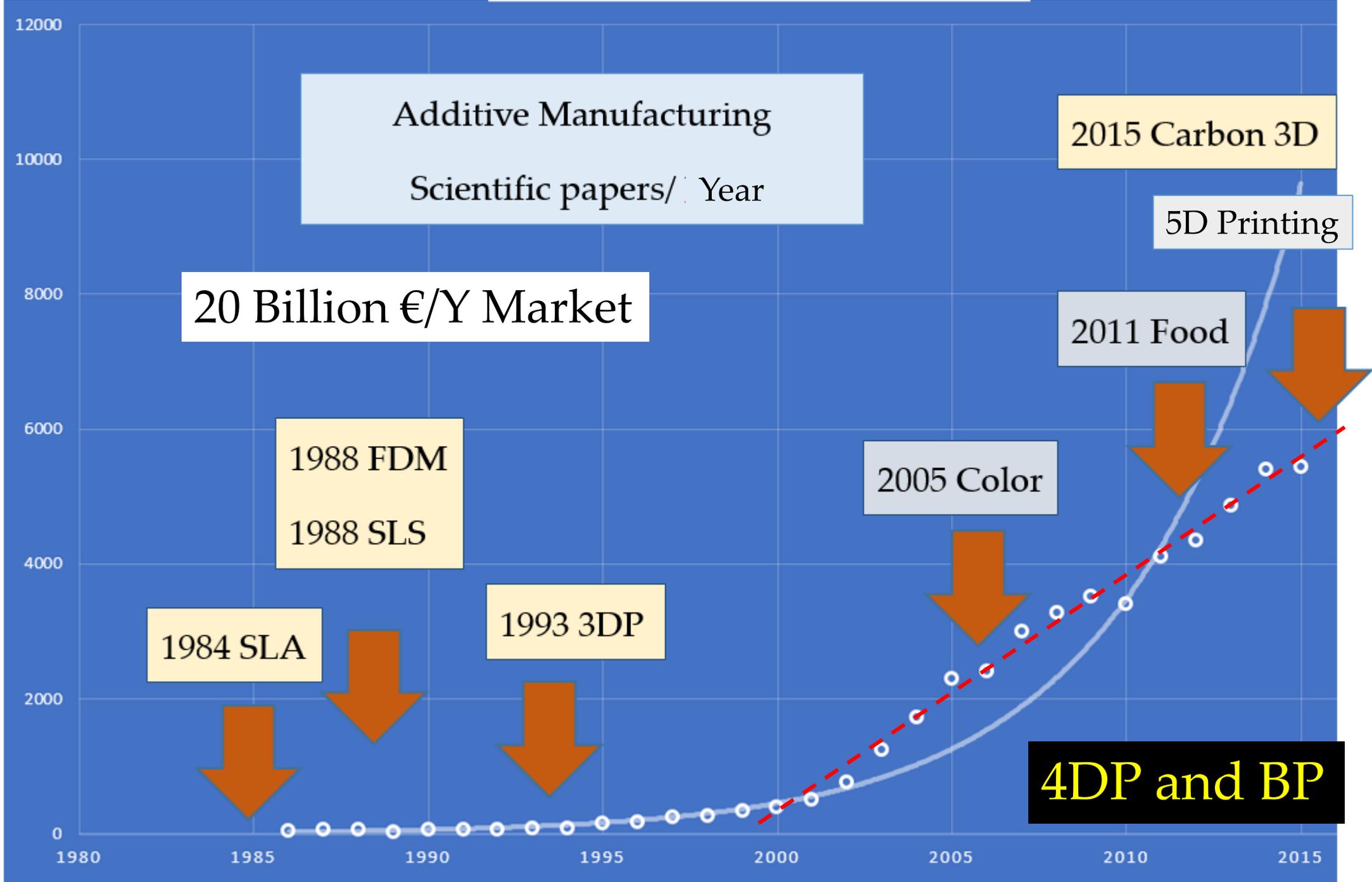
CNRS Hell?

RESULT



« Classical » 3D-Printing & incremental Innovation



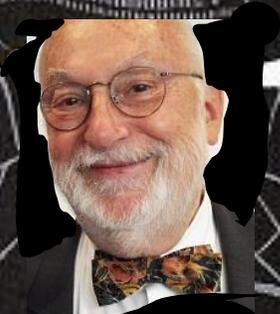




3DP



Now: From self-organization to 4D (Bio)-
Printing - A plea to go beyond exciting proof of
concept



Digital Manufacturing: From a « simple » electronic
avatar to all the possible living 3D copies?

“Technology is exponential, humans are linear”; “Data is the new oil”; “Artificial intelligence is the new electricity”; “Internet of Things is the new nervous system” (Gerd Leonhard, 2018 - <https://www.youtube.com/watch?v=ystdF6jN7hc>)

“Humanity will change more in 20 years than the last 3 centuries” ...

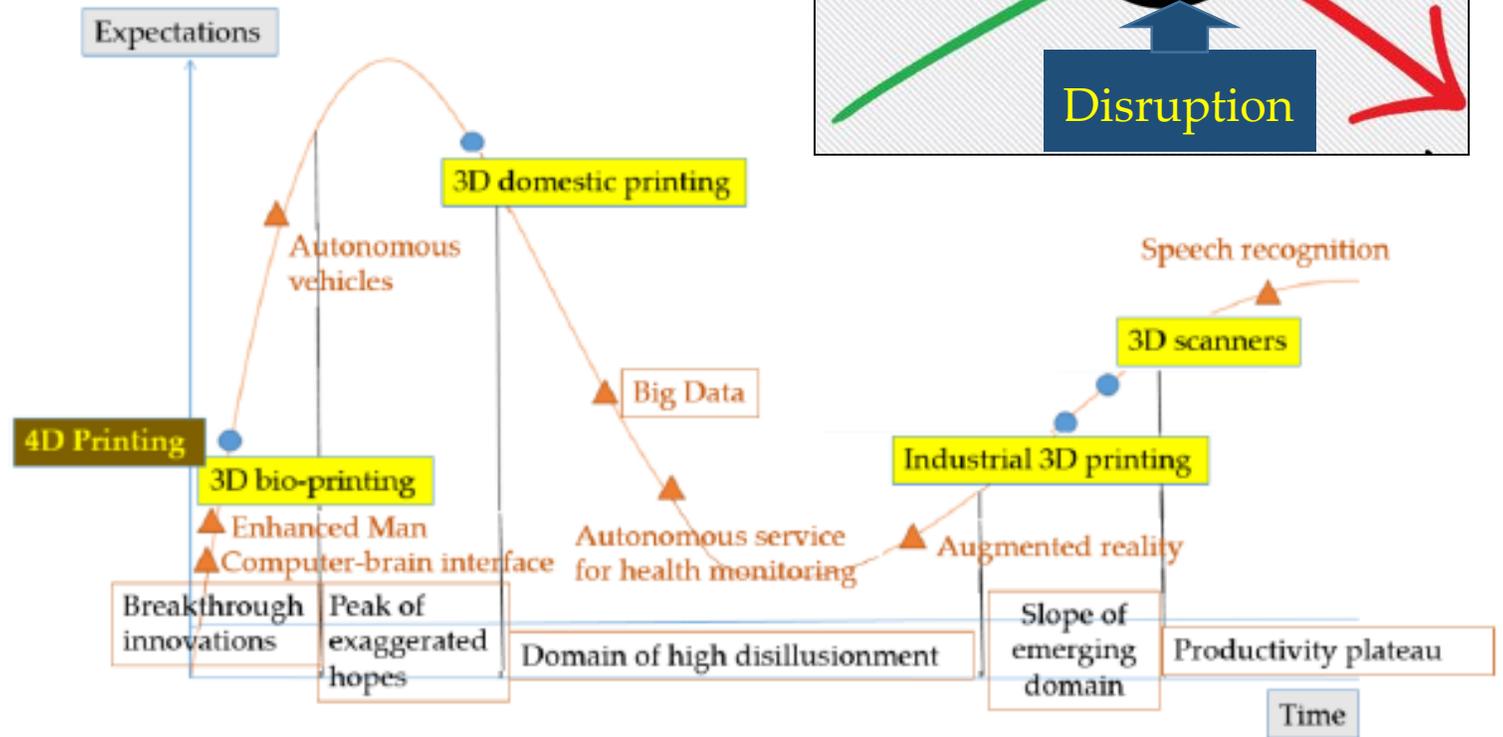
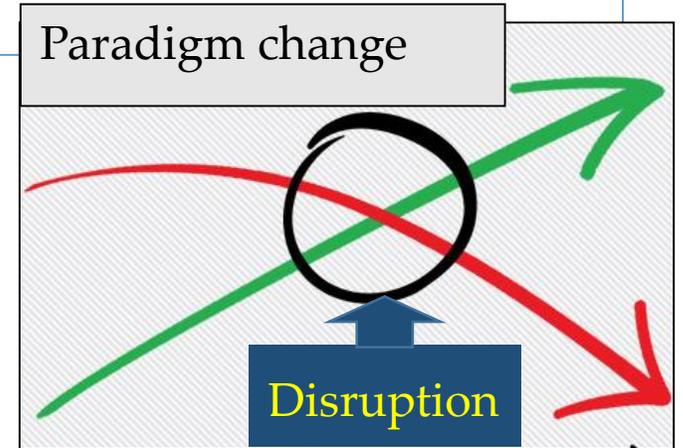
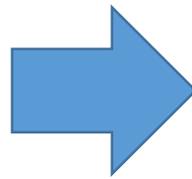
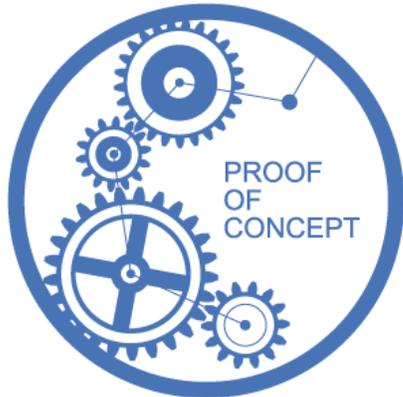
“The end of the linear thinking” ... Towards combinatorial... towards CONVERGENCE...

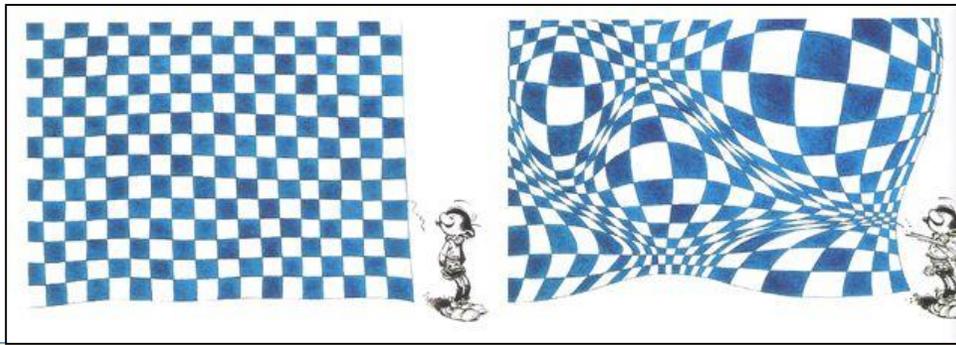
Etc.



Breakdown Domain; possibles futures

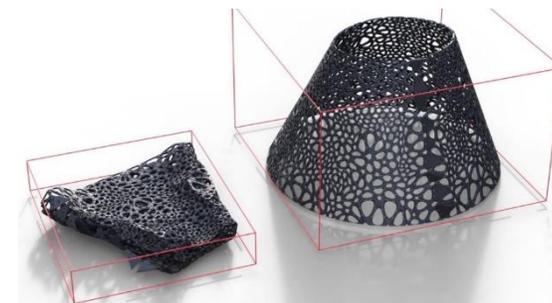
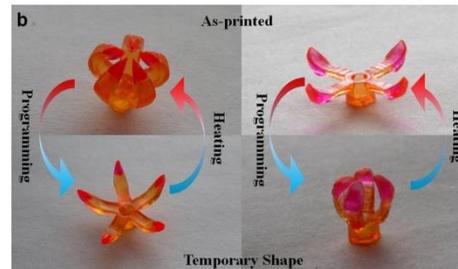
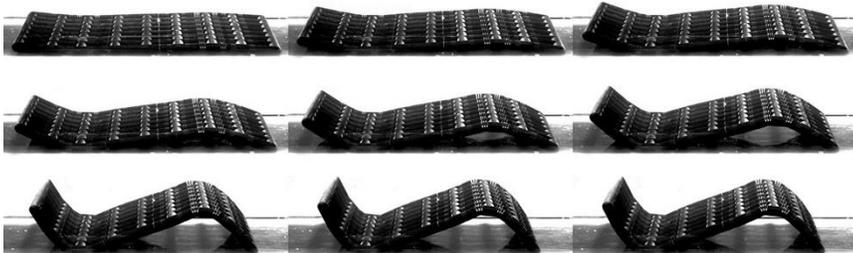
- Self – organization (SO)
- 4D Printing (4D)
- Bio-printing (4D+SO)

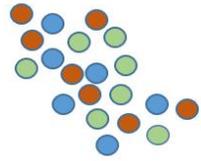
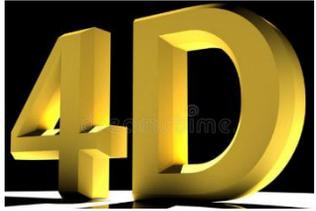




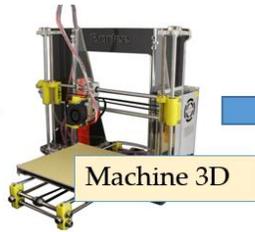
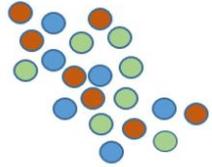
4D printing (4DP) from additive manufacturing processes attacks :

- The realization of objects by 3D printing and whose form and/or functionality can evolve according to time or external requests or stimulus;
- The assembly of objects or materials, which assemble by themselves, by the properties of the matter which composes them or "programmable matter". Programmable materials that "build themselves" would make assembly plants and heavy installation procedures superfluous. Robotization, the heart of productivity gains in the 20/21th century, could thus be integrated into the products themselves.





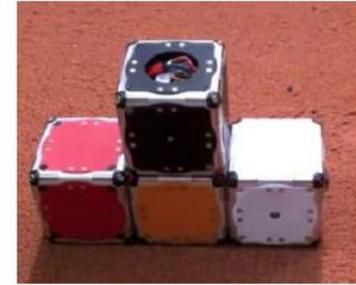
Mobile



Inerte



Mobile



<http://www.elishean.fr/retour-sur-la-matiere-programmable/>

Paul Valéry: “Master [...] get up at night to write your ideas in a little notebook?” ...

Albert Einstein: “Ideas? We have two or three in life” ...

Les devises Shadok



It is better to pump even if nothing happens than to risk that something worse happens by not pumping



I have an idea!

Disruptive thinking

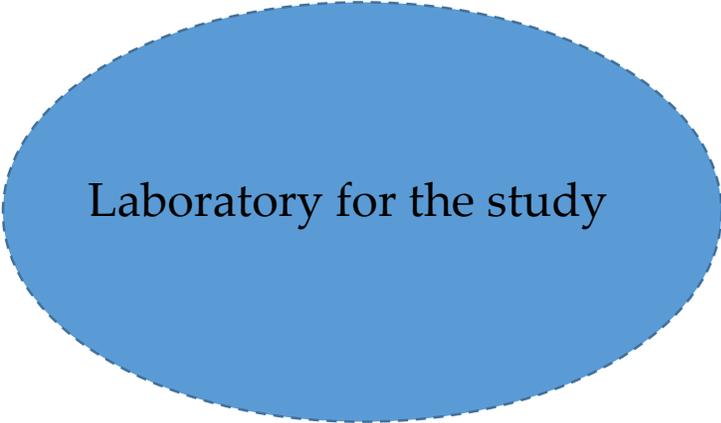
Naissance
d'un paradigme

System elements

How a paradigm
can emerge



Perturbation of the system



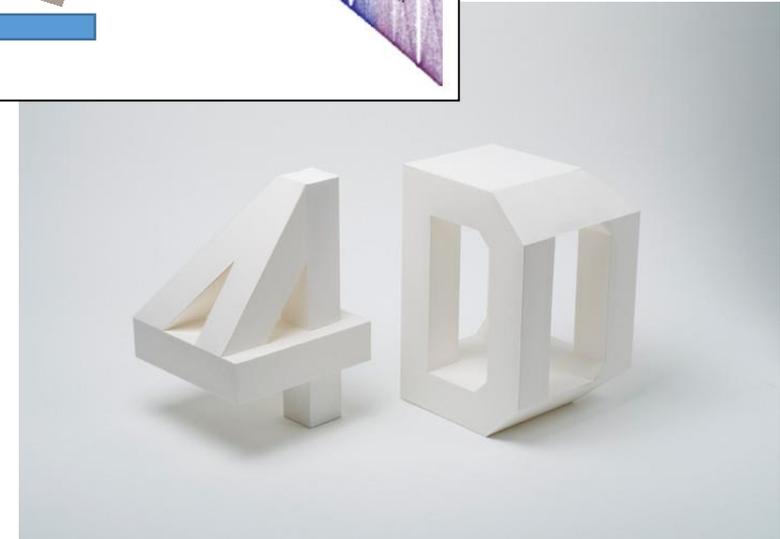
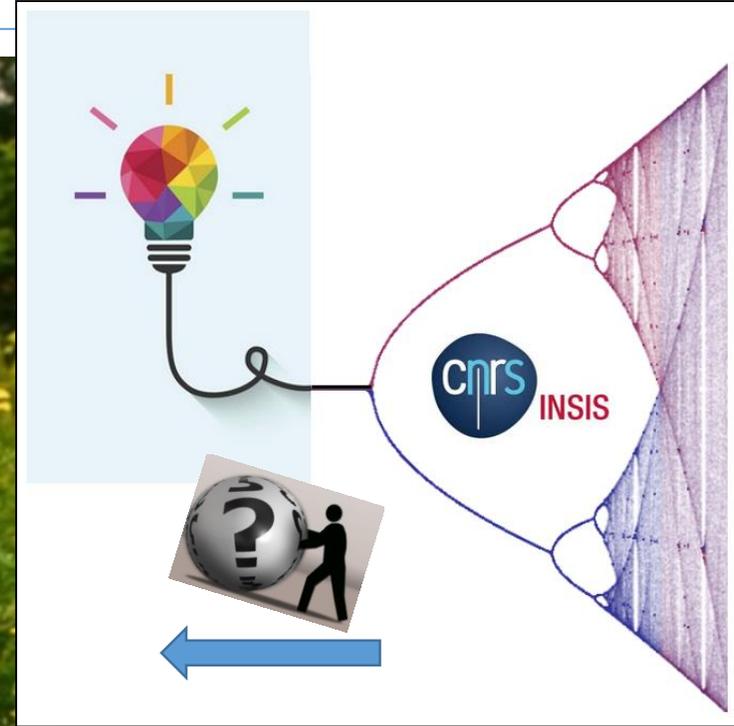
Output

Numerical Model (Relationship between
causes and consequences)

I- Exploration of the field of possibilities



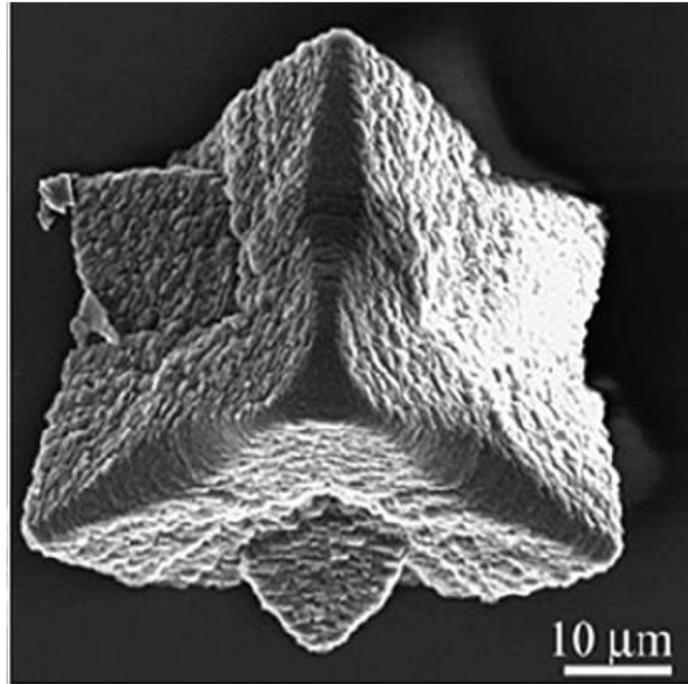
You are where everything (or more) is still possible...



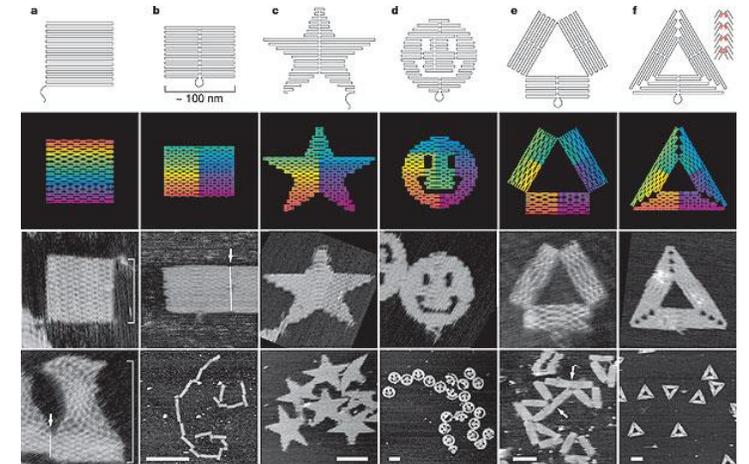
Programmable matter or informed matter



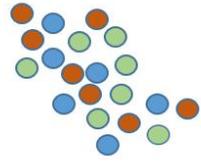
Leduc Osmotic Productions (1910)
Self-organization



CdS nano-Octopods (Mytza *et al*, 2011)

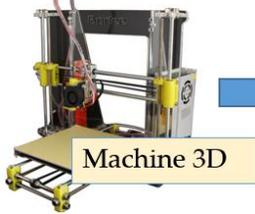
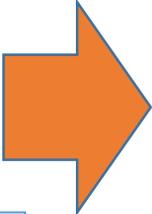


ADN Origamis (Rothemund,
2006)



Mobile

(a) Stimulated self-organization leading to a 3D part (1 step)

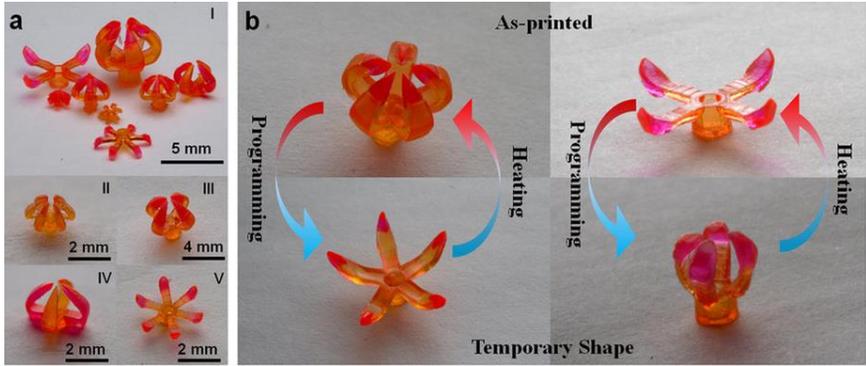


Inerte



Mobile

(b) Sequential production using informed matter (2 steps)



<http://www.elishean.fr/retour-sur-la-matiere-programmable/>

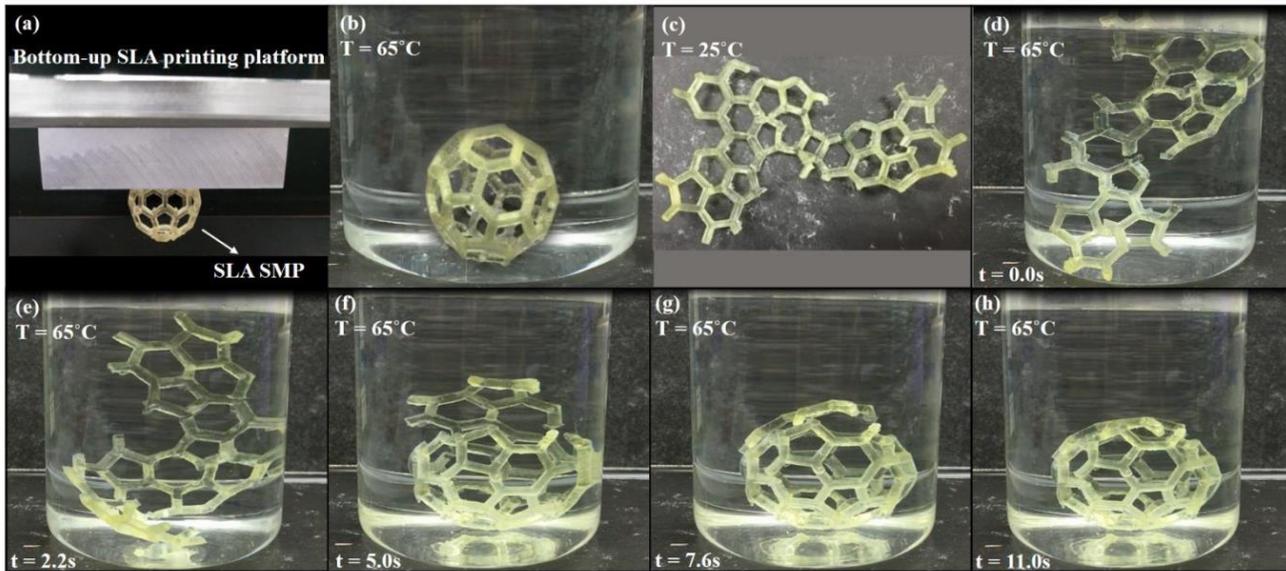
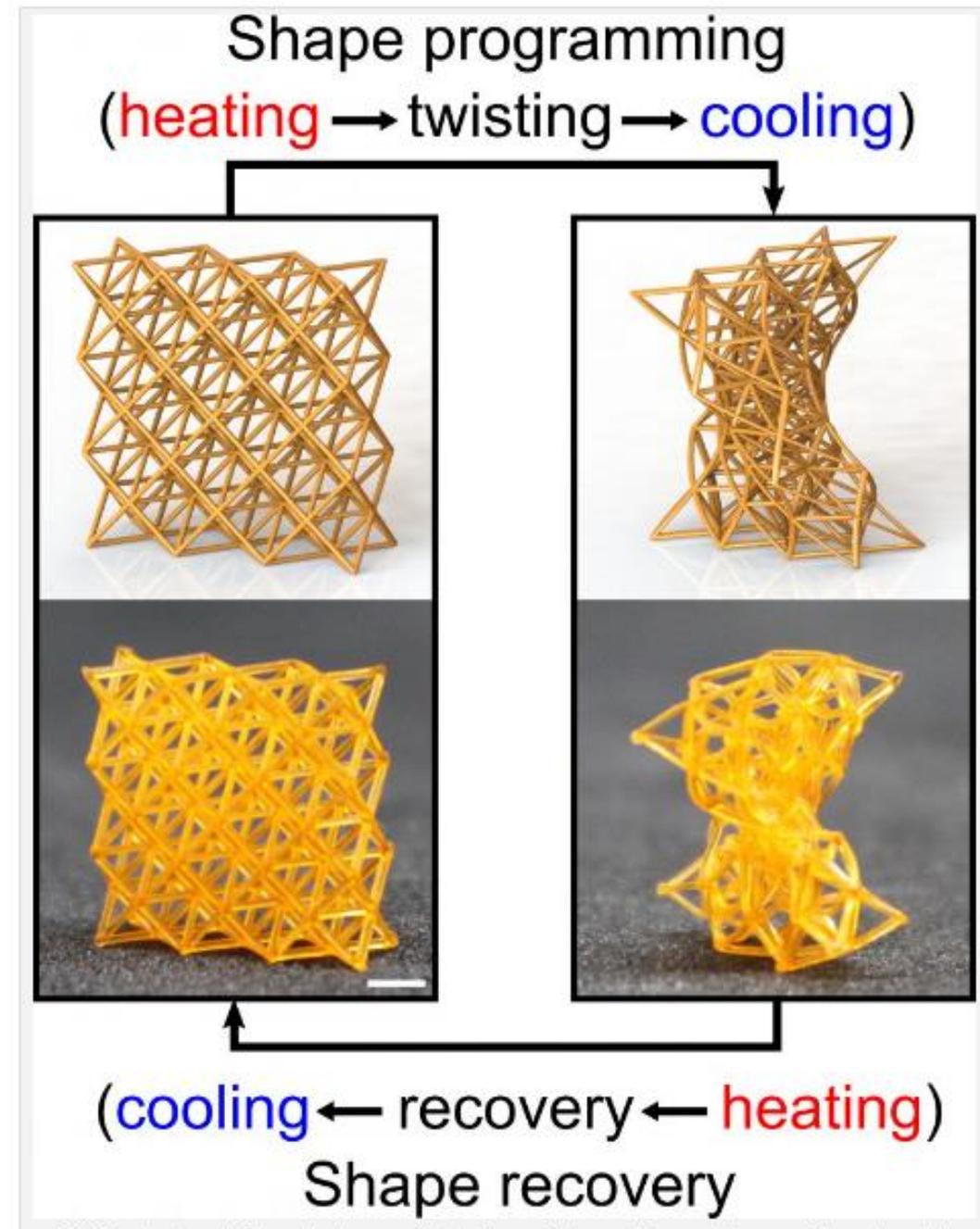
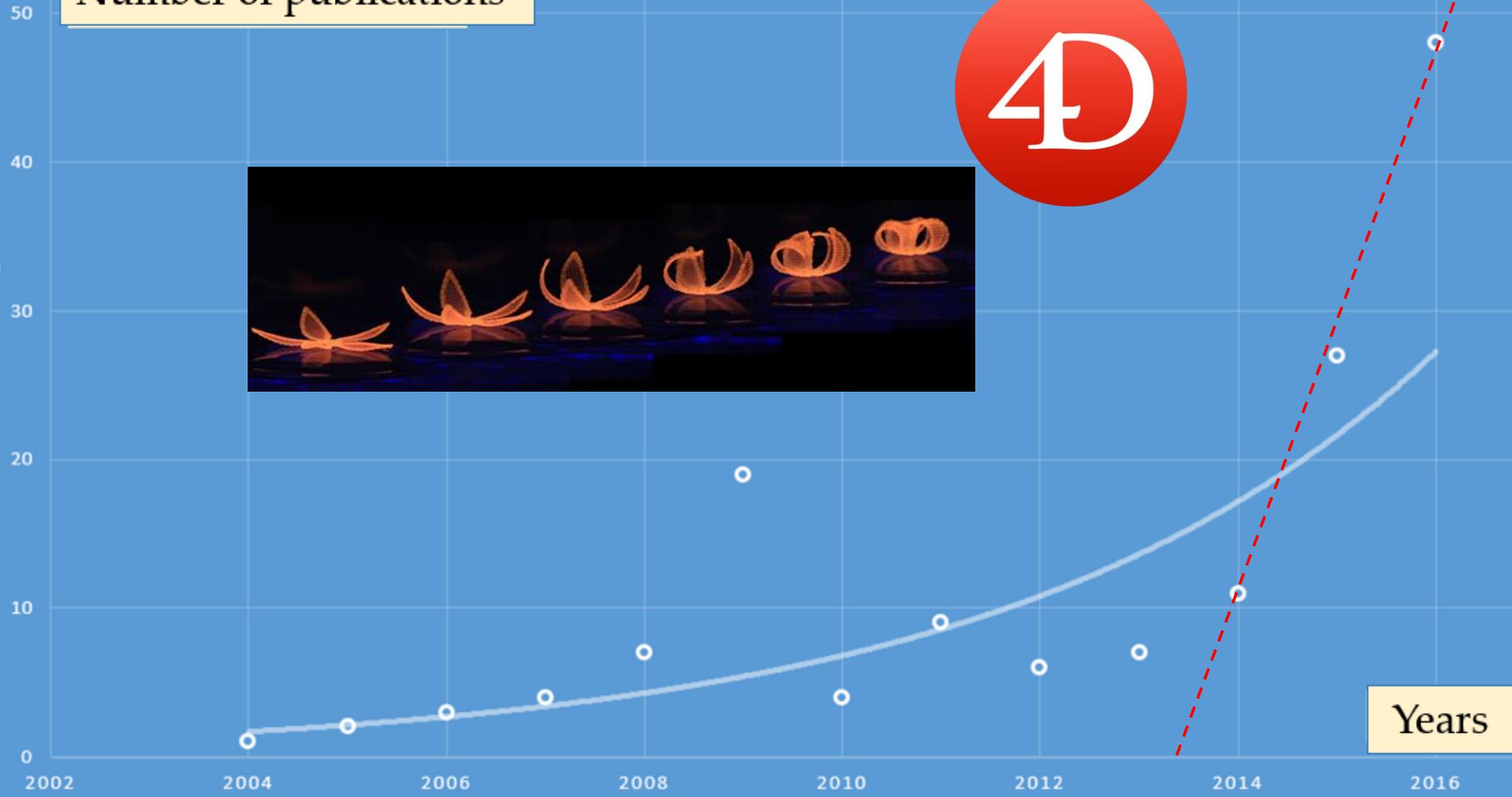


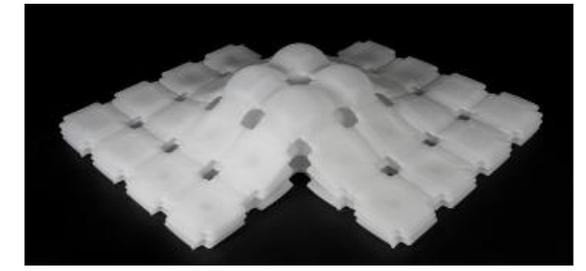
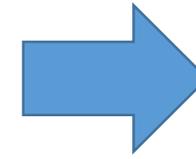
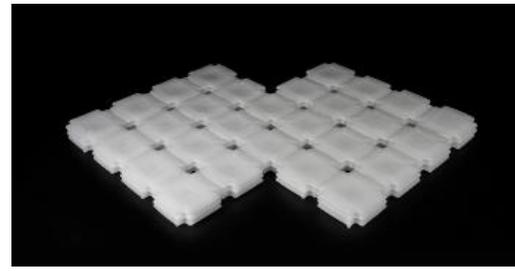
Figure 10. SLA SMP Buckminsterfullerene (or C60 bucky-ball) in printing (Figure 10a), unfolded after printing (Figure 10 b-c), and recovered its original bucky-ball shape by soaking at 65°C of water (Figure 10 c-h).



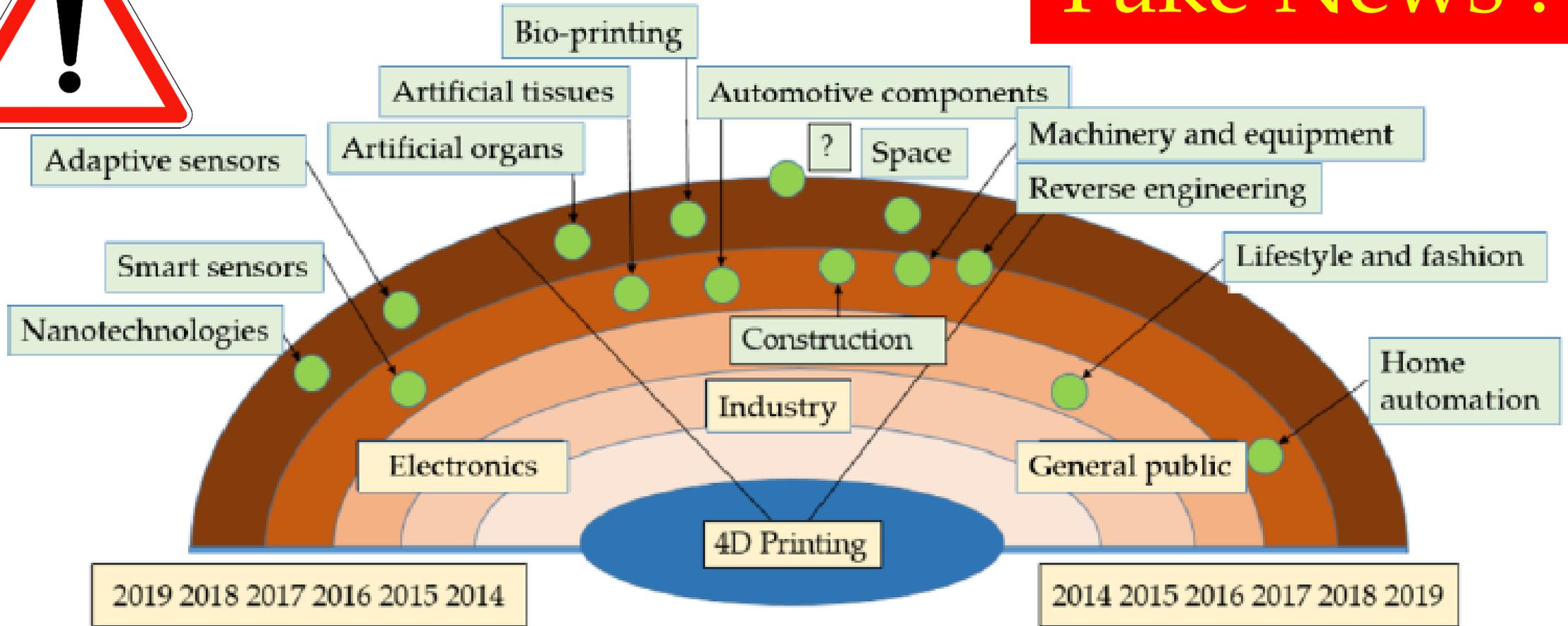
Number of publications



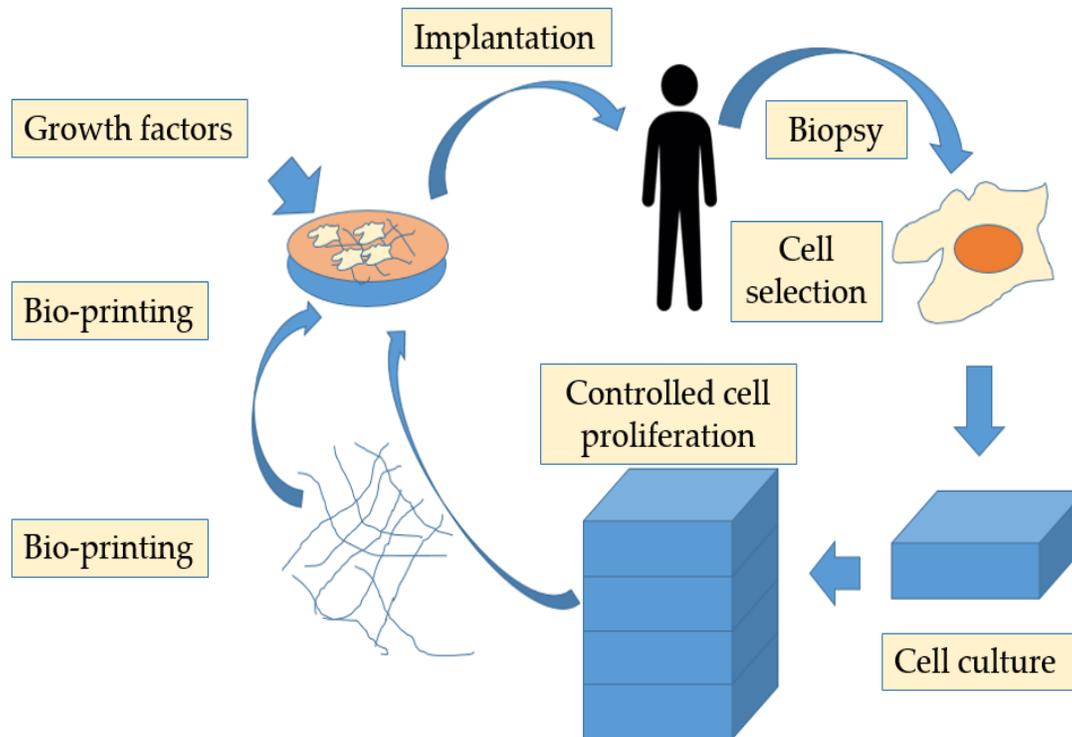
Years



Fake News !

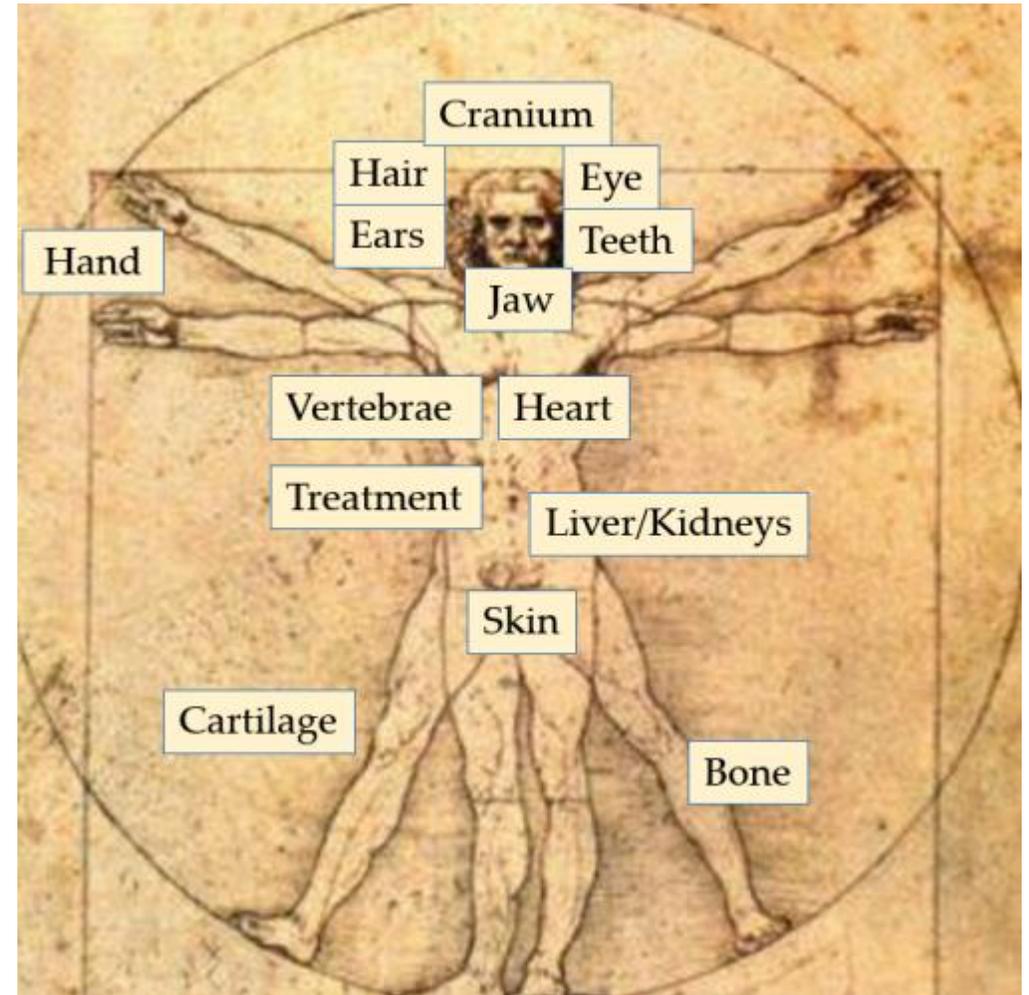


Bio-printing... 4D printing applied to the living



A humorous vision of bio-printing (TEDx Talks, 2014).

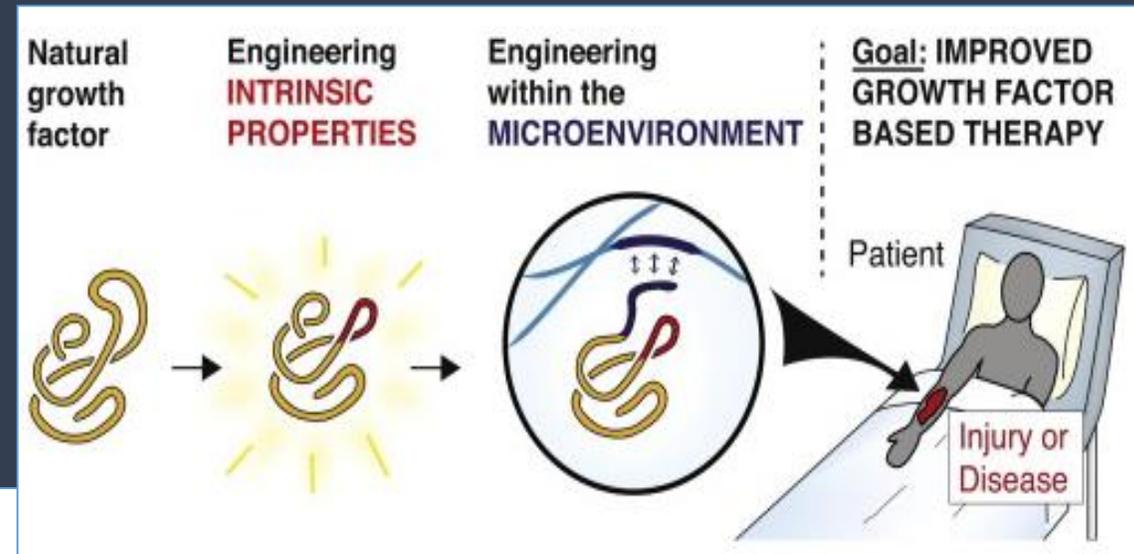
Bio-printing (BP) can be defined as the simultaneous positioning of biomaterials and living cells in a prescribed layer-by-layer stacking organization to fabricate engineered tissues and organs.



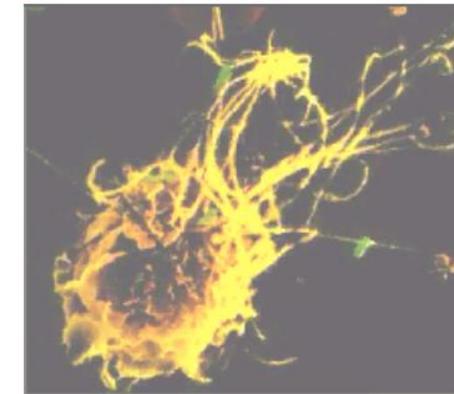
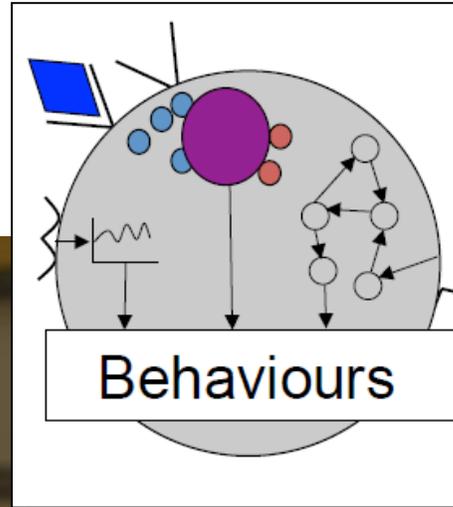
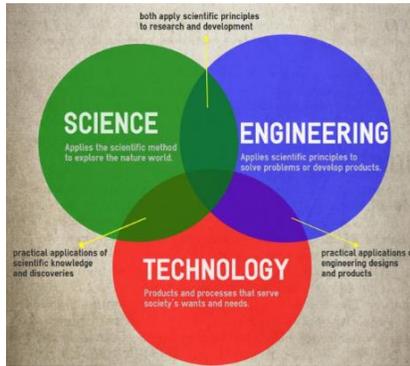
Need to "repair" the living being (injuries, illnesses, ageing)...

- Nano-medicine
- Prosthesis (smart or not)
- Exoskeleton
- Regenerative medicine
- Stem-cells
- Bio-Printing

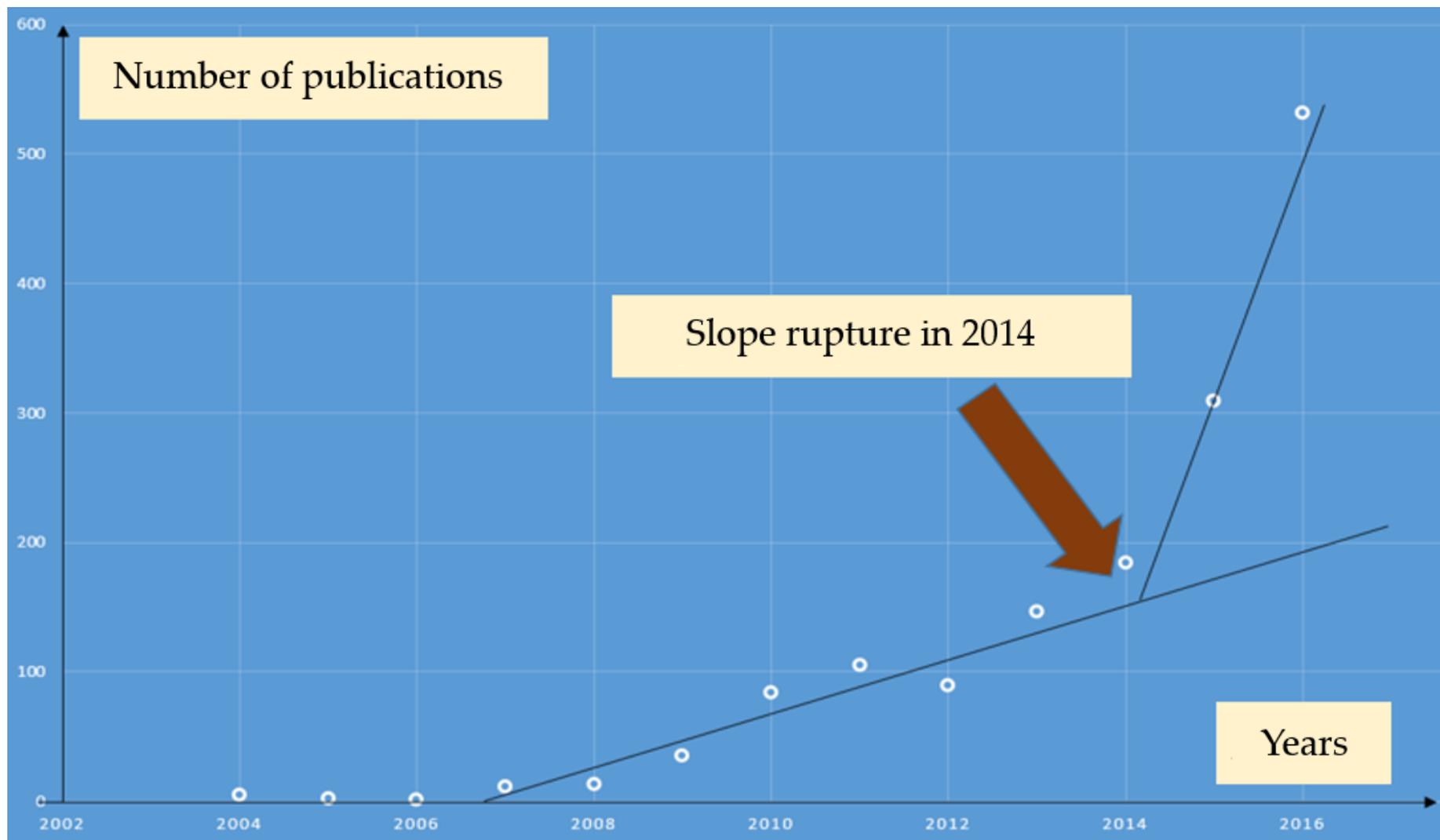
Market >> 100 B€/Y



The Bio-printing deterministic vision... How to master cells (and tissues) manufacturing for applications...



Cell



And later, may be

Tele-transportation



Death to death



4D soft sexual robots...



To conclude on the current “possible”: material - process coupling

- Informed matter (i.e. DNA, nano-materials)
- Intramolecular active materials, shape memory, etc.
- Multi-materials (ex. Bilame)
- Micro-robotics; bio-bots
- Swimming robots
- Bio-printing
- Sequential/Simultaneous production
- Reversibility or not...



Strong and may be some “negotiable” constraints

Les devises Shadok



FAKE NEWS

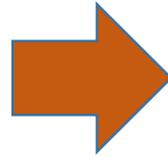
Can we trust our first impression, a desire to believe?



Optimization under constraints is the best that science has found to solve complex problems that humans alone cannot solve (Hervet C.).

Common sense is the best shared thing in the world, so is also bullshit!

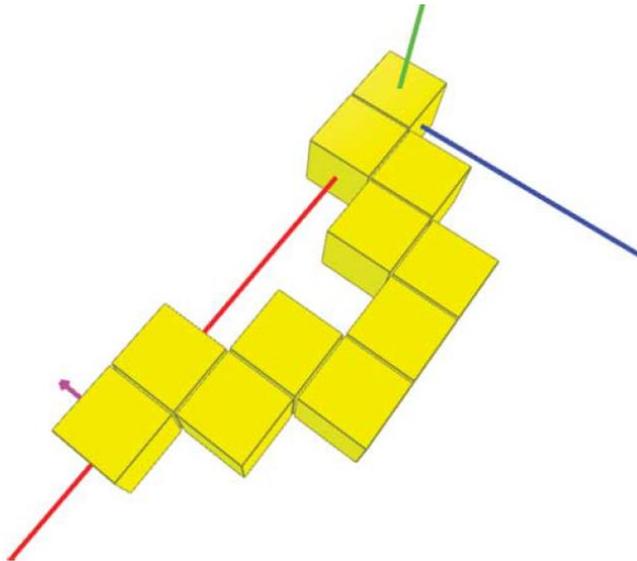
Programmable matter or informed matter



- Idea validated at the nano-scale (DNA)
- Number of chemical links to set up cube size
- Difficulty of introducing a rigorous determinism for larger scales leading to approximate forms
- Basic research in progress

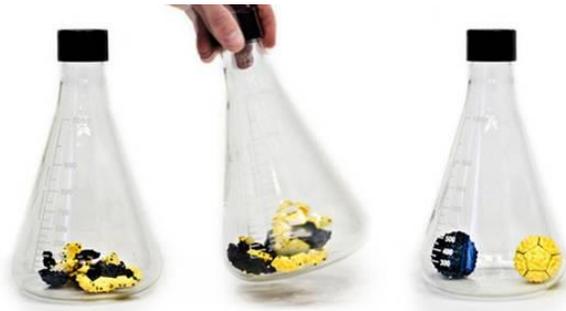


Voxels and time of realization of a 4D part



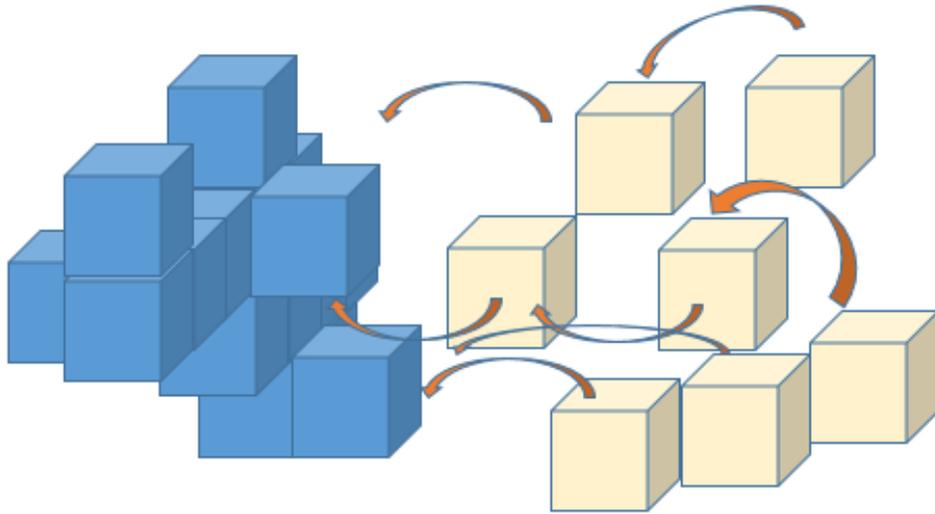
If the size of the voxel element is 1 cm, the realization of an object of 1 dm³ requires 1000 voxels, a time of $1000 \cdot \Delta T$ (ΔT being the average time of implementation, for example 1 second), then 15 minutes. For 1 mm, it would be 10 days and 0.1 mm 30 years ...

Need a collective approach

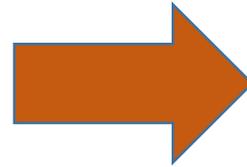


MIT Proof of concept : order from disorder...

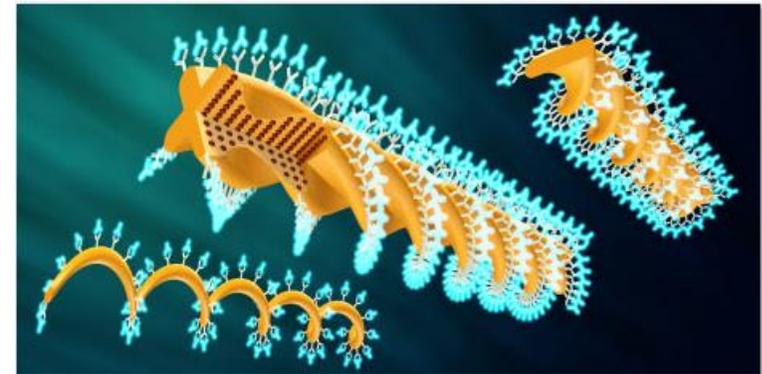
Associated questions



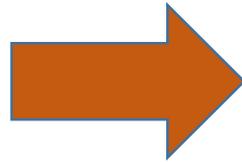
Collective approach



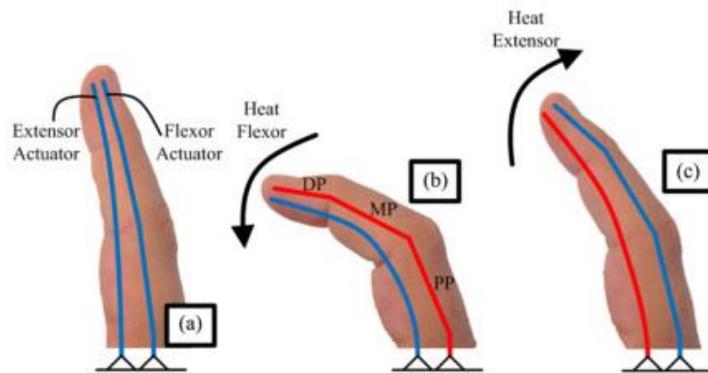
- Realization of Nano-robots?
- Collective programming?
- Avoidance of collisions?
- Idea of use of the concept of robot-swimmer? ...



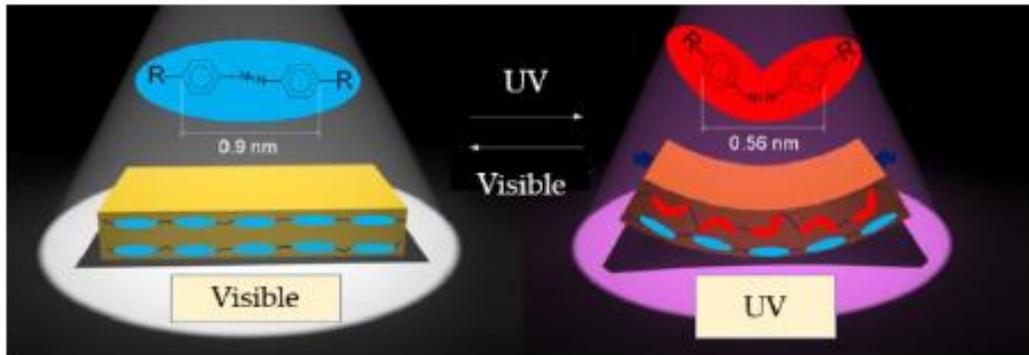
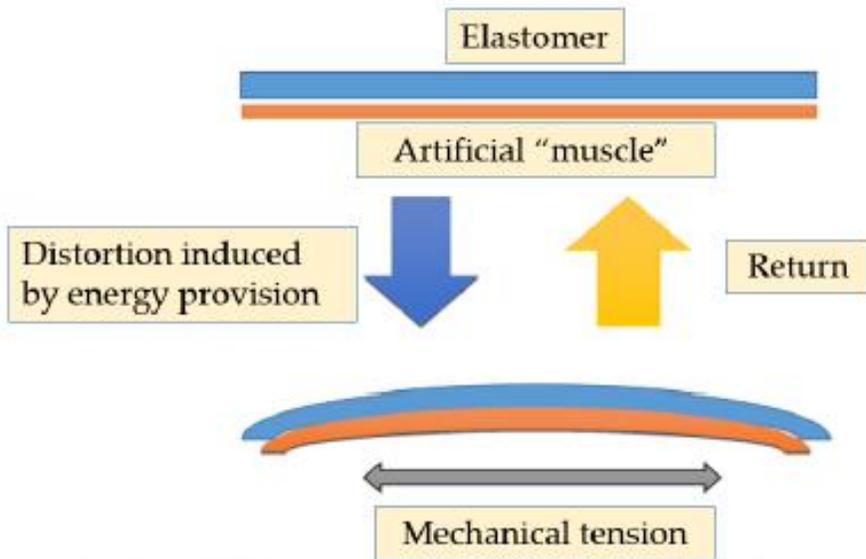
A return to conventional actuators



- Realizable in classical 3D Printing with flexible materials
- No problem of resolution, nor of time of realization
- Proof of concept widely validated
- But, today: one degree of freedom



Multi - materials



- Unrealizable easily today in classic 3D with elastic/plastic materials
- Proof of concept largely validated with bimetallic strips (but not really in 3D)
- But: rather a single degree of freedom

Need to invent new 3 / 4D technologies! (In progress...)

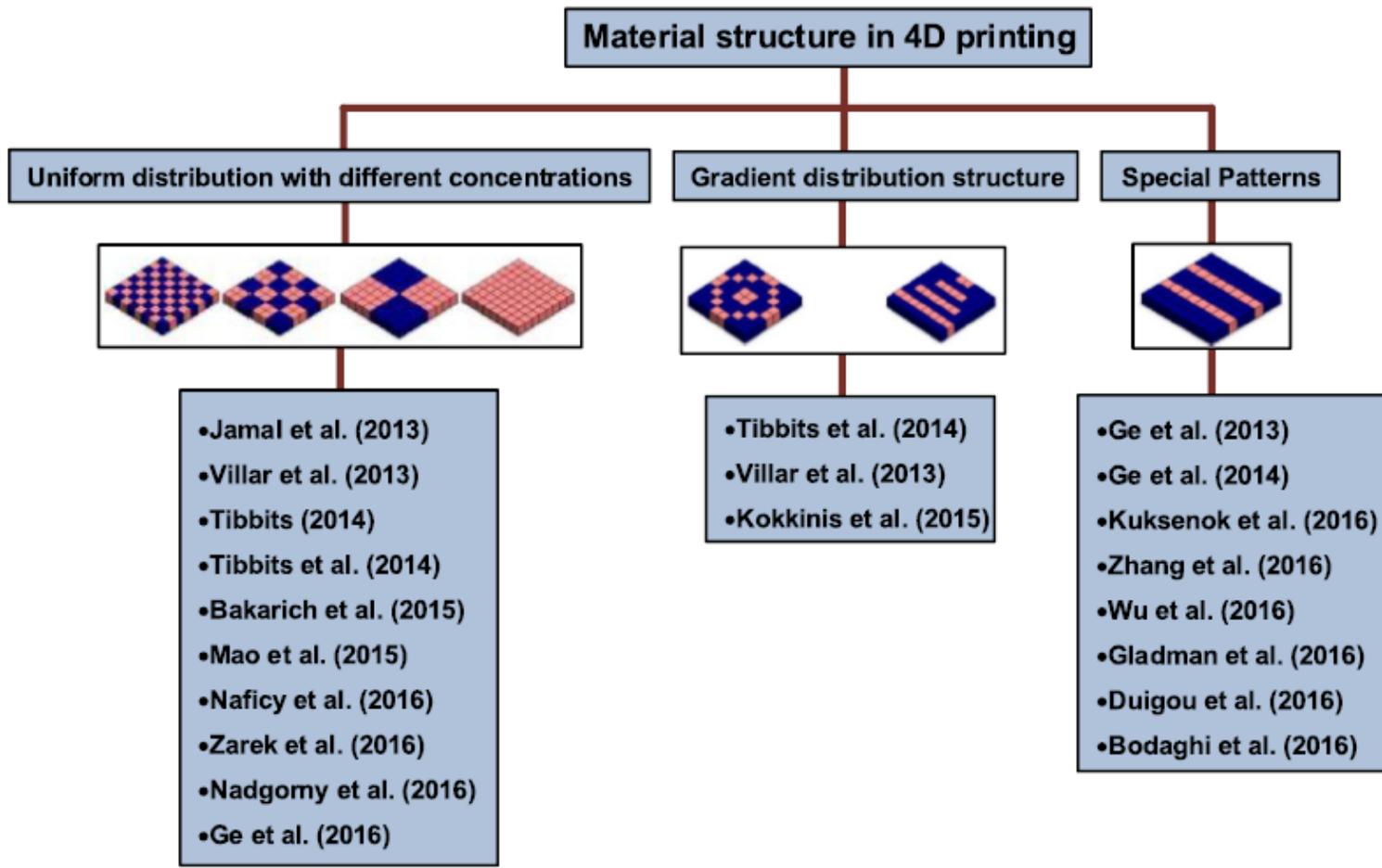
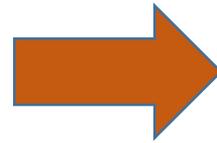


Fig. 46. Multi-material structures that have been used in 4D printing.

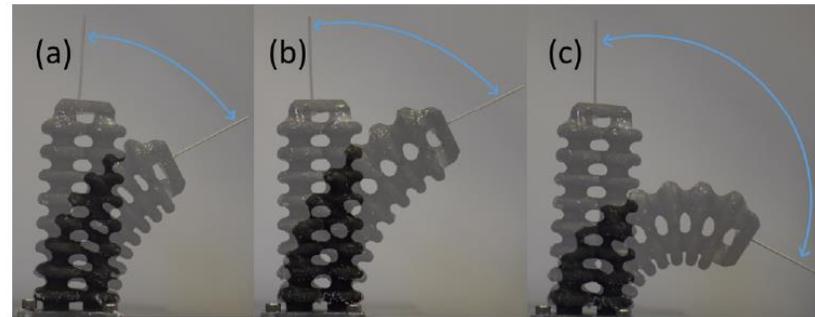
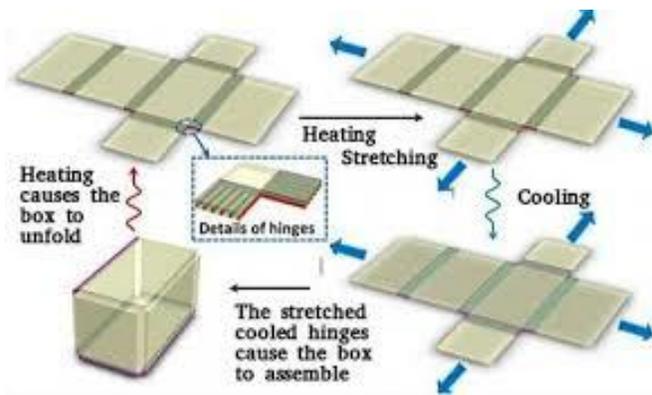
According to Momeni et al, 2017



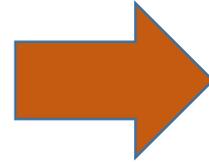
General goals for applications



- Actuators
- Micro-fluidics
- Adaptative form/Shape
- Soft-robots ordered without internal energy
- Etc.

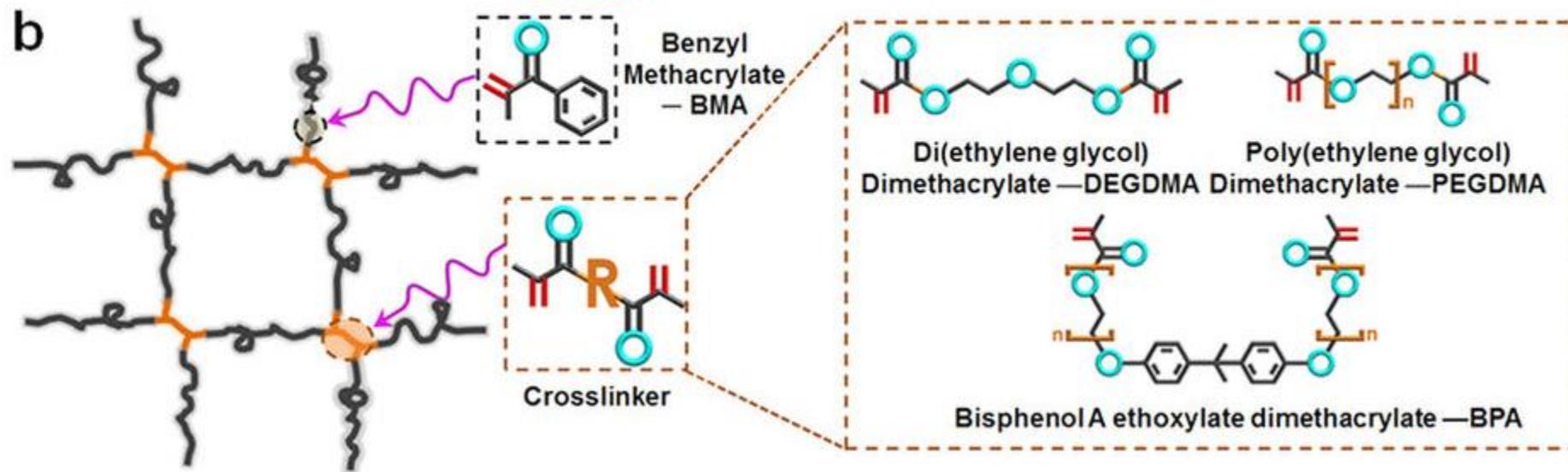
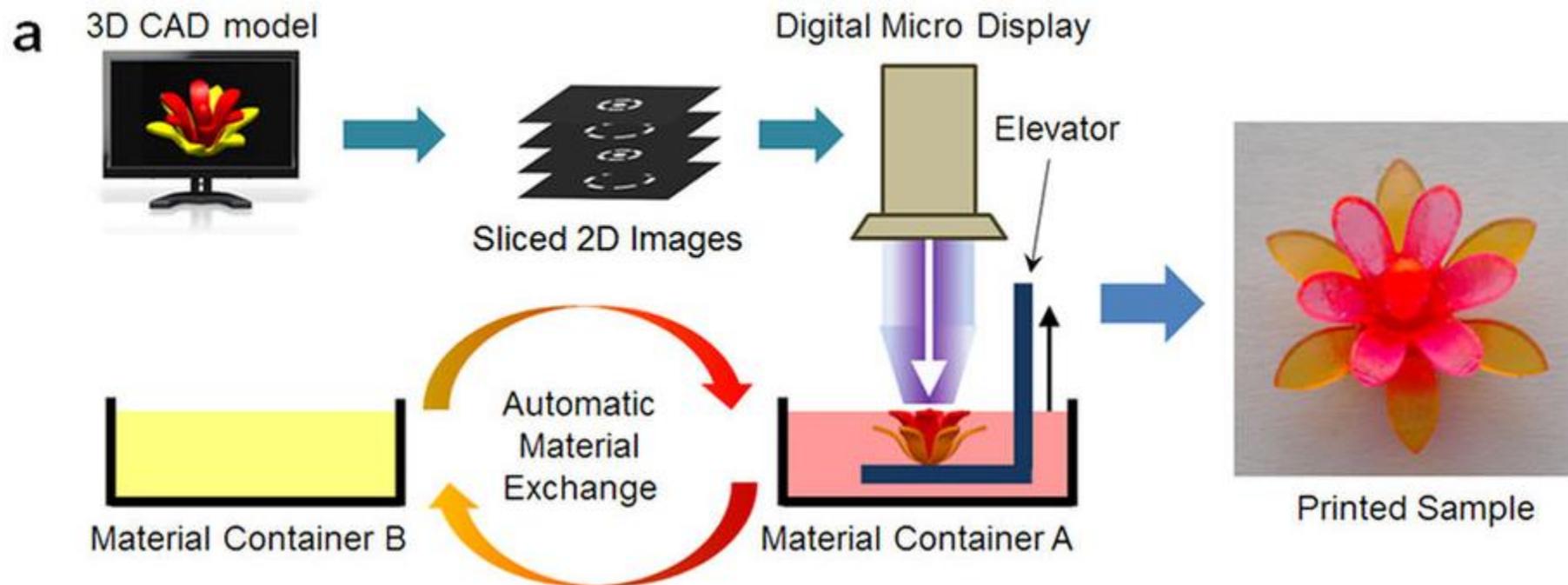


Not too much choice today: the programmable material?

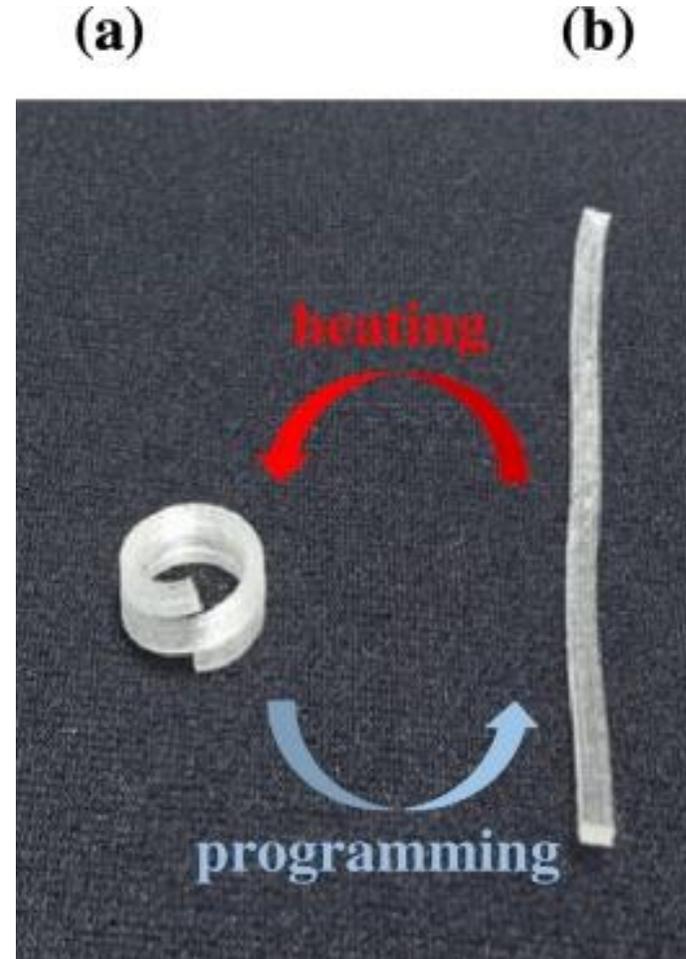
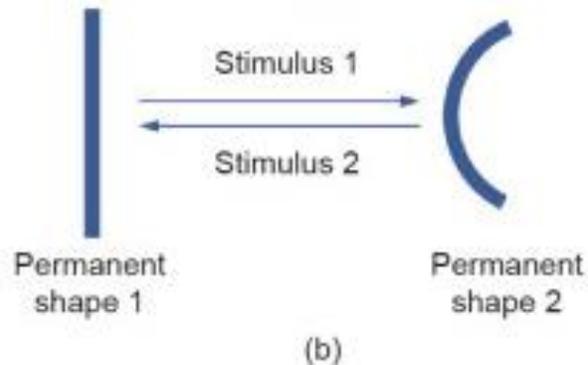
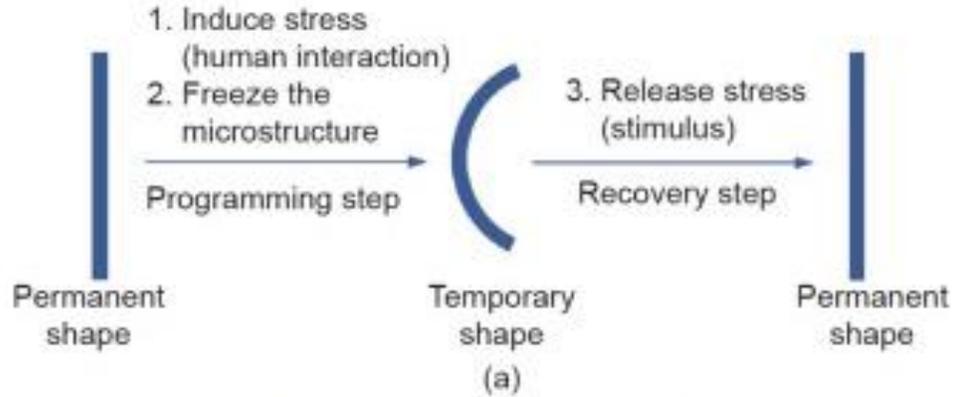


- Existing proof of concept with different types of soft materials
- Possibility to use classic 3D machines
- Several degrees of freedom possible
- Many applications (with reversible systems or not)



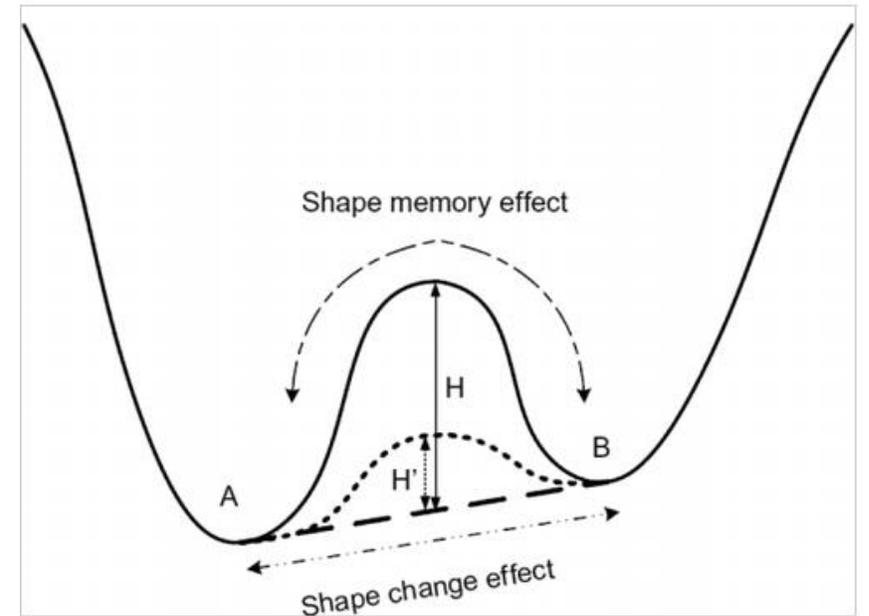
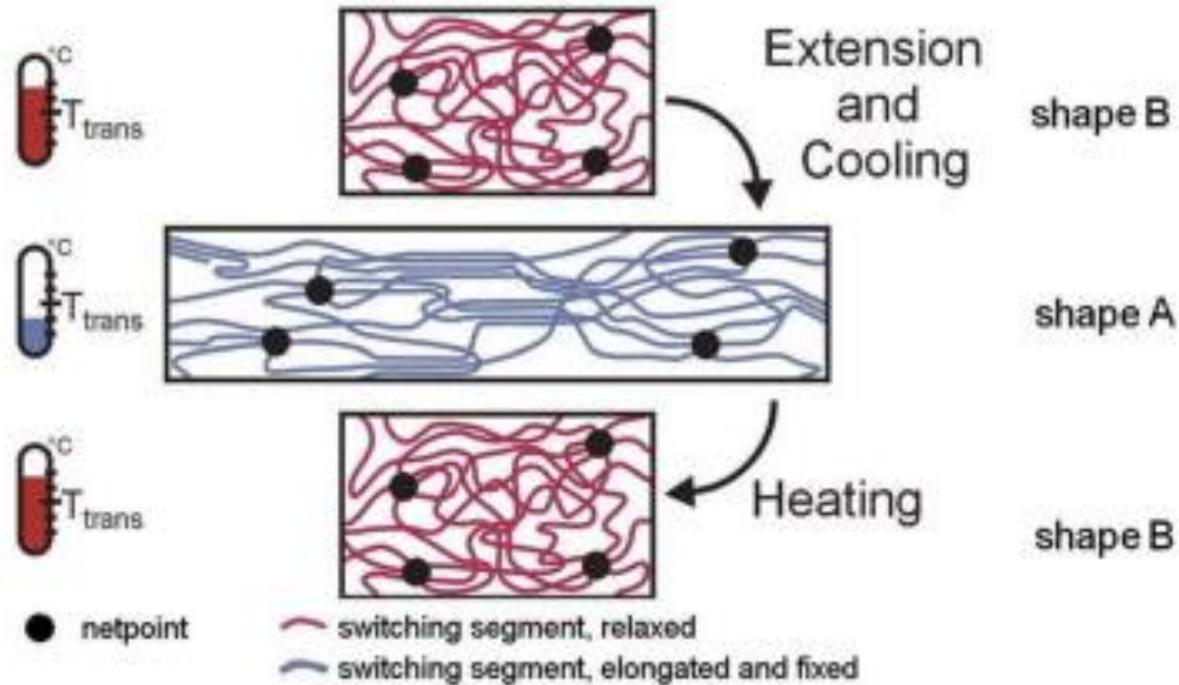


Stimulus

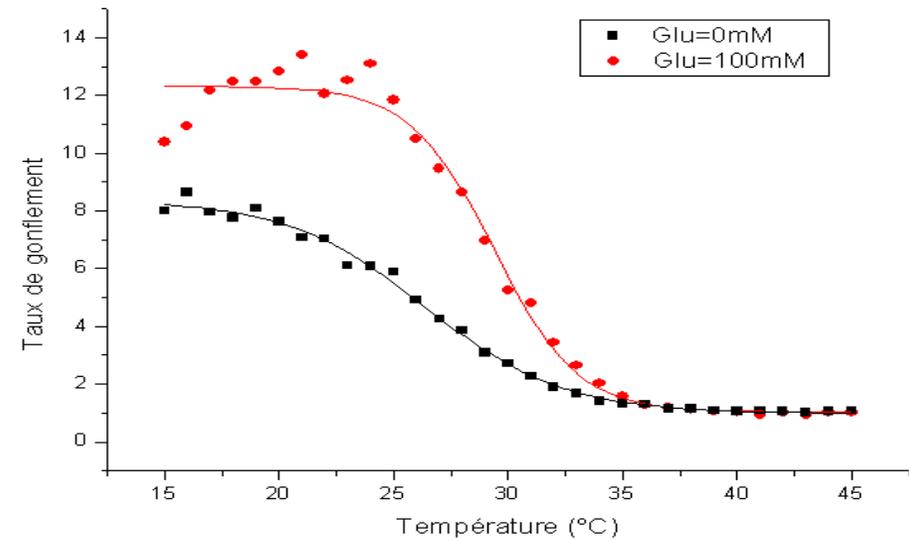
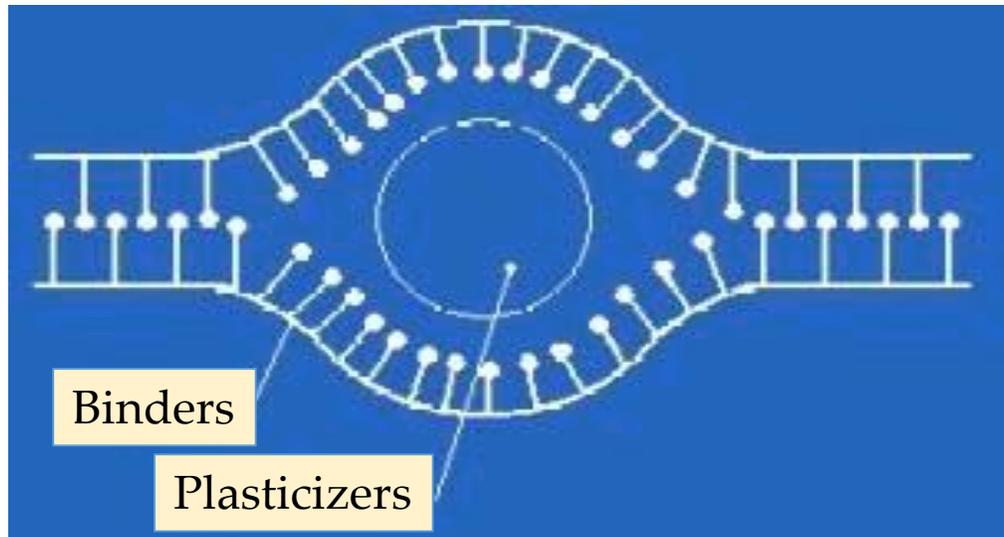


Example: Poly (N-isopropyl-acrylamide) (pNIPAM) is a thermosensitive polymer; it undergoes, between 30 and 35°C, a reversible transition. Under its transition temperature, it is hydrophilic and swells in aqueous solution; beyond that, it becomes hydrophobic and curls up on itself.

Shape memory polymer

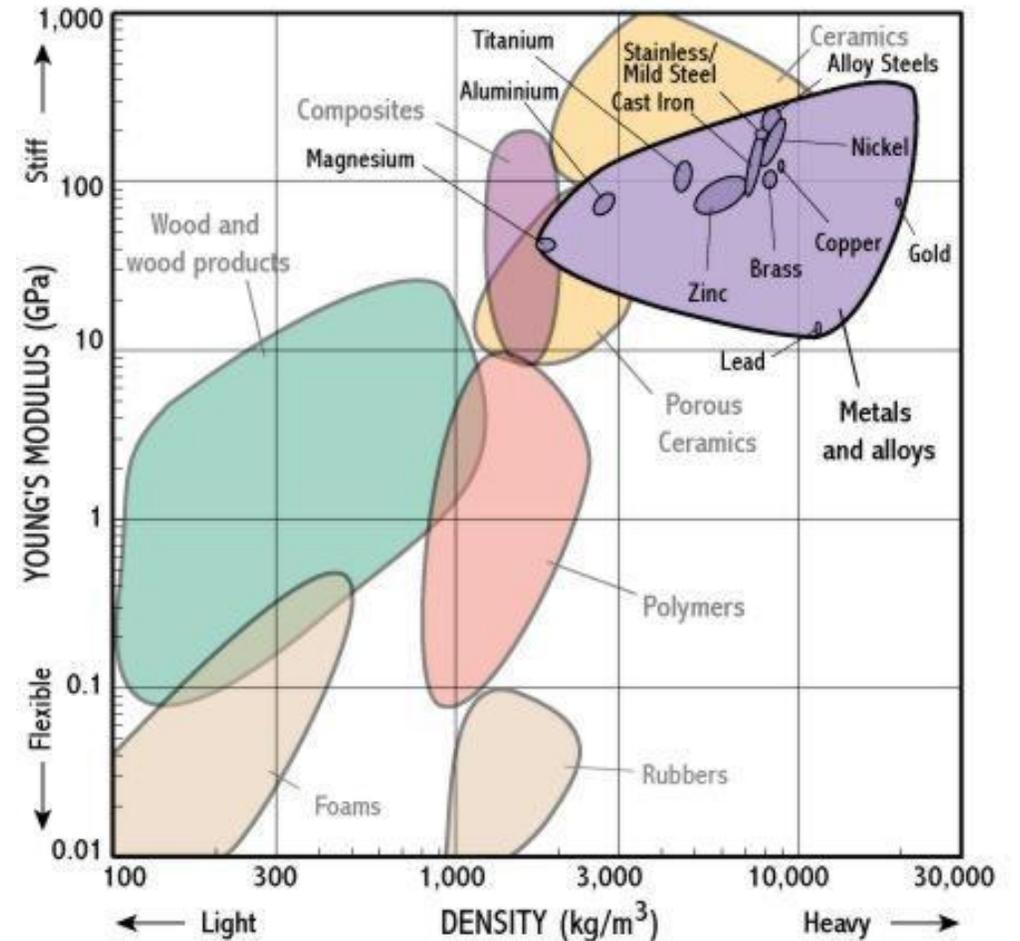
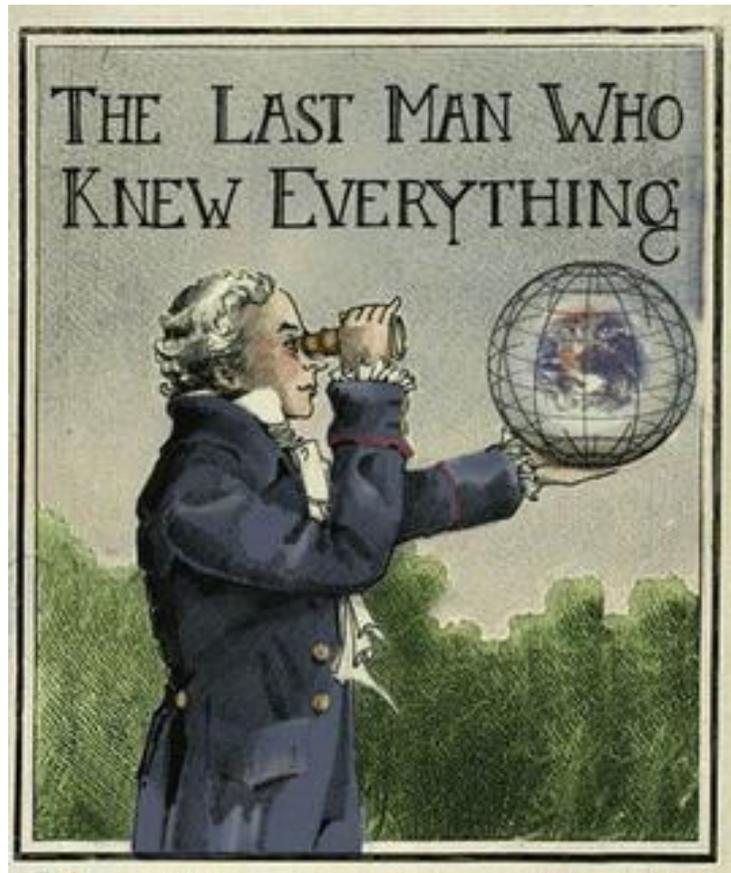


Swelling

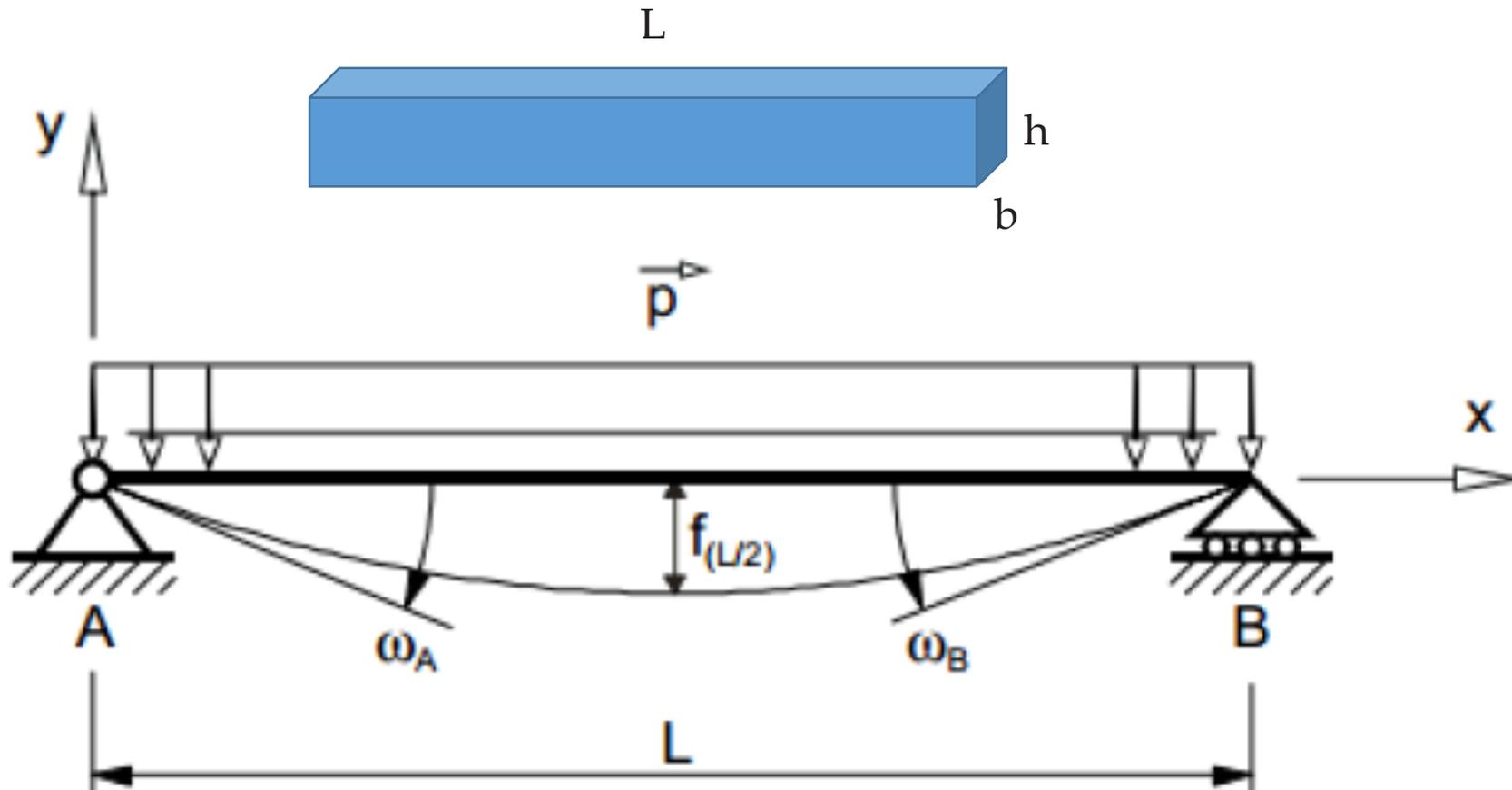


Swelling rate of a micro-gel NIPMAM, depending on the temperature and the presence of glucose

A first “pebble in the shoe”: Young's modulus



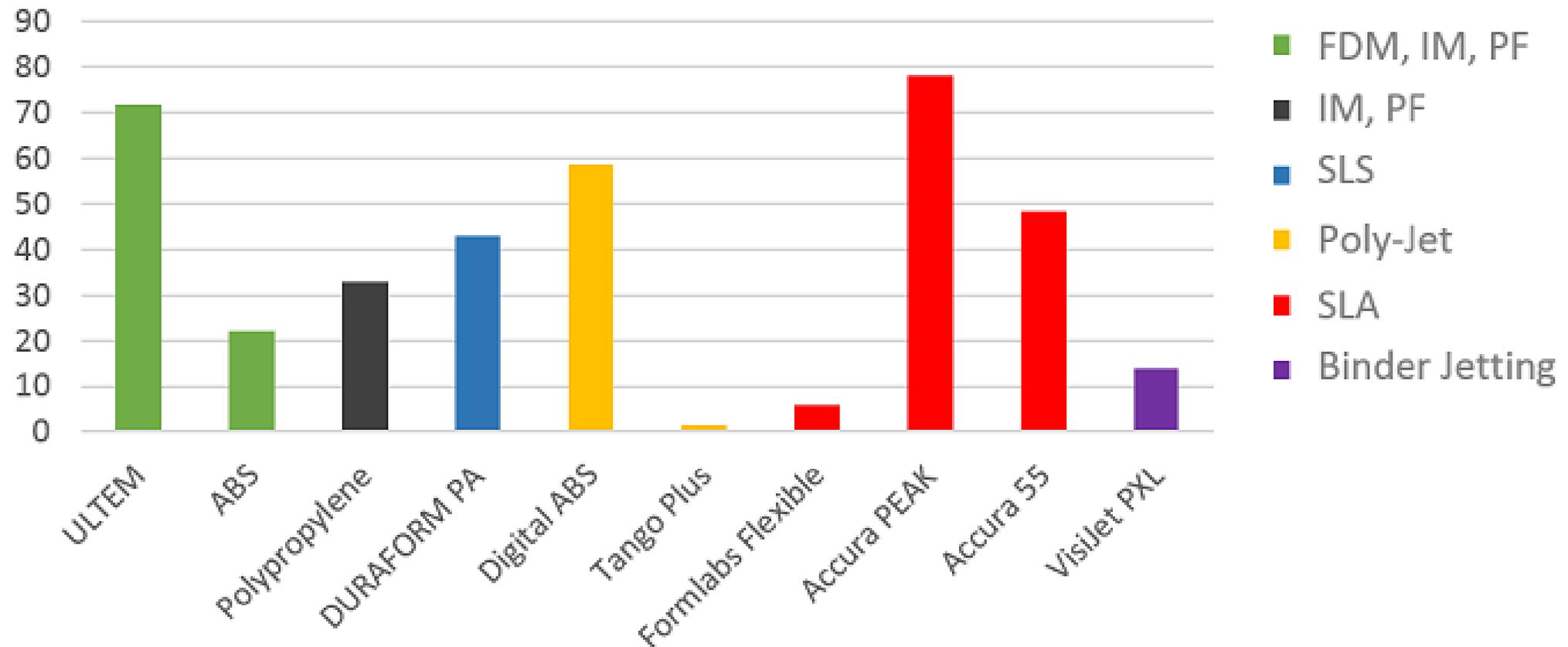
Young Modulus E



$E = 10^9$ Pascal. For $L = 1$ cm, $h = 0.01$ cm and $b = 0.1$ cm, to reach an arrow of 0.1 cm, p would have to be equal to 0.6 N / m corresponding to a force exerted on the order of $6 \cdot 10^{-3}$ N (or 0.6 gp) ...

Polymeric materials used in additive manufacturing

Approximate Tensile Strength (MPa)

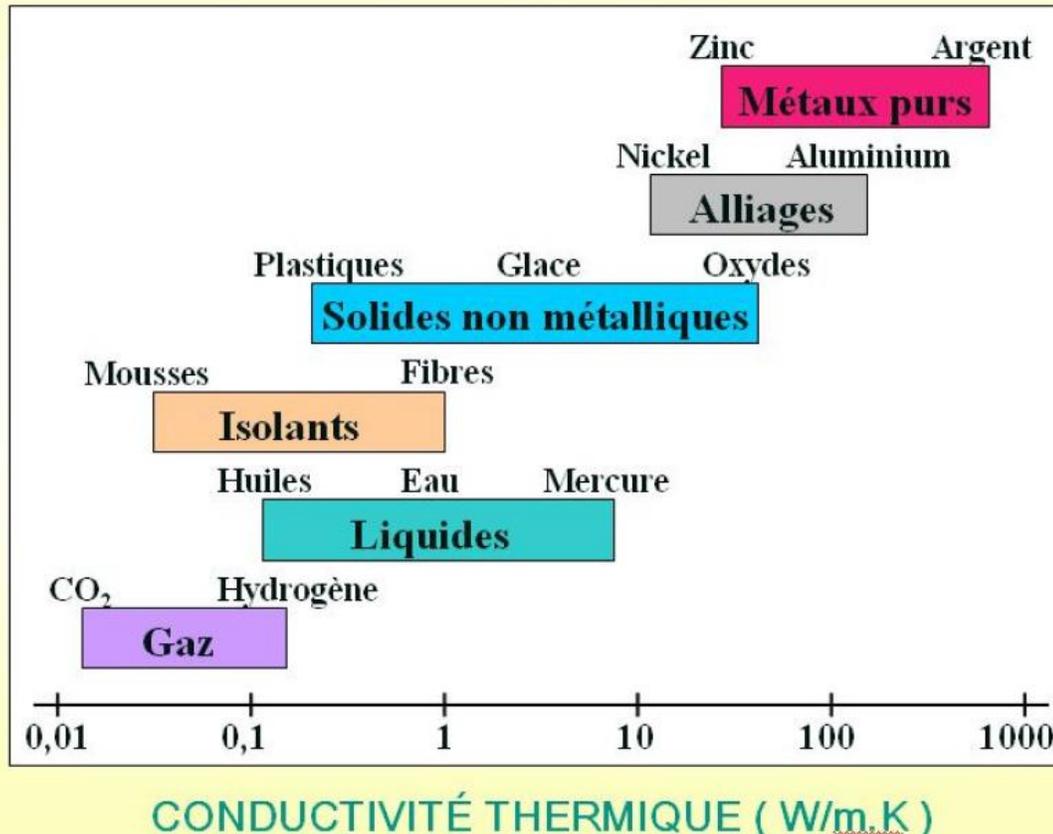


2- Thermal stimulation



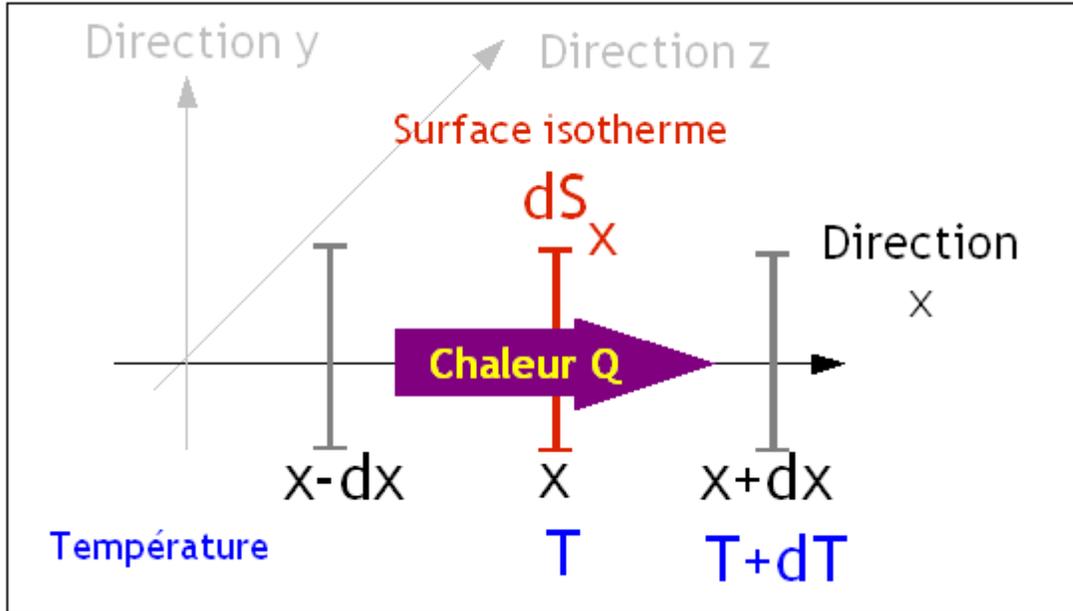
$$j_N = -D \cdot \text{grad}n$$

Thermal conductivity of different materials

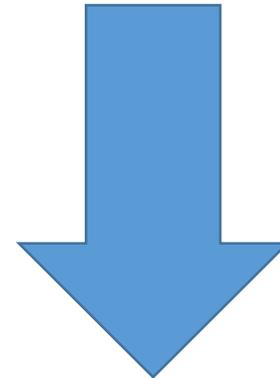


Fourier's Laws

Heat transfer



With k the thermal conductivity, C_p the heat capacity, ρ the density, the thermal diffusivity α is expressed in m^2/s

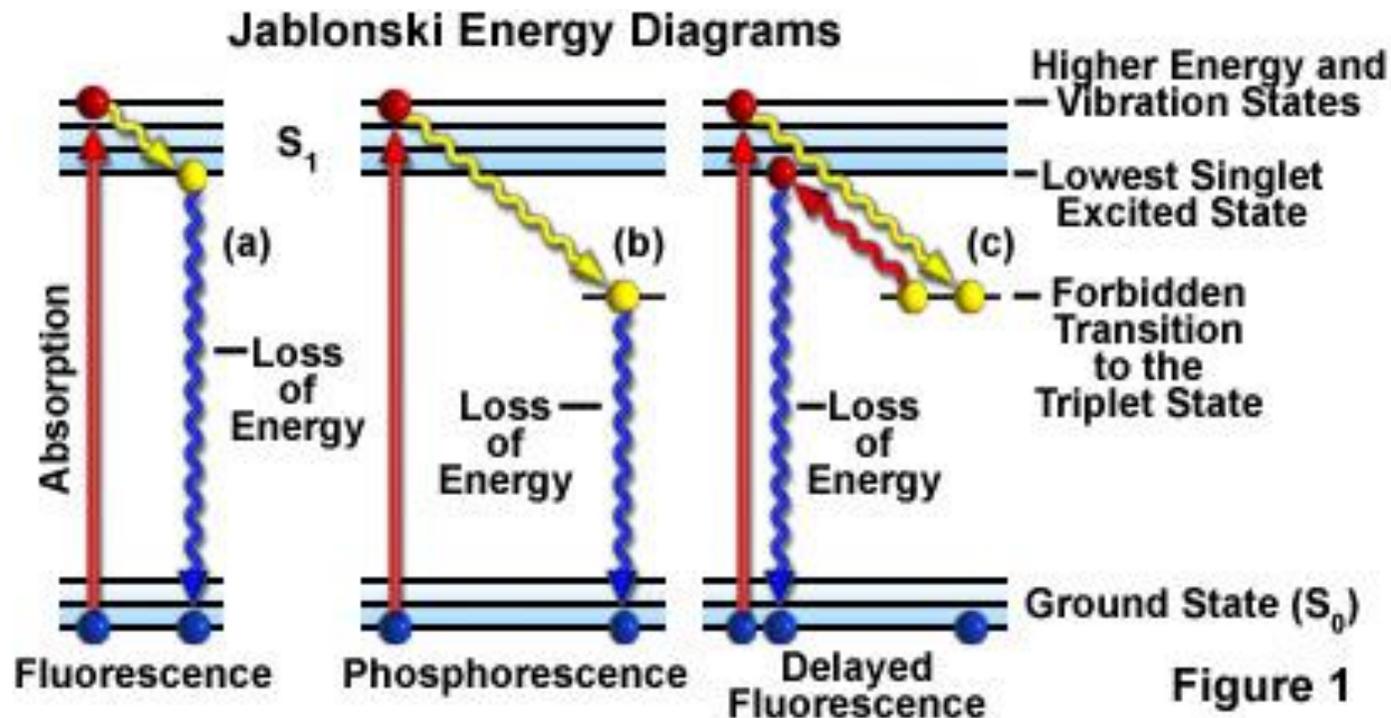


Average heat transfer time T is expressed substantially as d^2/α . With $d = 1 \text{ cm}$, $\alpha = 10^{-3} \text{ cm}^2.\text{s}^{-1}$, this time is of the order of 10^3 seconds (15 minutes!)

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q'''}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad \alpha = \frac{k}{\rho C_p}$$

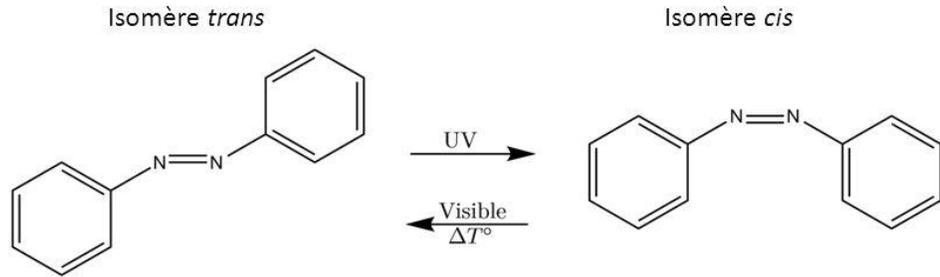
3- Quantum yield (SLA)

The quantum efficiency (Φ) of a radiation-induced process is equal to the number of times a given event is divided by the number of photons absorbed by the photonic system



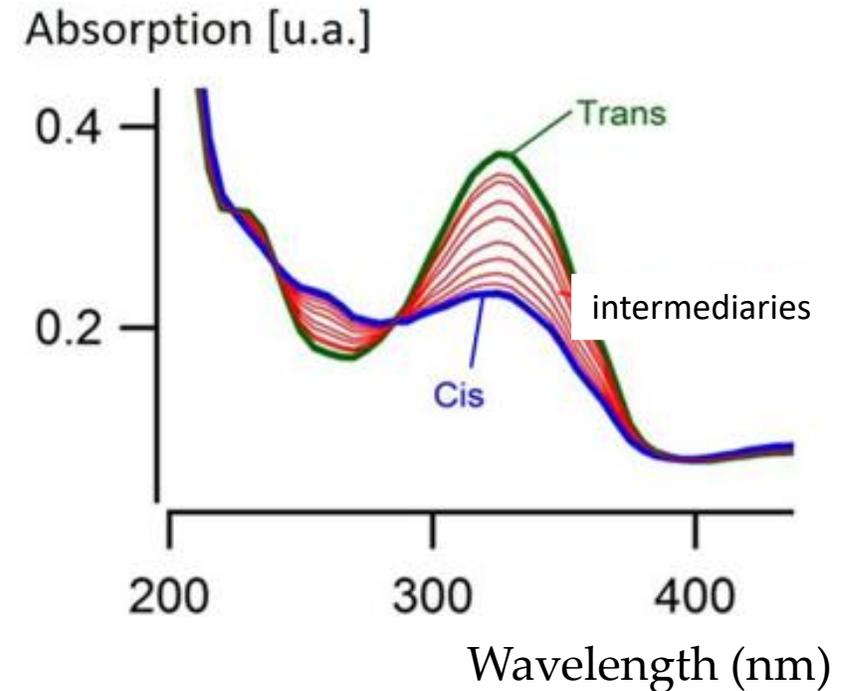
In the previous example if Φ is for example 0.5, 150 J are used to heat the cm^3 of material. With a heat capacity of 0.3 Cal/g/° , this corresponds to a rise in temperature (in the absence of heat transfer) of $120\text{-}150^\circ \text{C}$!

Photo-chemical stimulus: Azo-benzene isomerization

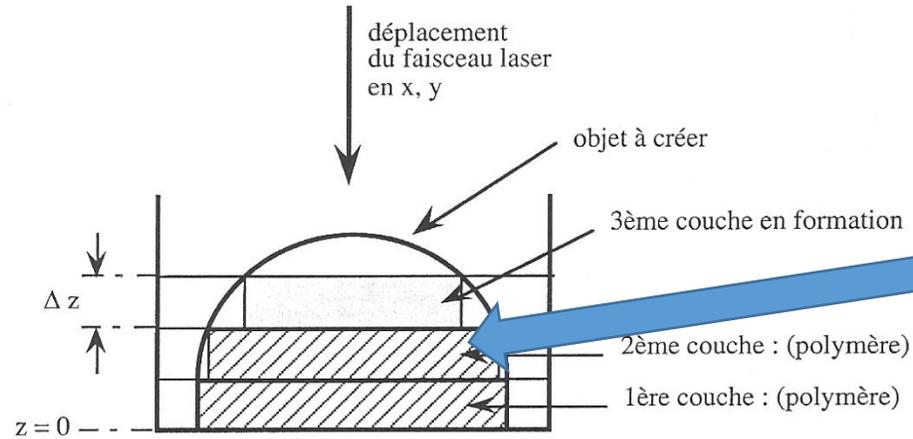


Hypothesis need to excite 1 M.l-1 Azo-dye in 1 cm^3 , i.e. 10^{-3} Einstein; this corresponds to $300 \text{ KJ} \cdot 10^{-3} = 300 \text{ J}$ with a quantum efficiency equal to unity.

A 100 watt source emits approximately 1 watt in the right wavelength range. To achieve the objective, it would take at least 5 minutes of irradiation (with the reversible reaction, it seems rather difficult to achieve) ... Hence applications with laser sources and smaller volumes!



4- Anisotropy in the manufacturing by successive layers (SLA-AM!)



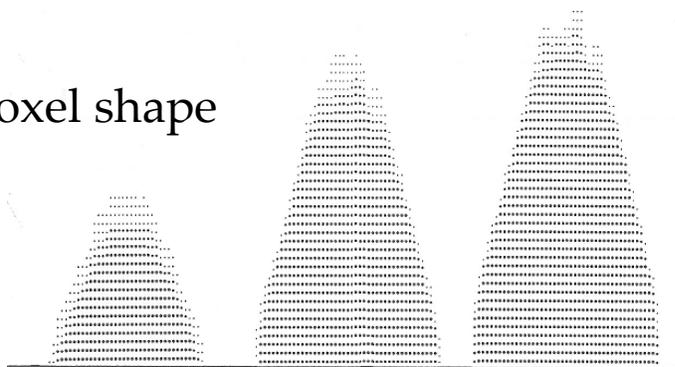
Gradient of mechanical properties

Anisotropy of the polymerization (or the deposit)

=

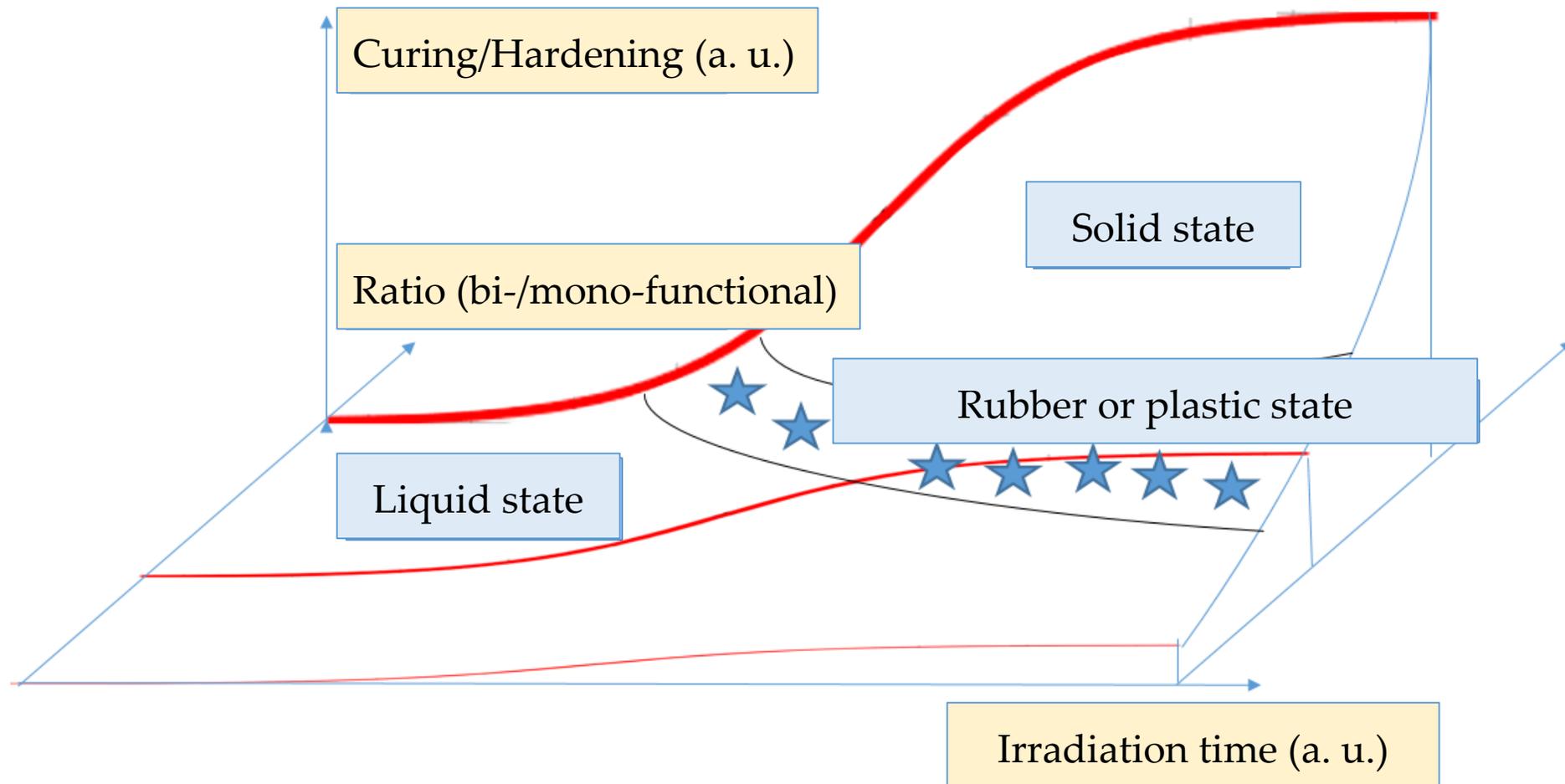
Vertical anisotropy of mechanical characteristics

Voxel shape

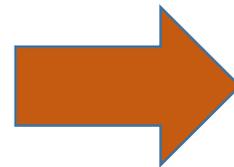
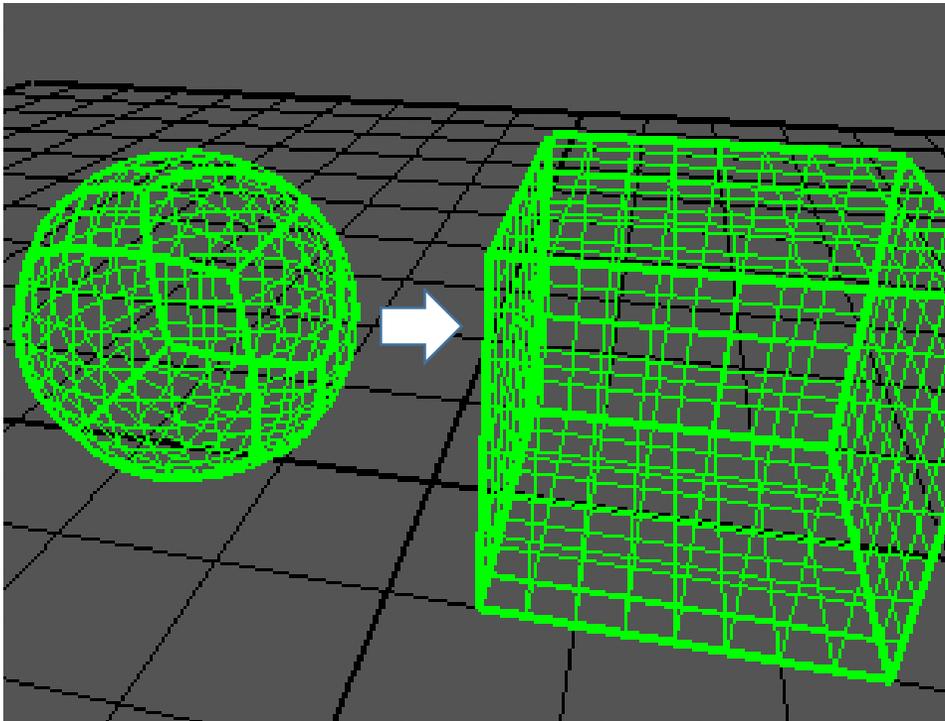


Time irradiation exposure →

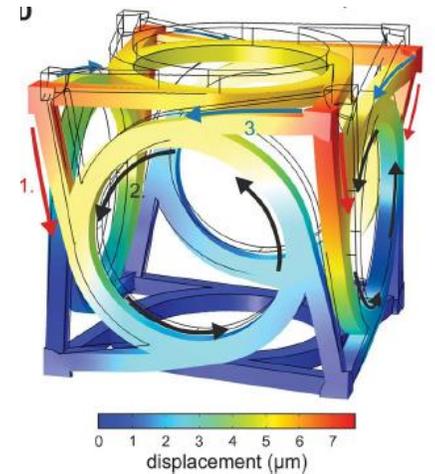
Mechanical anisotropies



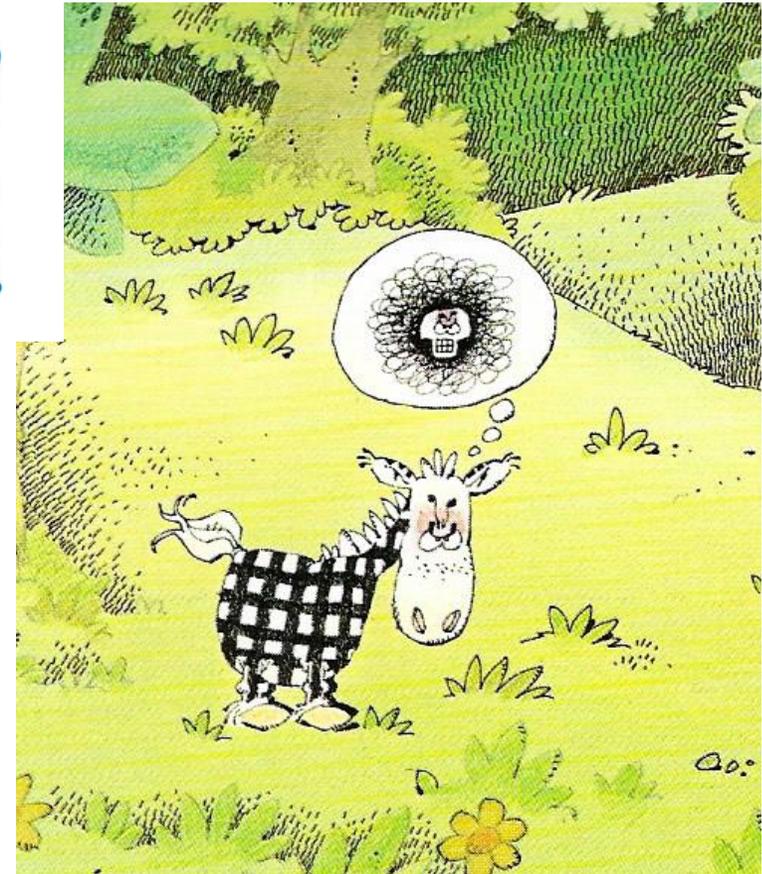
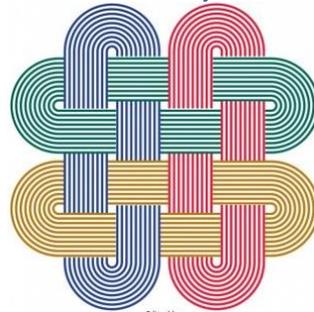
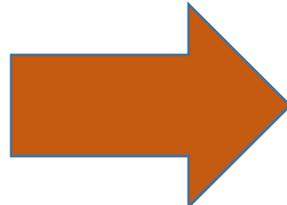
5- Modelling of desired deformations



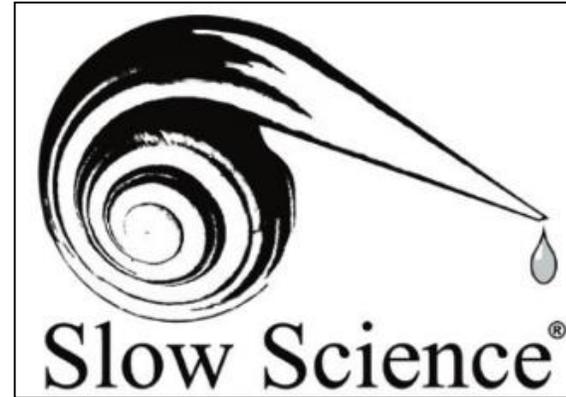
Modeling to do and
reverse problem solving...



6- Interdisciplinary actions



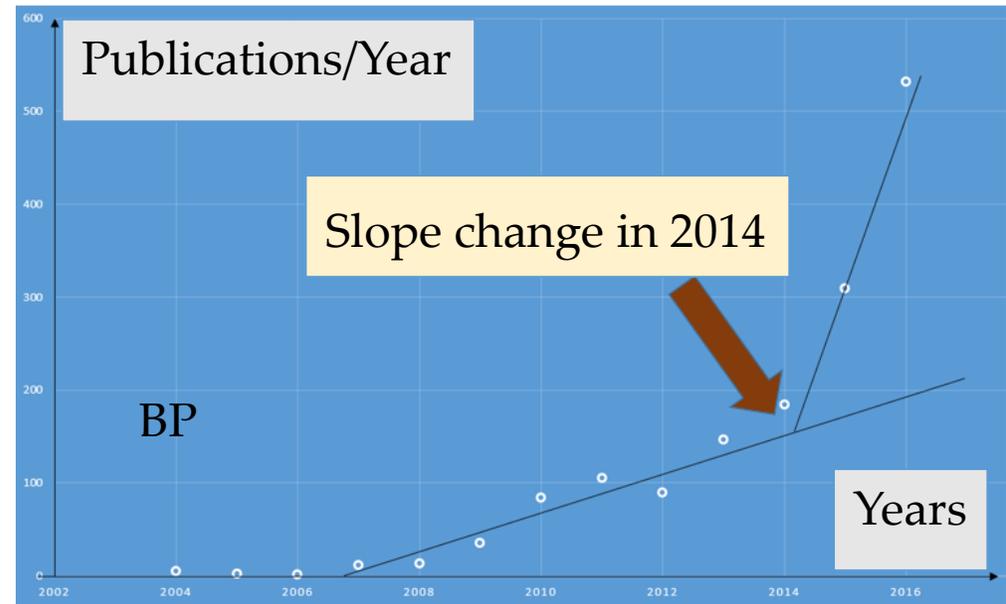
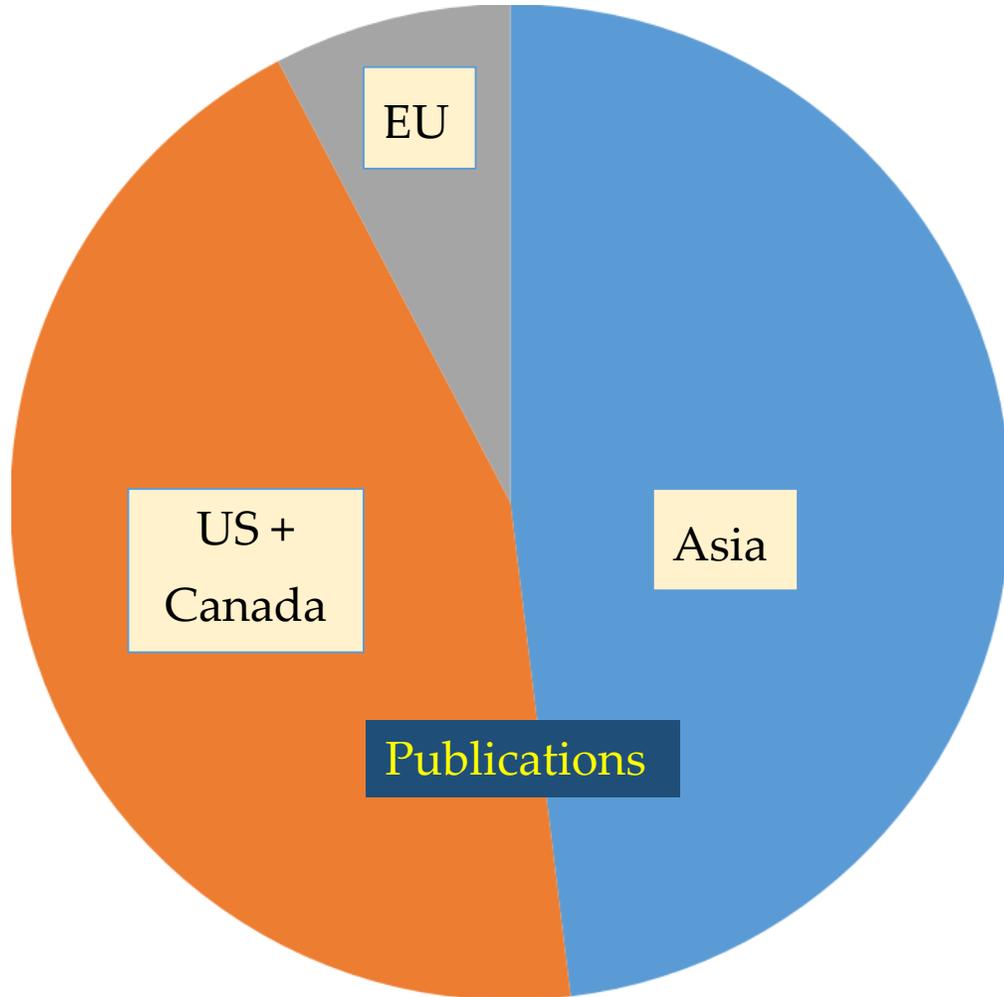
Other...



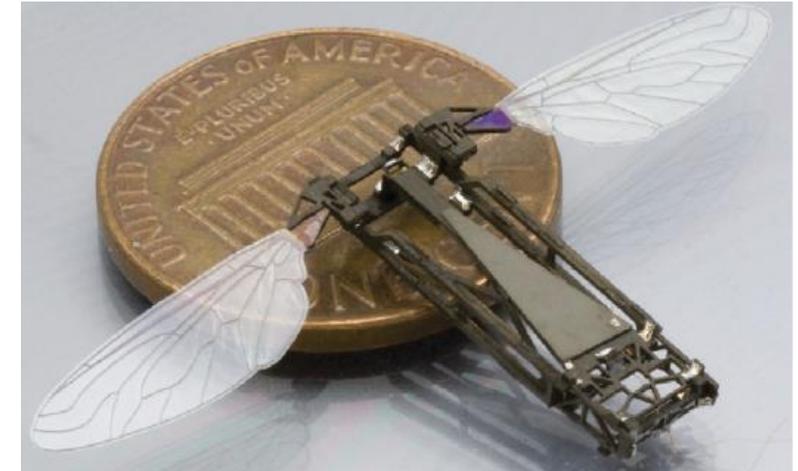
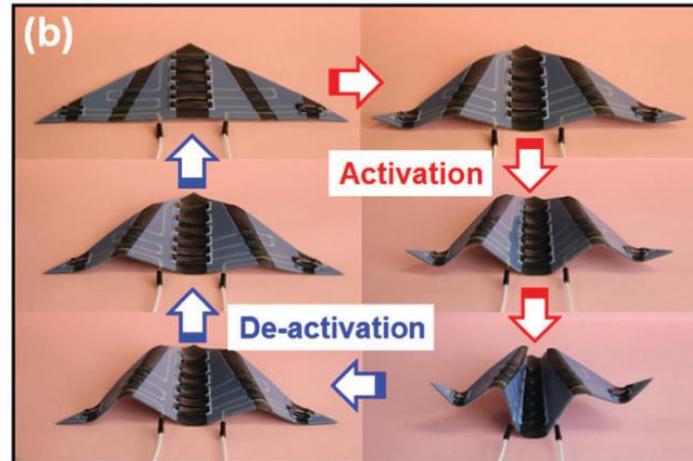
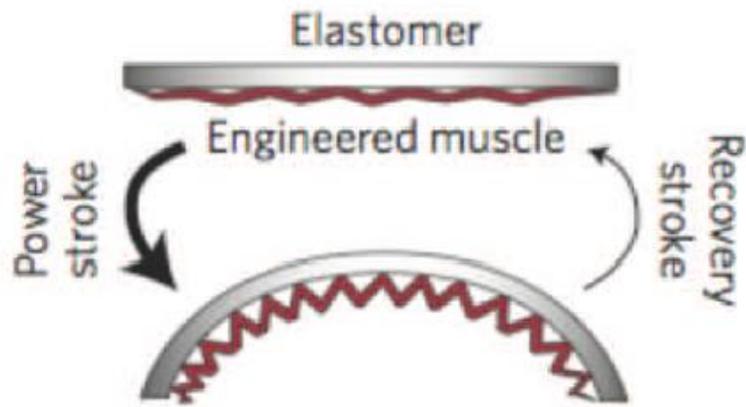
- 7- Researcher's culture (paradigm) and open-minded education
- 8- Weakness of competent population in 3D at academic level
- 9- New Public Management – Rapid return on investment
- 10- Too short term research proposal
- 11- Absence of support of epistemology for complex questions
- 12- Insufficient financing for risky research



Place of EU Research in the world competition on 4D/BP



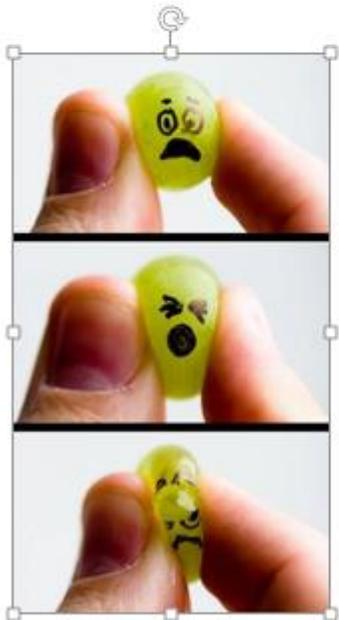
Some examples: 4DP and BP



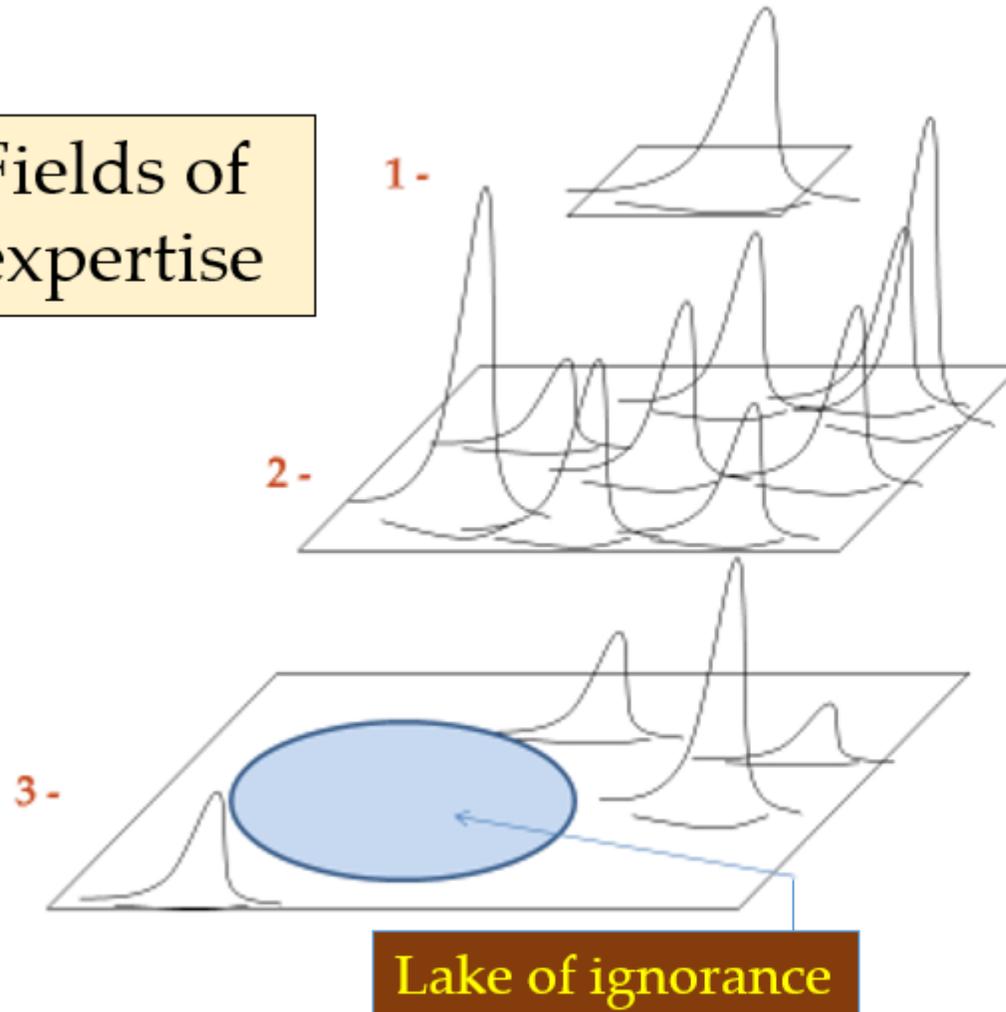
Heuristics – Time for thinking



OR



Fields of expertise



Broadening the scope of expertise

Causal

1984 first patent

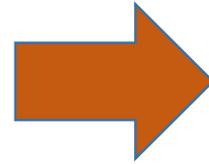
Algorithmic

2005 4D Printing,
2017 no layer 3D

Heuristic (unverified
presumptions)

Bio-printing, tele-
transportation, soft-
robots

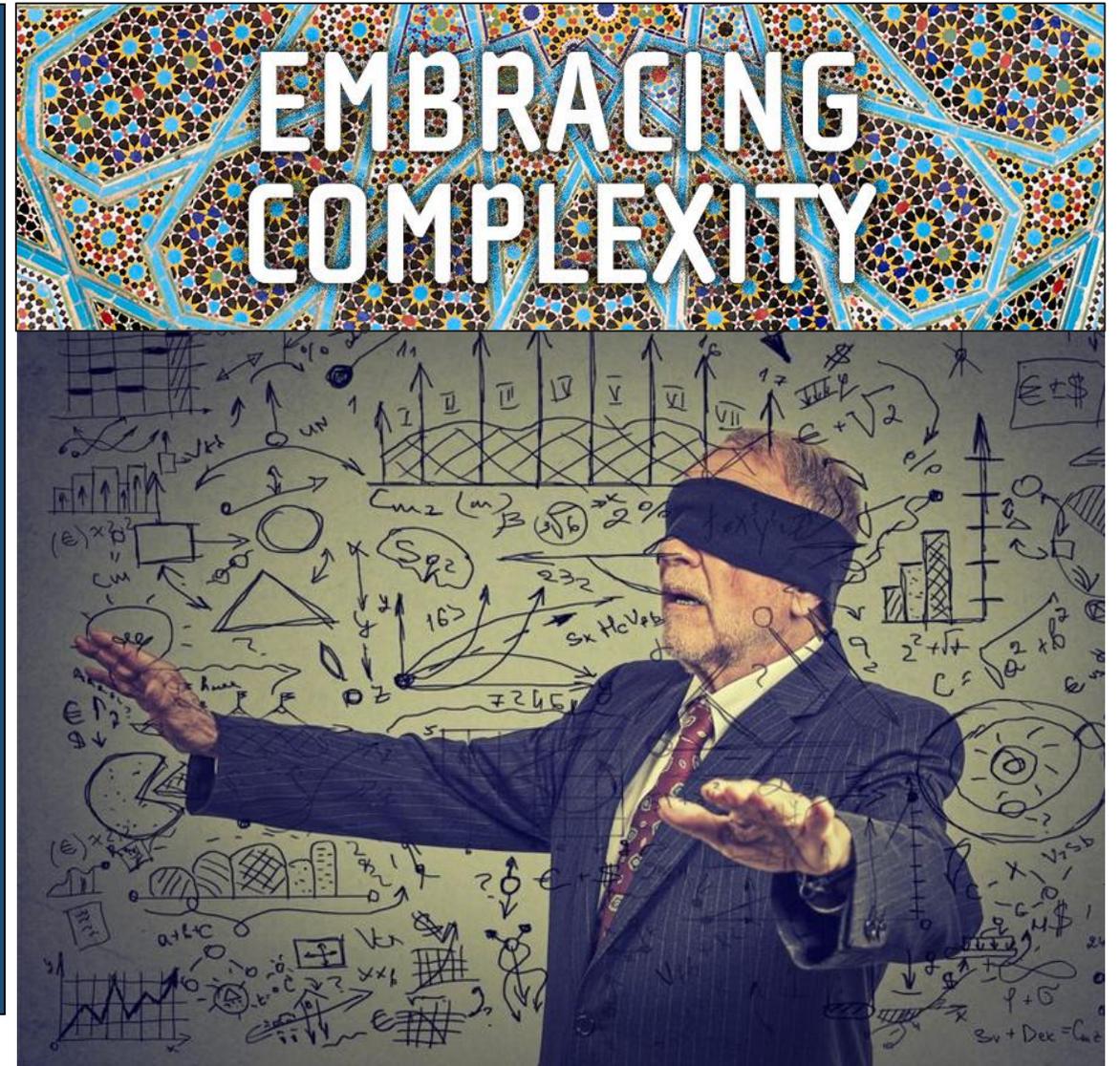
Not too much intellectual choice today: the programmable material?



- Existing proof of concept with different types of soft materials
- Possibility to use classic 3D machines
- Several degrees of freedom possible
- Many applications (with reversible systems or not)

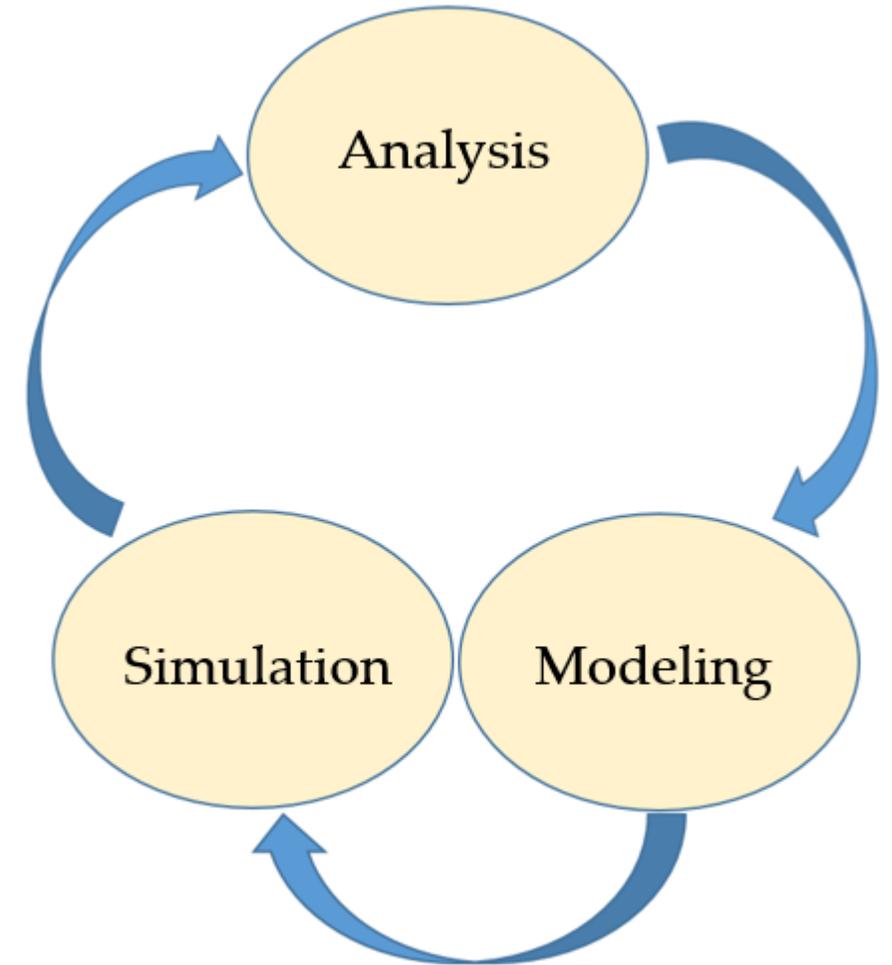
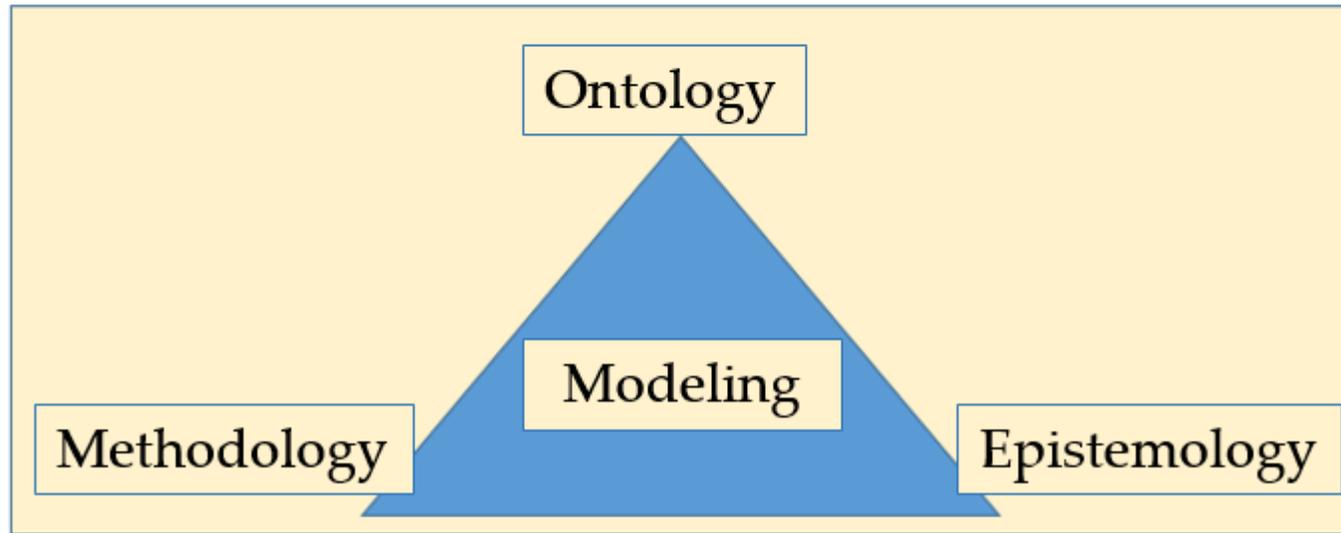
Hell is not solely in the detail (no more)...

“We can't understand why we can't do it anymore. All these problems have only one cause, but one that goes unnoticed: we have lived for at least three hundred years on fruit that was just waiting to be picked.... Now, for forty years, these fruits have begun to become rare, and we have acted as if they were still there. We didn't want to acknowledge that we had reached a technological plateau and that the tree was much more bare than we wanted to admit” (Cowen, 2011).



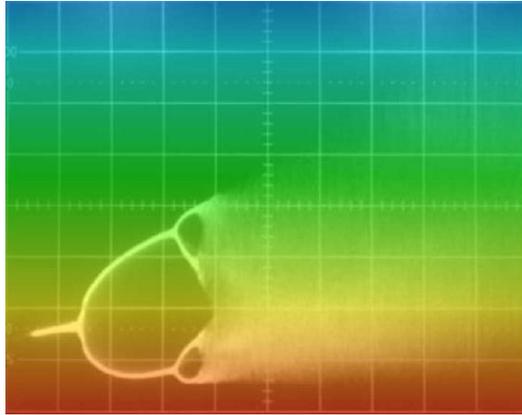
Ontology: concerned with the nature of research objects,

Epistemology: Manner in which its research objects will be understood and known

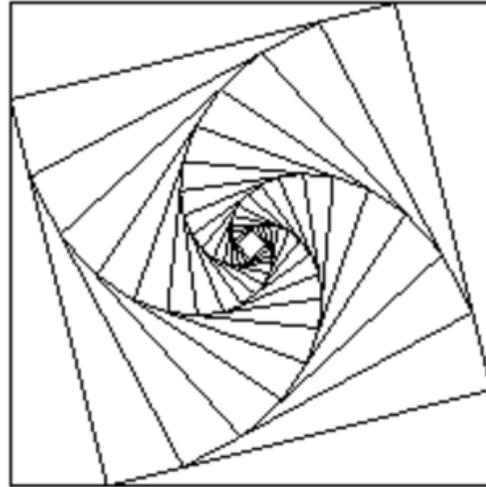


Some not so “little” (but heavy) questions...

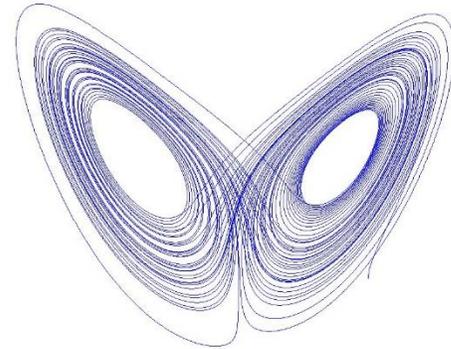
Bifurcations



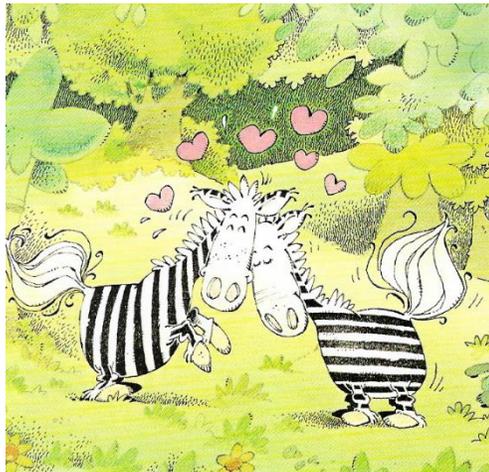
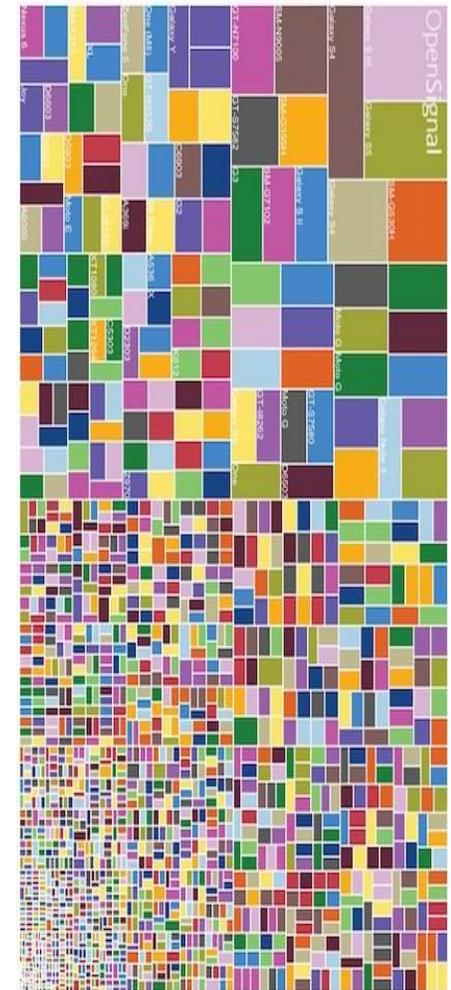
Recursivities



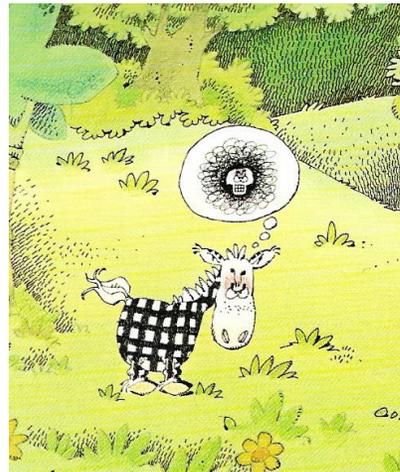
Non - linear behavior



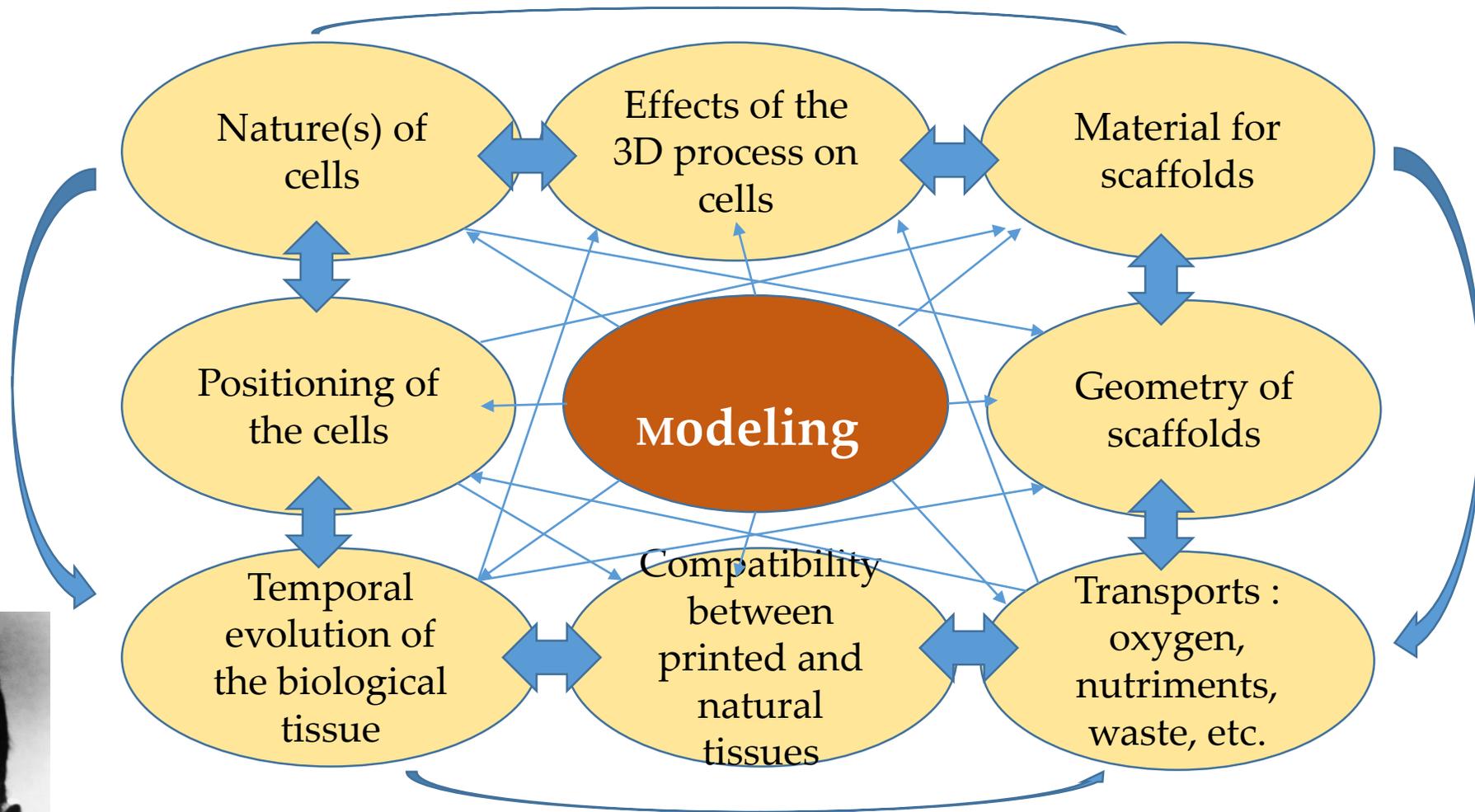
Complexity



Interdisciplinarity



BP Complexity



Recursivity and Non-Linearities



Convergence and facts...

Convergence, combining technologies is an important source for innovation, because technological breakthroughs often take place on the boundaries between scientific disciplines, technologies and industrial sectors. In particular, the BP/4DP convergence actually in every aspect of society, (may be) characterizes the **information revolution**

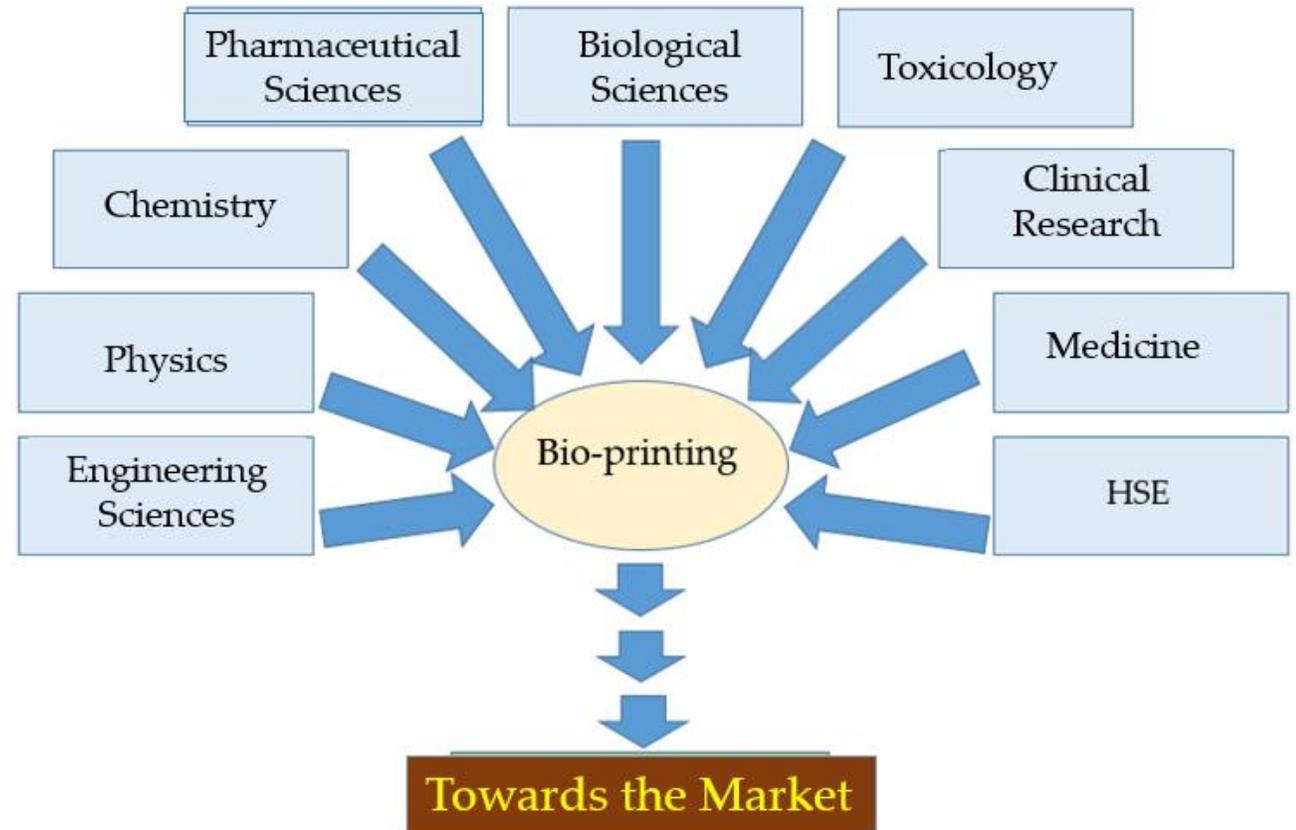
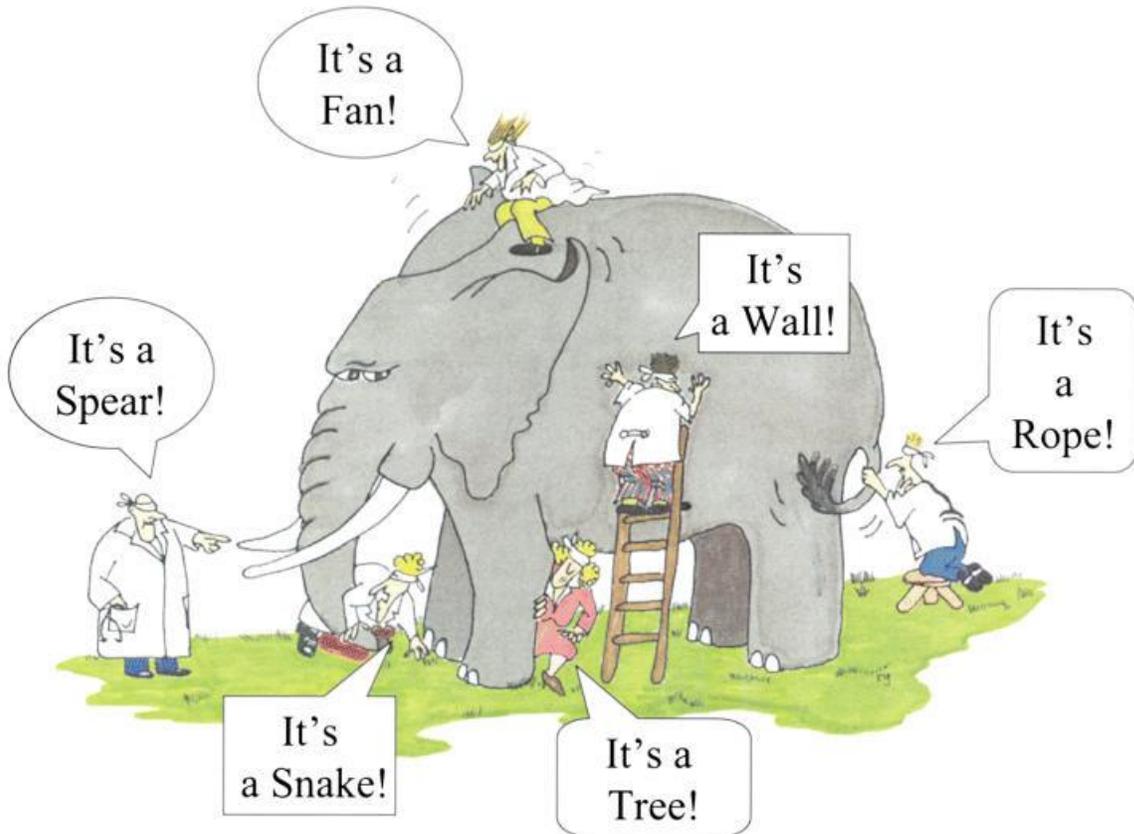
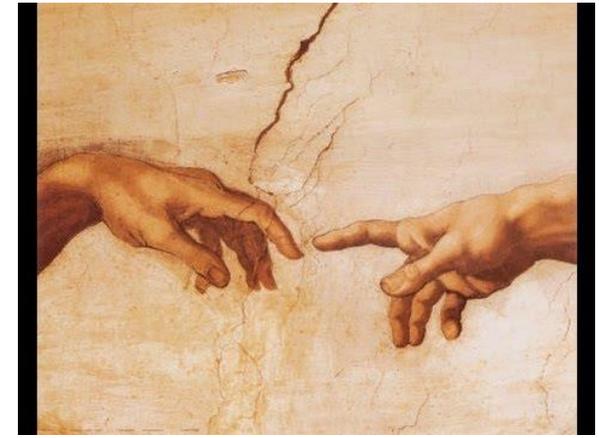


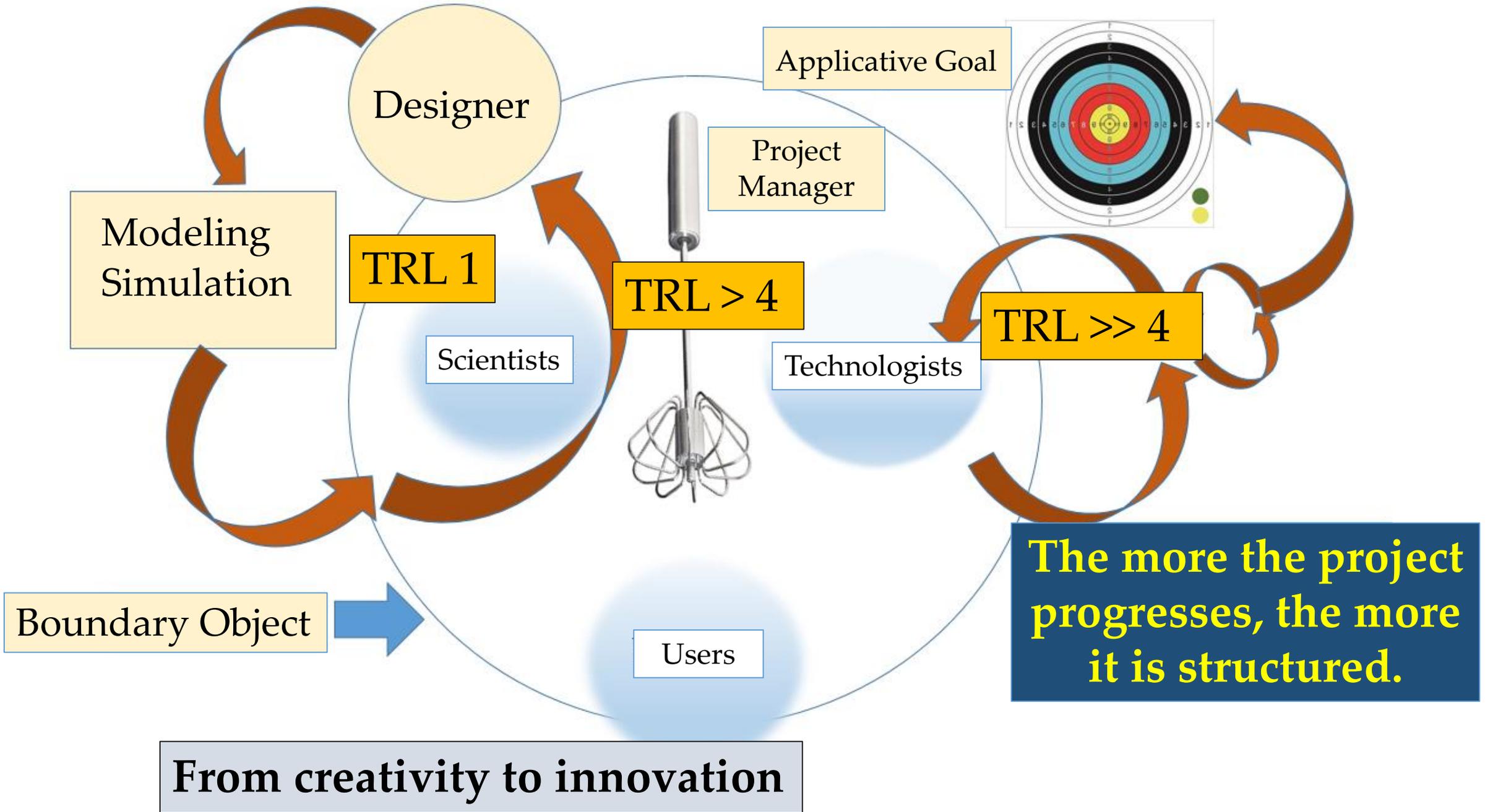
To converge means...





Convergence

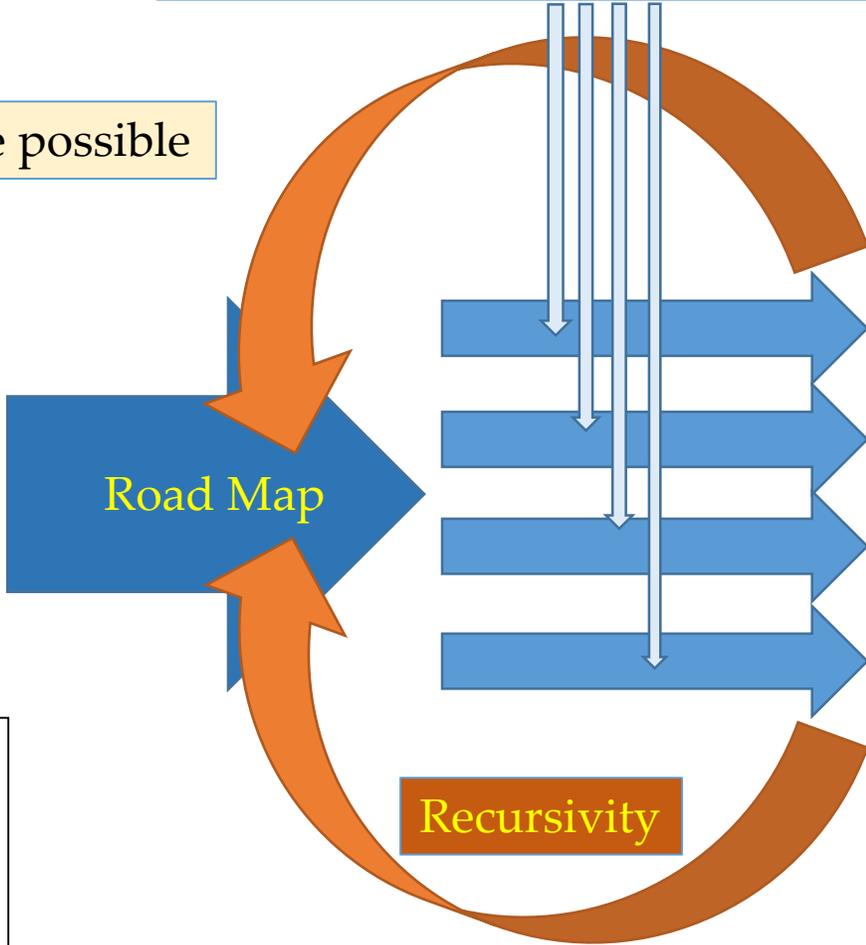
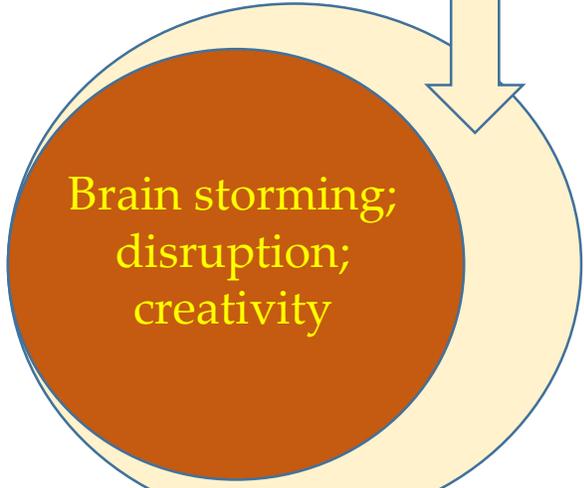




**Success is not final,
failure is not fatal:
it is the courage to
continue that counts.**
Winston Churchill

Disciplinary and interdisciplinary research

Knowledge of the real and the possible



At the same time...

- With growth rates $> 20\%$, people already trained go into production or sales/consulting
- A-creative training (at best incremental)
- Strong dilution of R activities in France, and in EU modest readability
- Few people trained in R
- 3D Printing is it really R? 4D is too young!
- Funding for modest interdisciplinarity
- No support for too risky operations
- Just proof of concept?
- No time for epistemology...



But (2)...

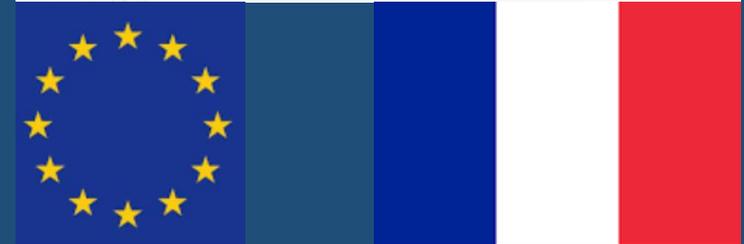


- (Too) Narrow researcher's culture (paradigm)
- Weakness of competent population in 3D at academic level
- Teams diluted in the space (no critical mass)
- New Public Management – Rapid return on investment
- A too short term research
- Absence of epistemology for complex questions
- Insufficient financing risky research



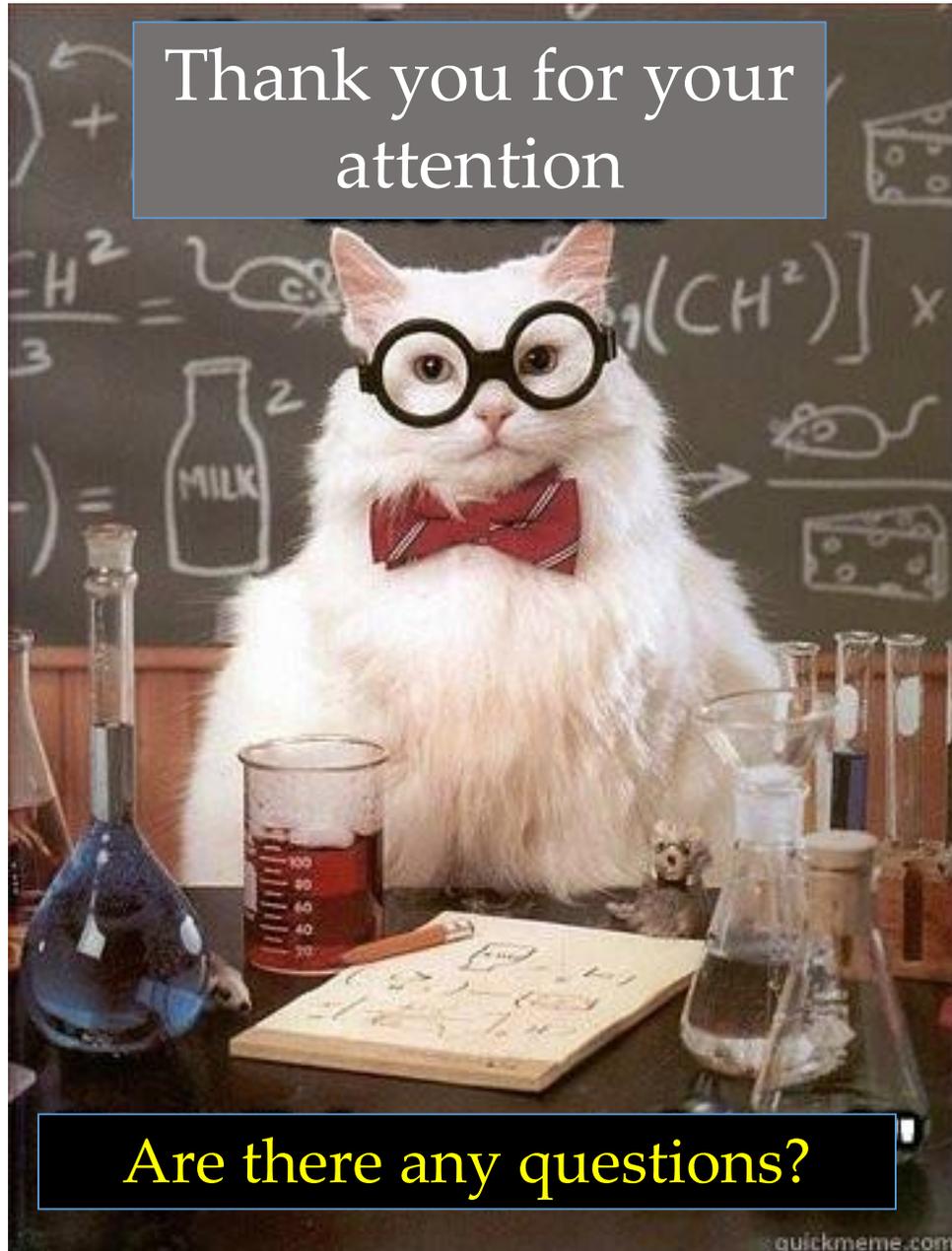
So, in the absence of “disruptive” new research... Business as usual...

- New proofs of concept, etc.
- Micro-fluidic Orientations
- Shape memory systems + 3D
- Small object size
- Non-polymeric materials?
- No functional changes



- The question of the place of the EU is raised in the current dynamics... FP9 (Horizon Europe) happens...

Thank you for your attention



Are there any questions?

quickmeme.com

