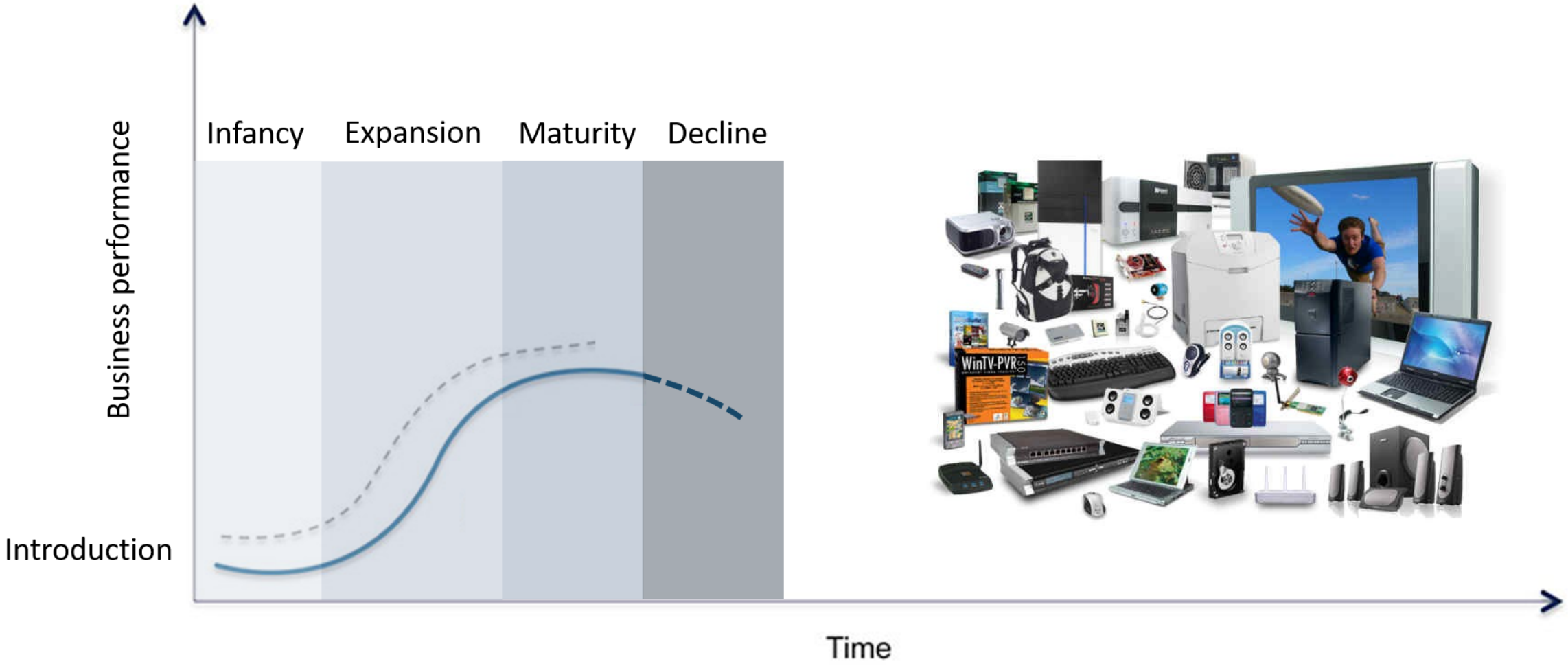
# 4D additive manufacturing: the way to program 3D printed objects

Giancarlo Rizza
Laboratoire des Solides Irradiés (LSI)
Ecole polytechnique
CEA/DRF/IRAMIS

# S - CURVE
BUSINESS LIFE CYCLE

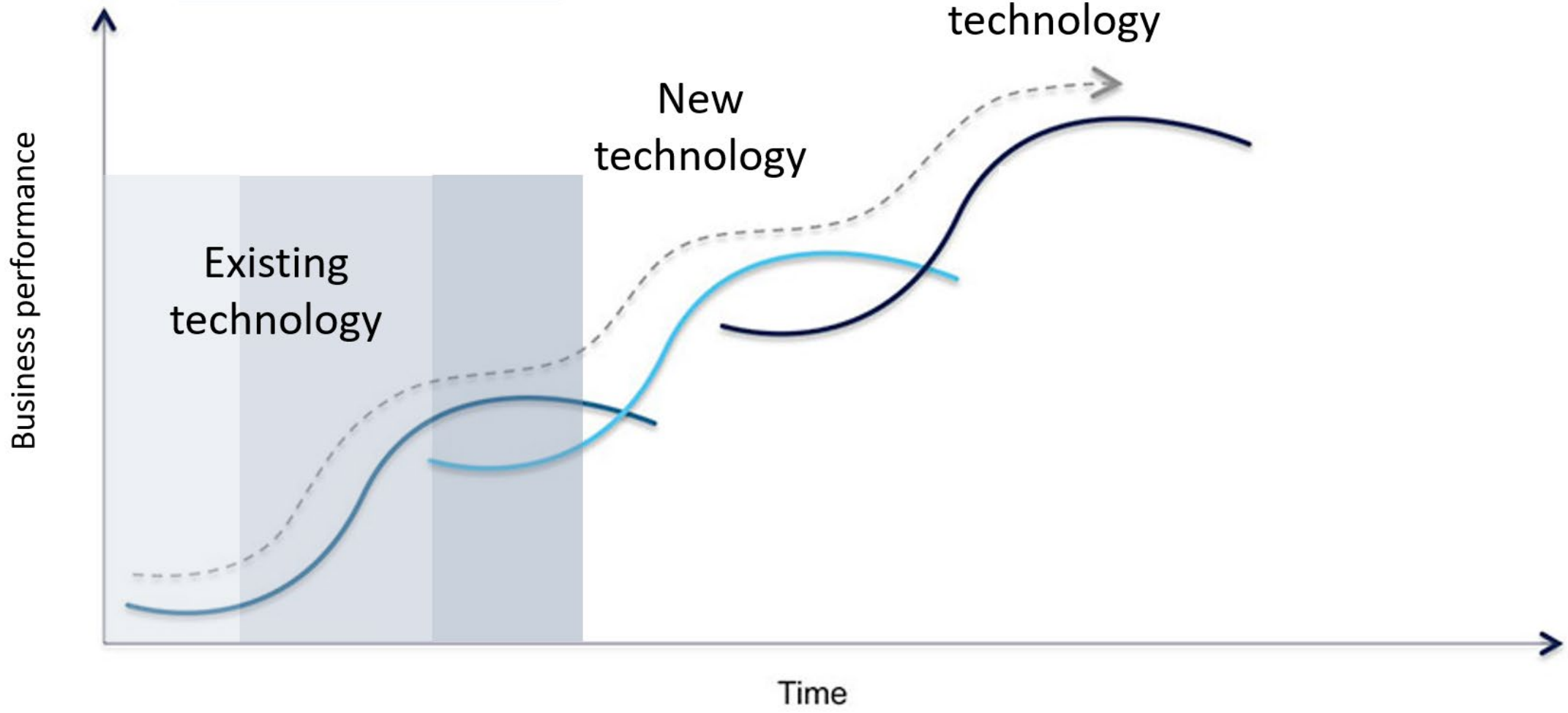




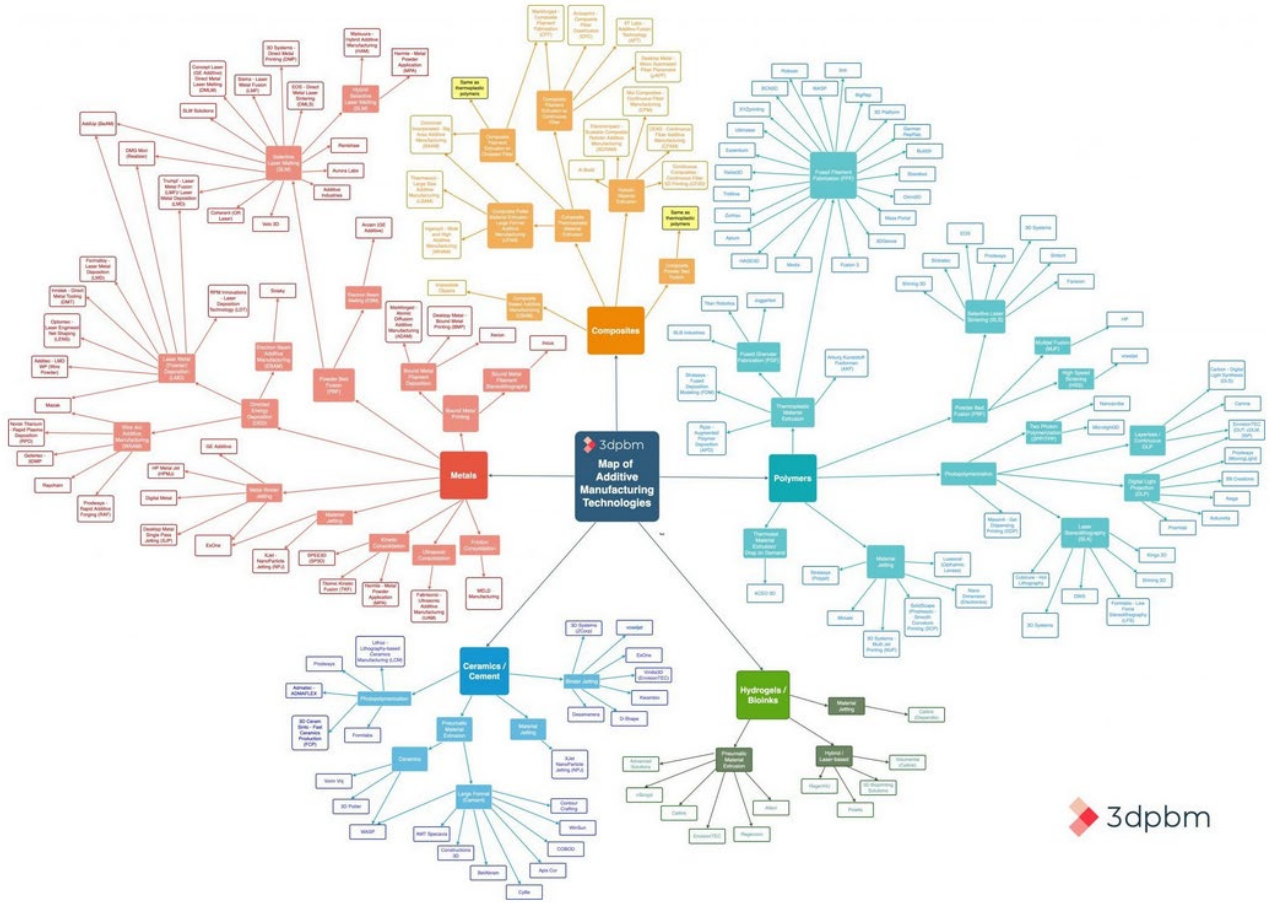


enfance

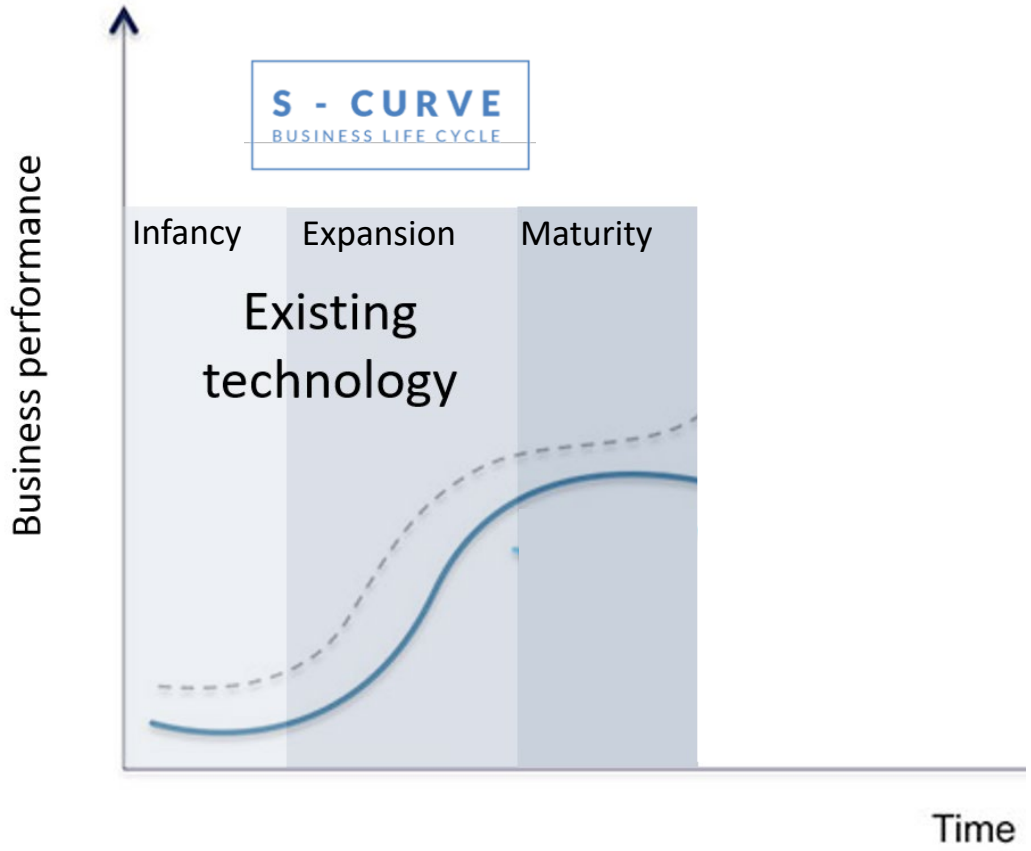
# S - CURVE
BUSINESS LIFE CYCLE



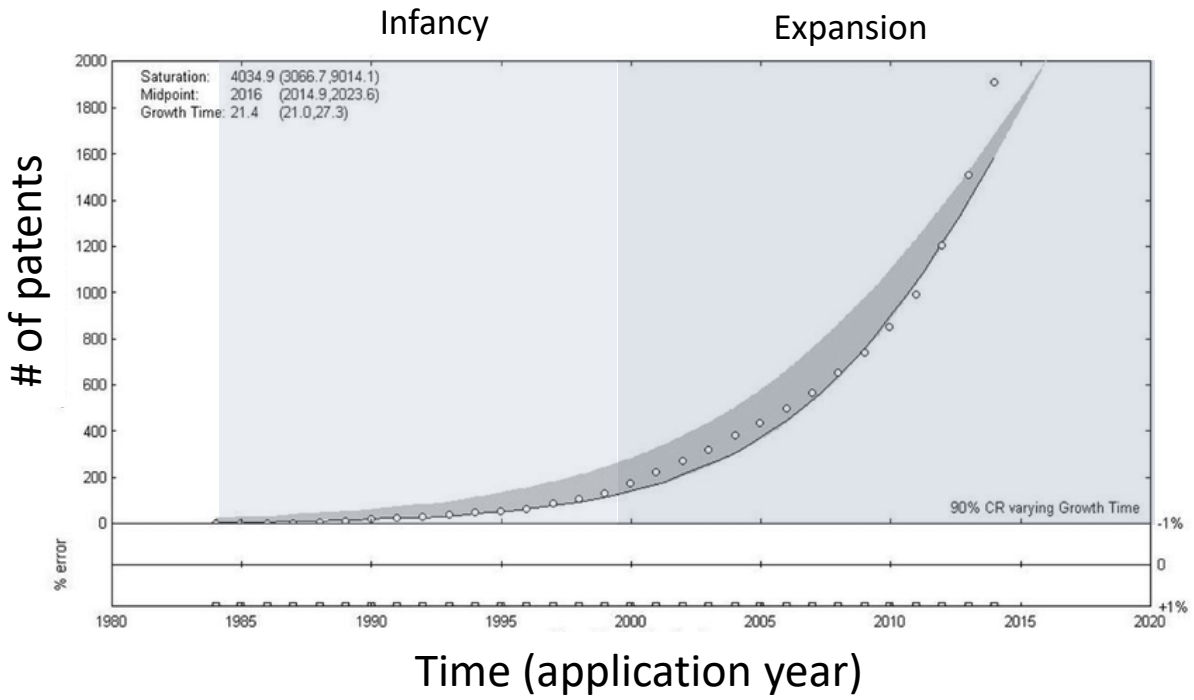
# Map of 3D Printing technology



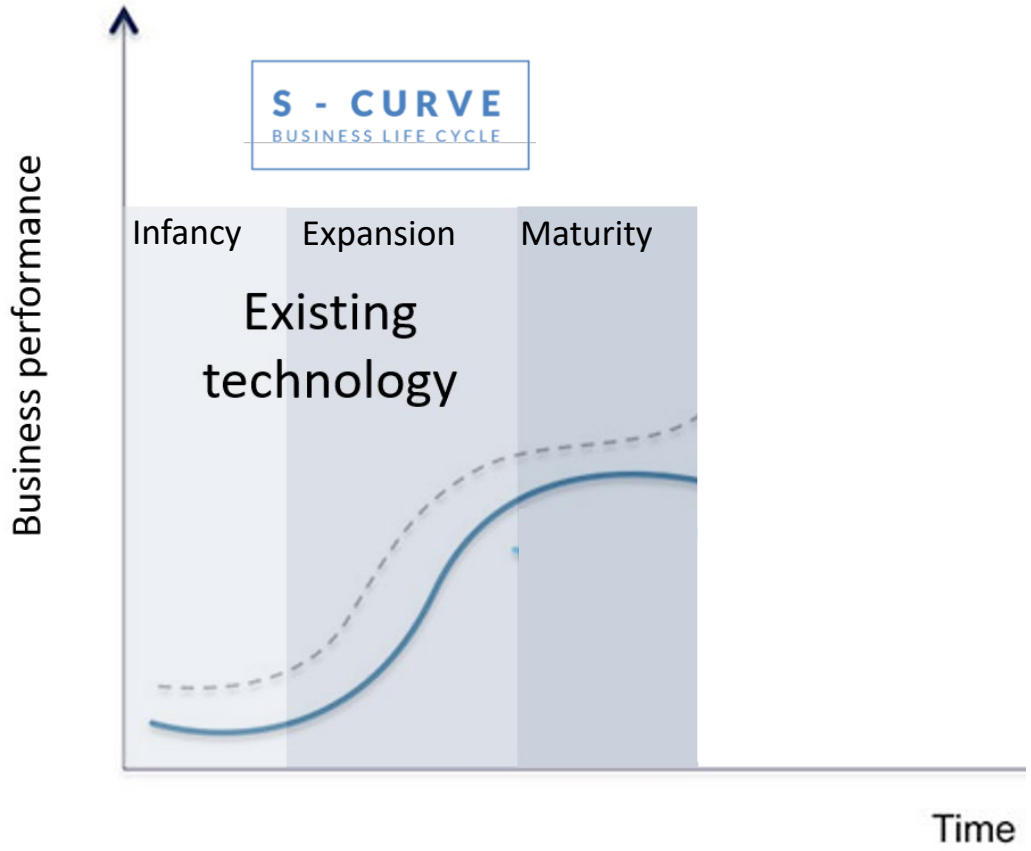

# 3D Printing where we are ?



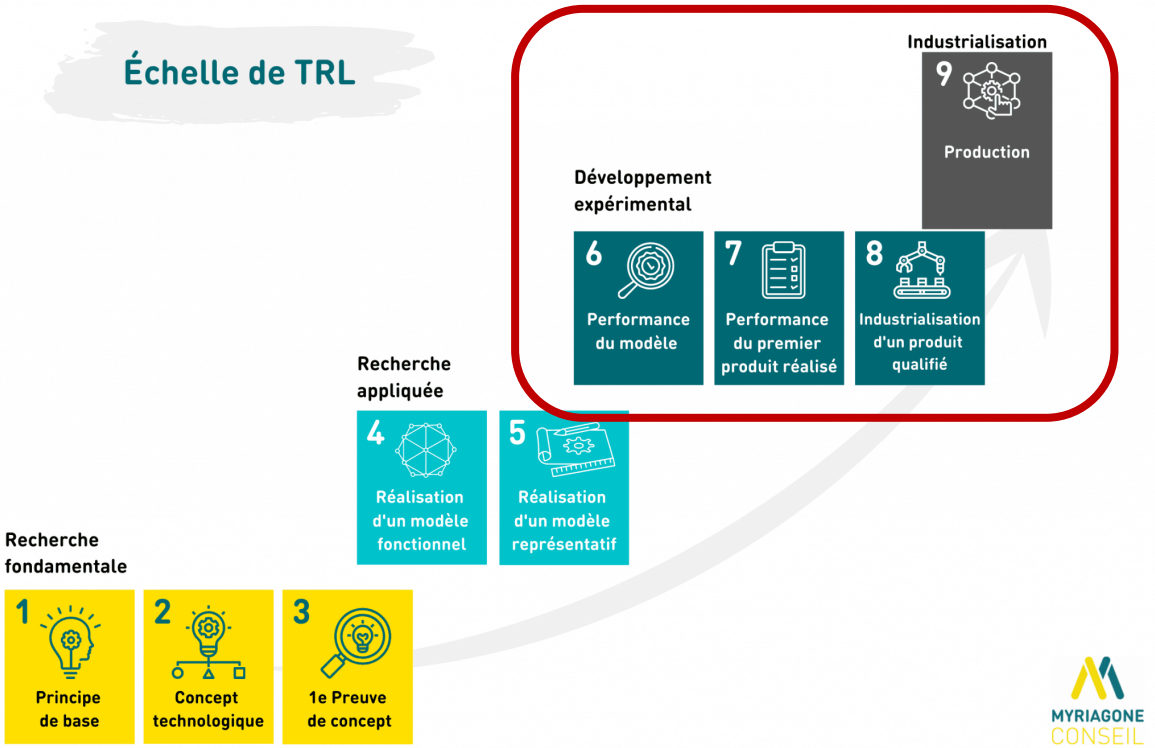
# 3D Printing
# where we are ?



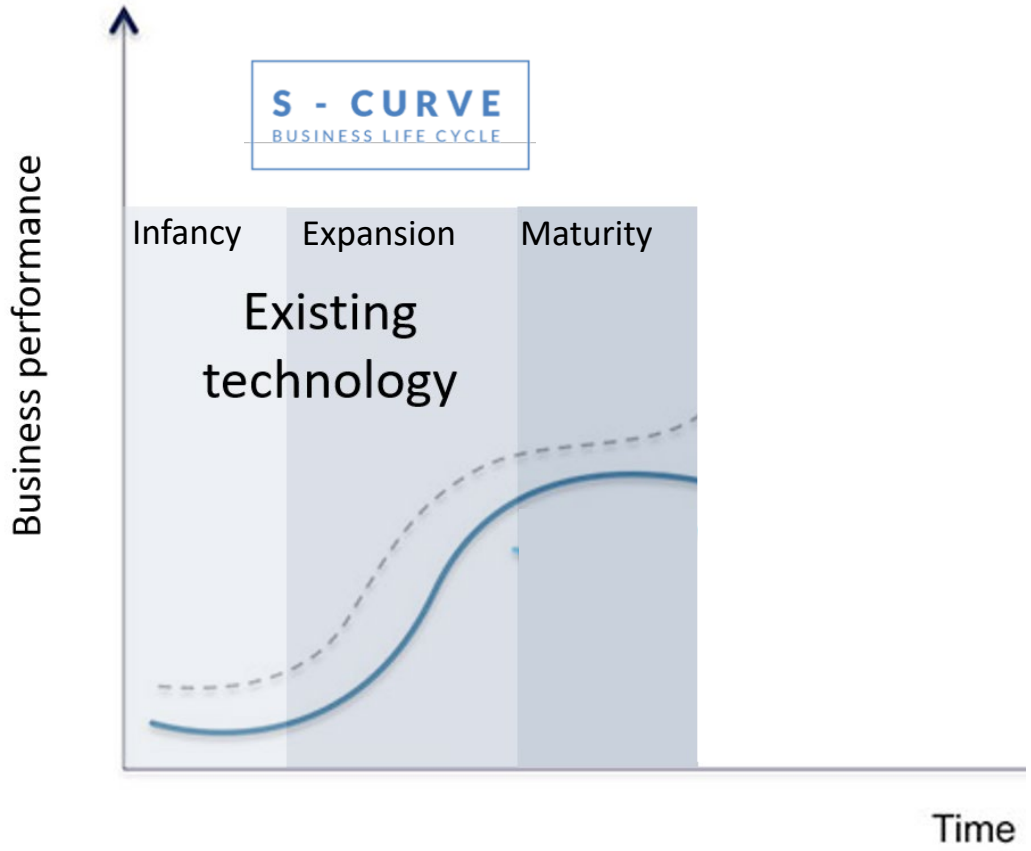

Porter *et al* Scientiometrics, 111 (2017) 185




enfance




# 3D Printing where we are ?



**Introduction of a NEW paradigme/concept**

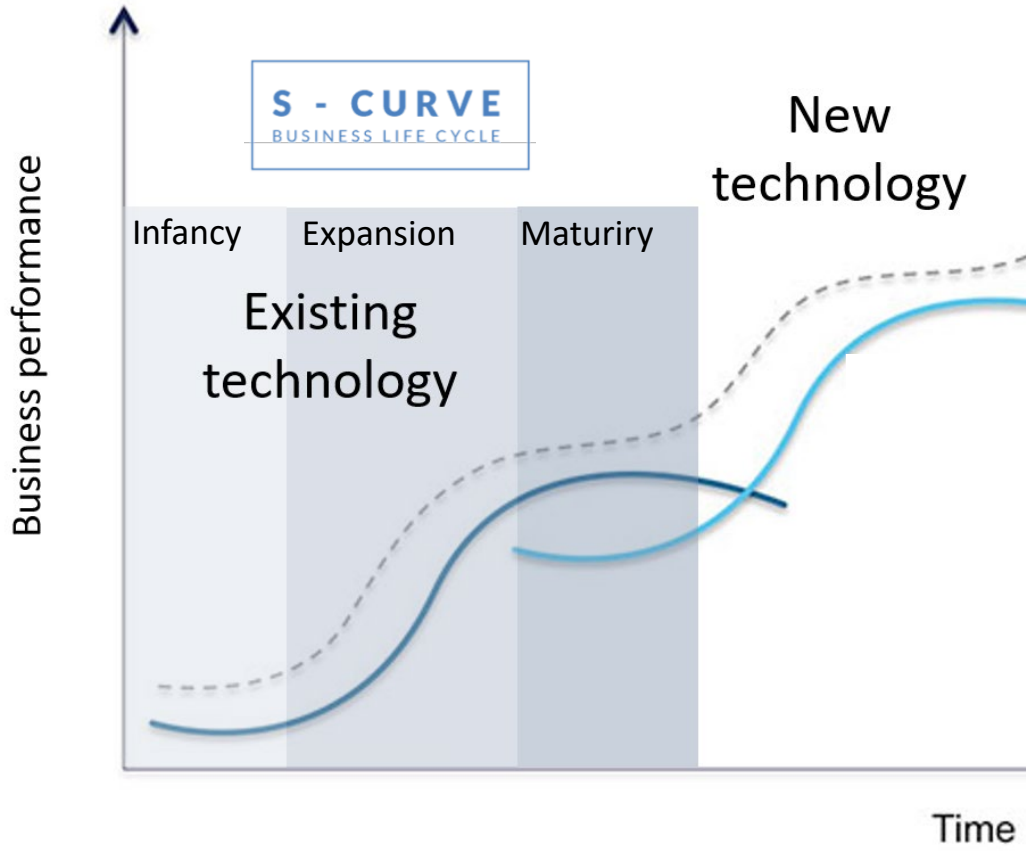
3D printing

↓

**Programmable Matter**

The ability for the matter to change its physical properties in a programmable fashion

What's the next New technology ?

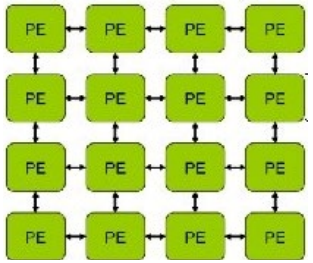


# Introduction of a NEW paradigme/concept

**PROGRAMMABLE MATTER: CONCEPTS AND REALIZATION**

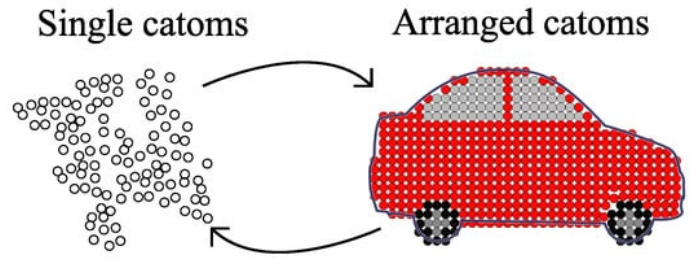
Tommaso TOFFOLI and Norman MARGOLUS
*MIT Laboratory for Computer Science, Cambridge, MA 02139, USA*

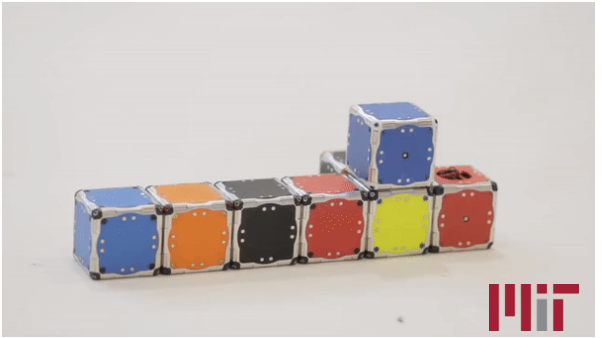
Physica D 47 (1991) 263–272
North-Holland




Fine-grained compute nodes distributed throughout space which communicate using only nearest neighbor interaction

## Modular robotics & Claytronics



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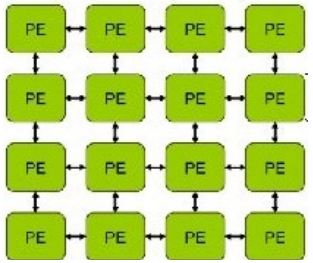
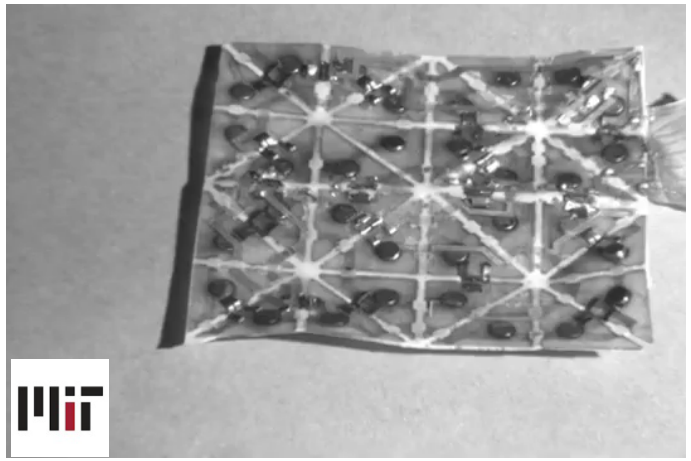



Fine-grained compute nodes distributed throughout space which communicate using only nearest neighbor interaction

**Defense Advanced Research Projects Agency (DARPA)**

Programmable matter Program (2004)



Agence pour les projets de recherche avancée de défense

## Skylar Tibbits

TEDx 2012

SELF-ASSEMBLY LAB

What's the next
New technology ?

3D printing of programmable matter

4D Printing

**3D PRINTING**

- Engineers

**Smart Materials**

- Physicists
- Chemists
- Biologists

# 4D Printing

COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK

**time**

Functional and Dynamical 3D printed structures

# 4D printing

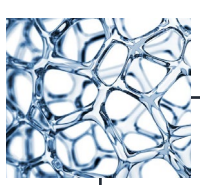
## Self-healing

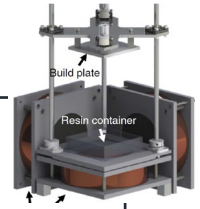
## Self-adaptability


## Self-assembly

Stimuli-responsive materials

Additive 3D manufacturing (AM)





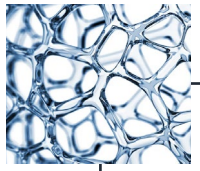

COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK


Environmental stimuli

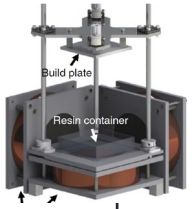
Design, Modelling & Simulation

4D printing **is not** a simple 3D printing process as it requires the combination of several pieces of knowledge and involves multiple research fields

Stimuli-responsive materials



Additive 3D manufacturing (AM)




COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK


Environmental stimuli

Design, Modelling & Simulation


## Thermo-responsive

Zarek, Advanced Materials 2015

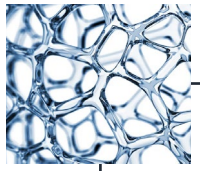
## Light-Responsive

Yang, Advanced Materials 2017

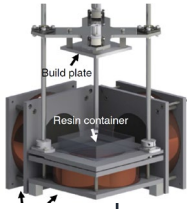
## Magneto-responsive


Kim, Nature 2018

Stimuli-responsive materials



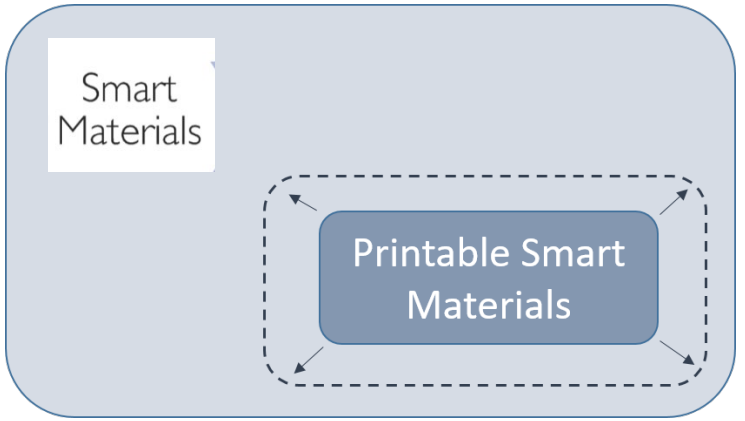
Additive 3D manufacturing (AM)




COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK


Environmental stimuli

Design, Modelling & Simulation




- Polymers
- Ceramics
- Metals

## Thermo-responsive

Zarek, Advanced Materials 2015

## Light-Responsive

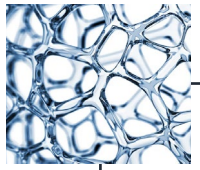
Yang, Advanced Materials 2017

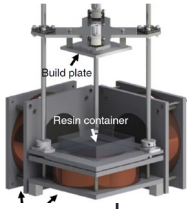
## Magneto-responsive


Kim, Nature 2018

Stimuli-responsive materials

Additive 3D manufacturing (AM)



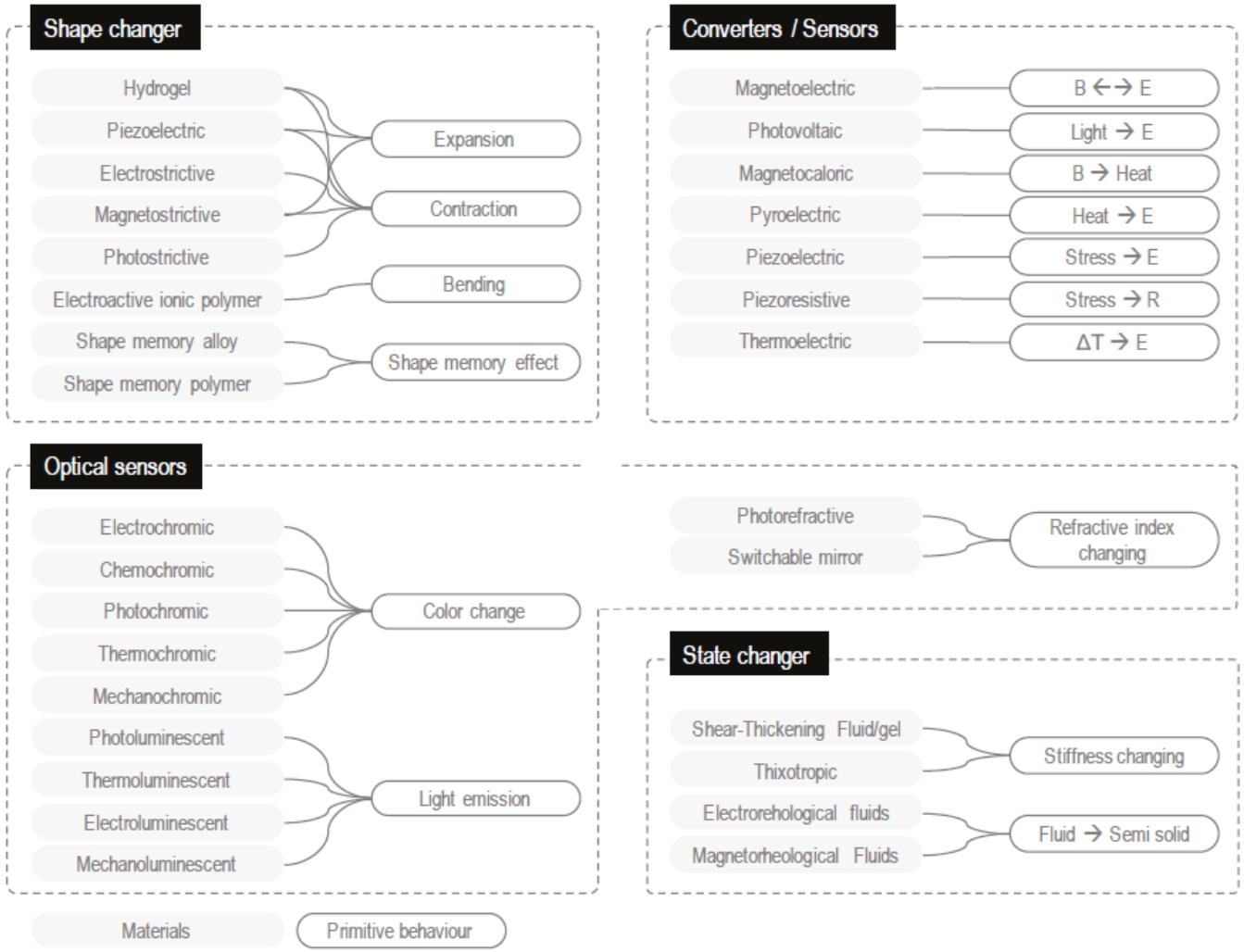



COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK


Environmental stimuli

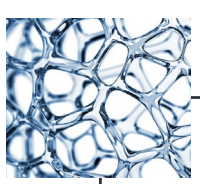
Design, Modelling & Simulation

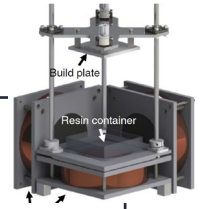
You need to apply external stimuli



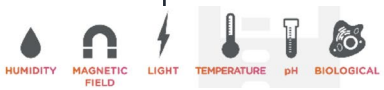
Stimuli-responsive materials

Additive 3D manufacturing (AM)





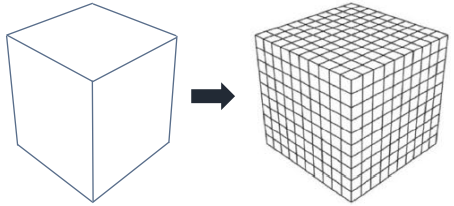

COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK

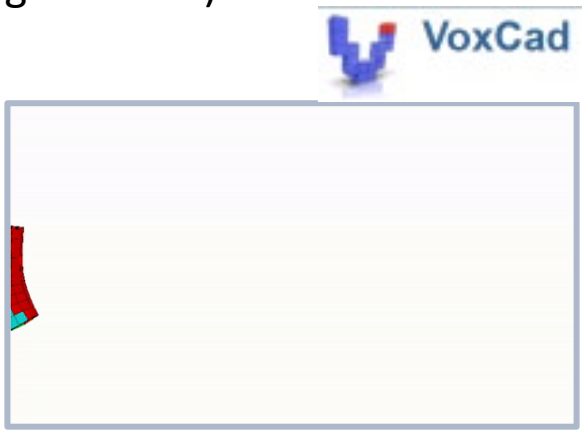



Environmental stimuli

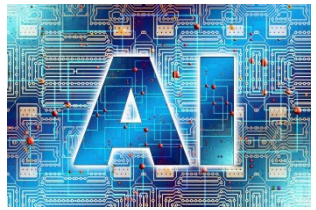
Design, Modelling & Simulation

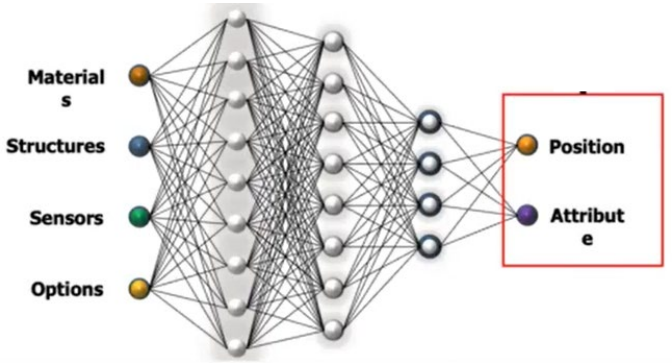
Simulating the motion of the object
(Inverse Engineering Problem)




https://www.creativemachineslab.com

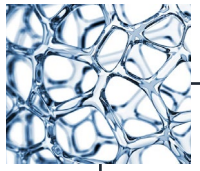


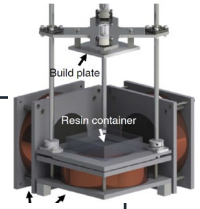




Modeling and prediction of the behavior of the object
due to the nonlinearity of the material
(Artificial Intelligence & Machine Learning)

Stimuli-responsive materials

Additive 3D manufacturing (AM)





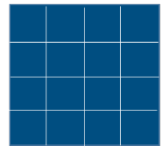

COURTESY OF SELF-ASSEMBLY LAB / MIT / STRATASYS / AUTODESK


Environmental stimuli

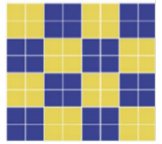
Design, Modelling & Simulation

Multi-smart-materials 3D Printers

Single smart material

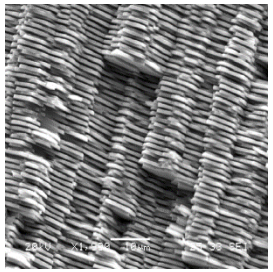


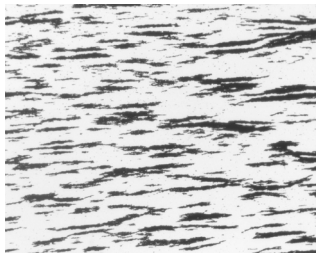

Multi-materials distribution



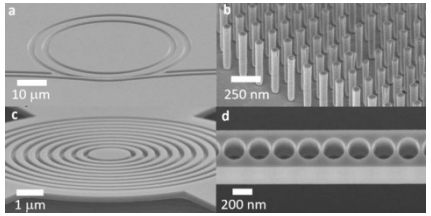

Microstructure distribution


Stimuli-adapted 3D printers





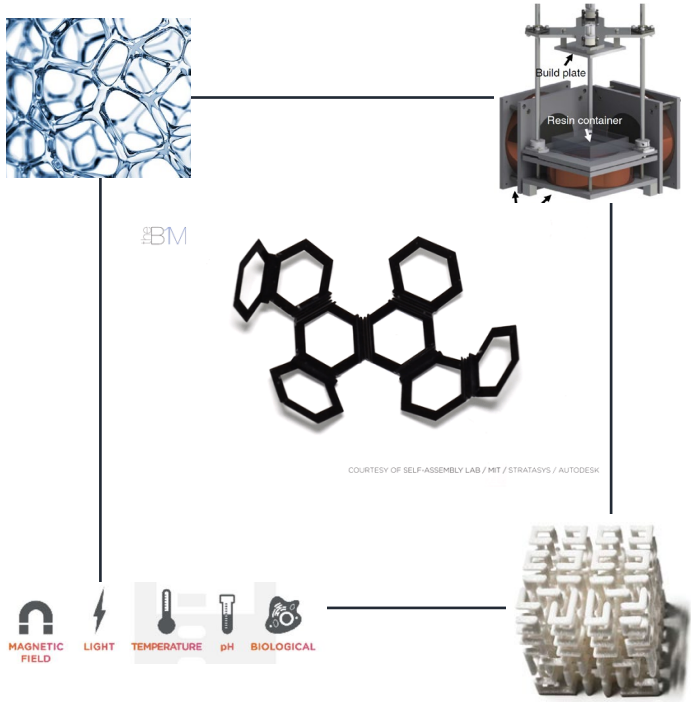
How to introduce Micro&Nano structuration during the printing process?



# *4D printing of magneto-actuated devices with tunable mechanical and magnetic properties*

Stimuli-responsive materials

Additive 3D manufacturing (AM)




Environmental stimuli

Design, Modelling & Simulation

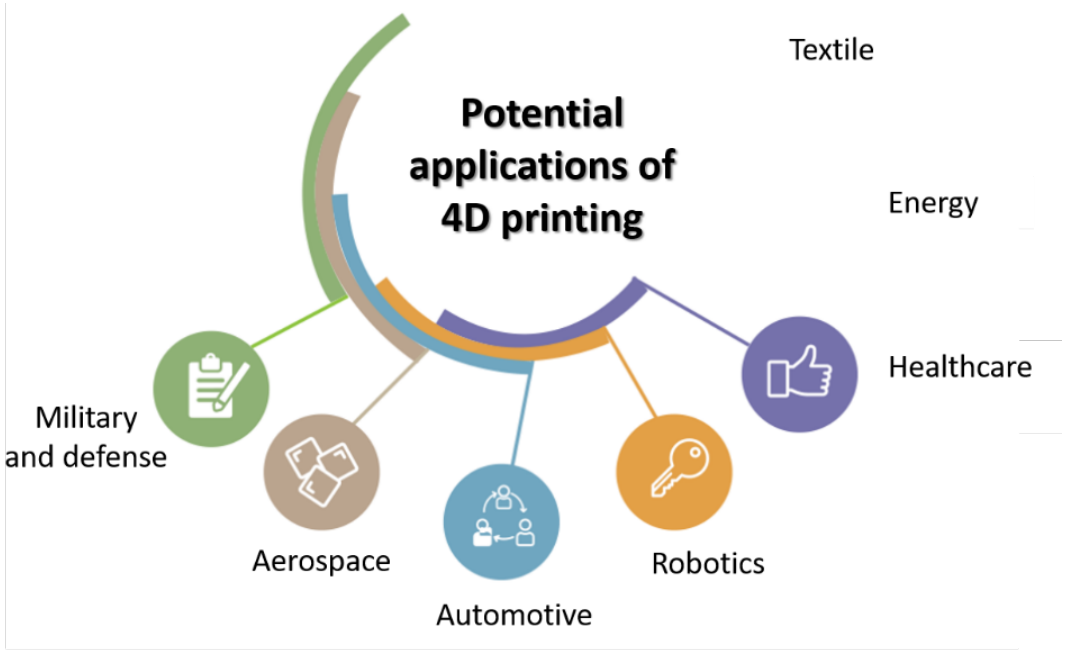
**Programme d'investissements d'avenir (PIA4)**

**Programmes et Equipements Prioritaires de Recherche (PEPR)**
1 Md€

Dispositifs Intégrés pour l'Accélération du DEploiement de Matériaux Emergents
(**DIADEME**)
(TRL 1-4)

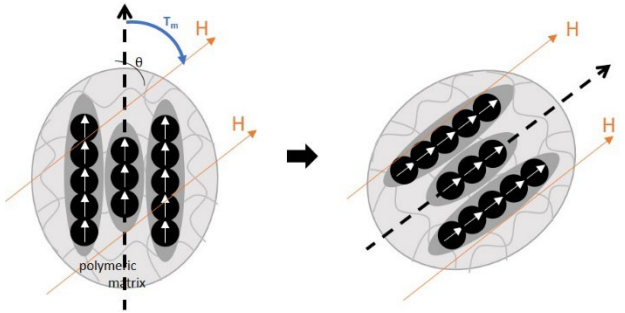
Combiner de façon intégrée
- modélisation
- simulation numérique
- intelligence artificielle (IA)
- technologies de synthèse/criblage
- caractérisation à haut débit

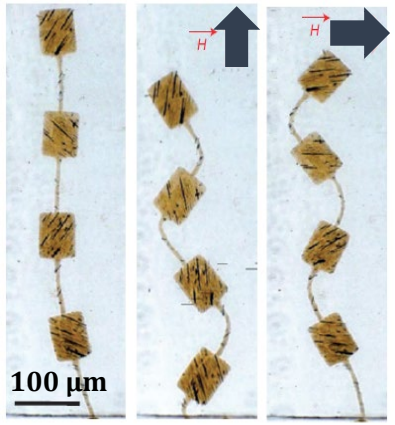
# Potential applications



# Soft Robotics

## Actuation by magnetic torques



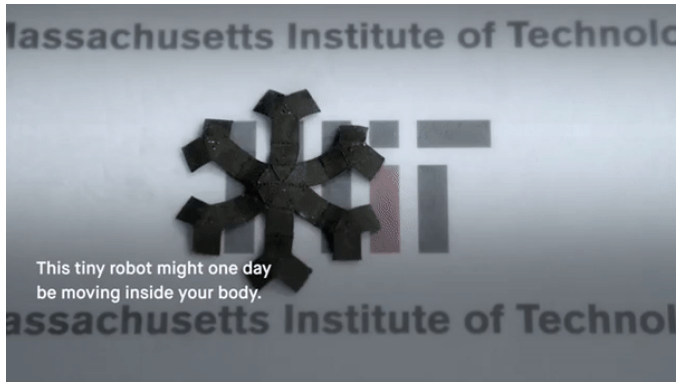




Kim, Nature materials 2011

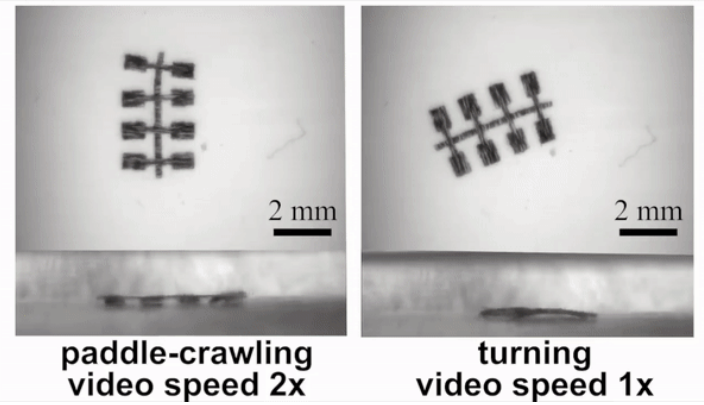
## Magnetic-driven robots


Lu, Nature Communication 2018


Hu, Nature 2018

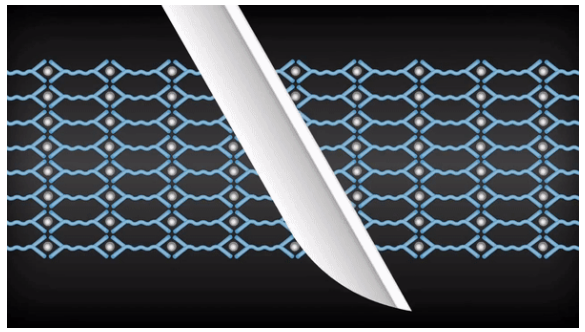


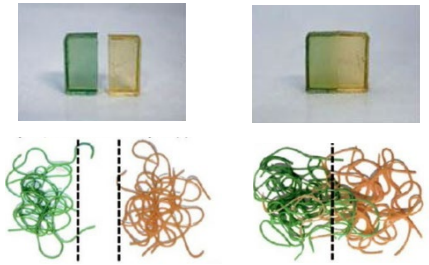

Kim, Nature 2018

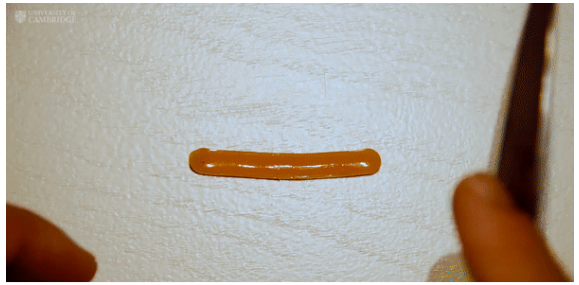



Kim, Advanced Science 2020

# Self-Healing Materials

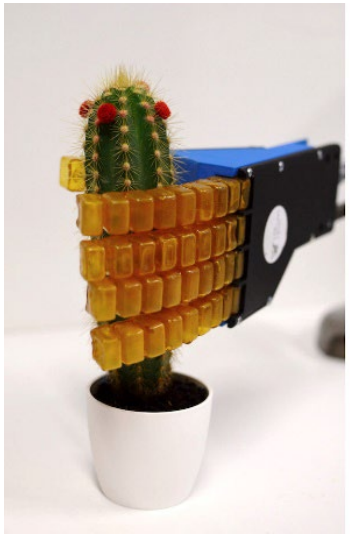






## Self-Healing Soft Robots

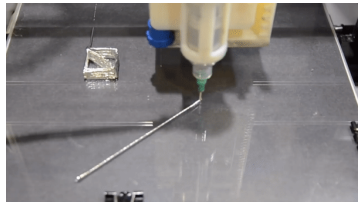
SHERO

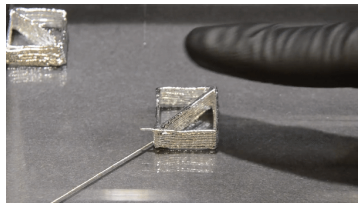


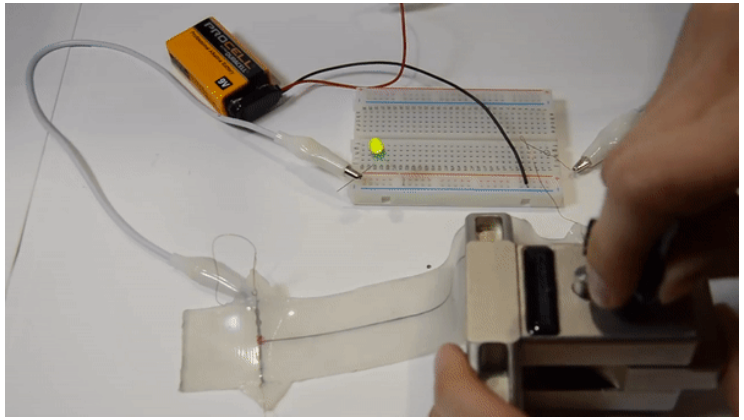
HORIZON 2020

## Hybrid 3D Printing of Soft Electronics

Liquid metal-based stretchable interconnects, antennas, and self-healing electronics

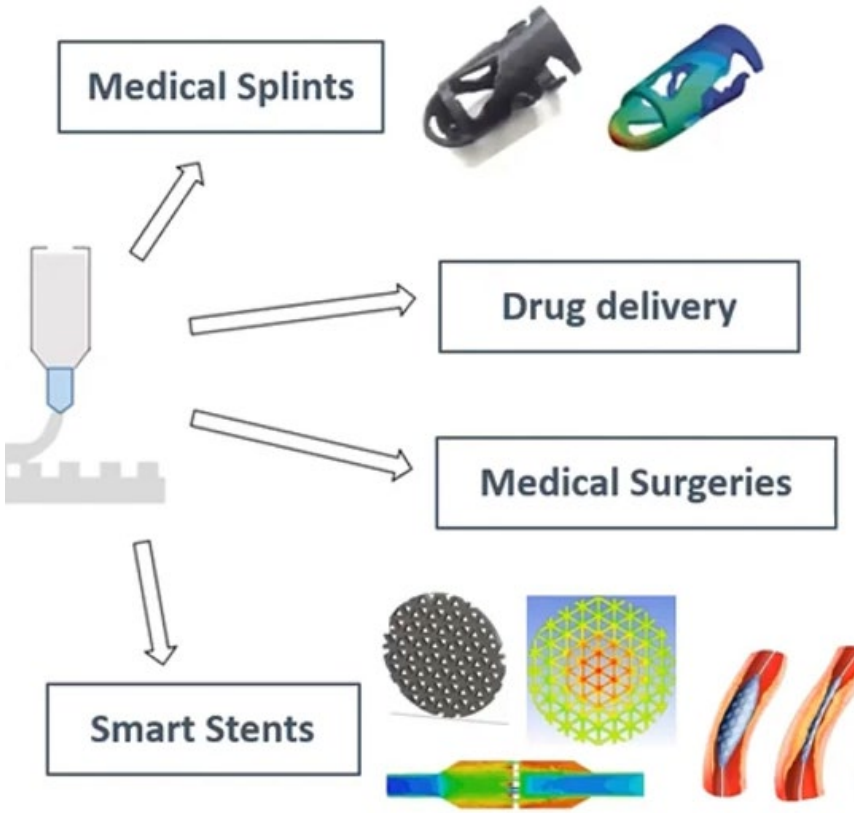




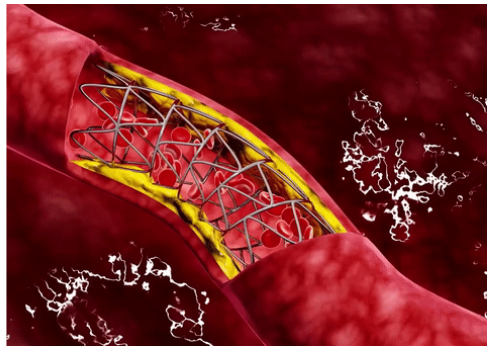


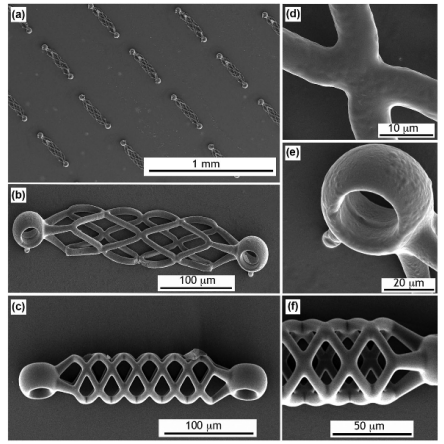
Valentine, Advanced Materials 2017

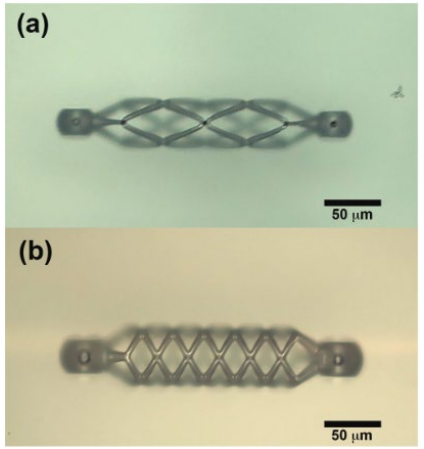
# Healthcare




## Smart stents

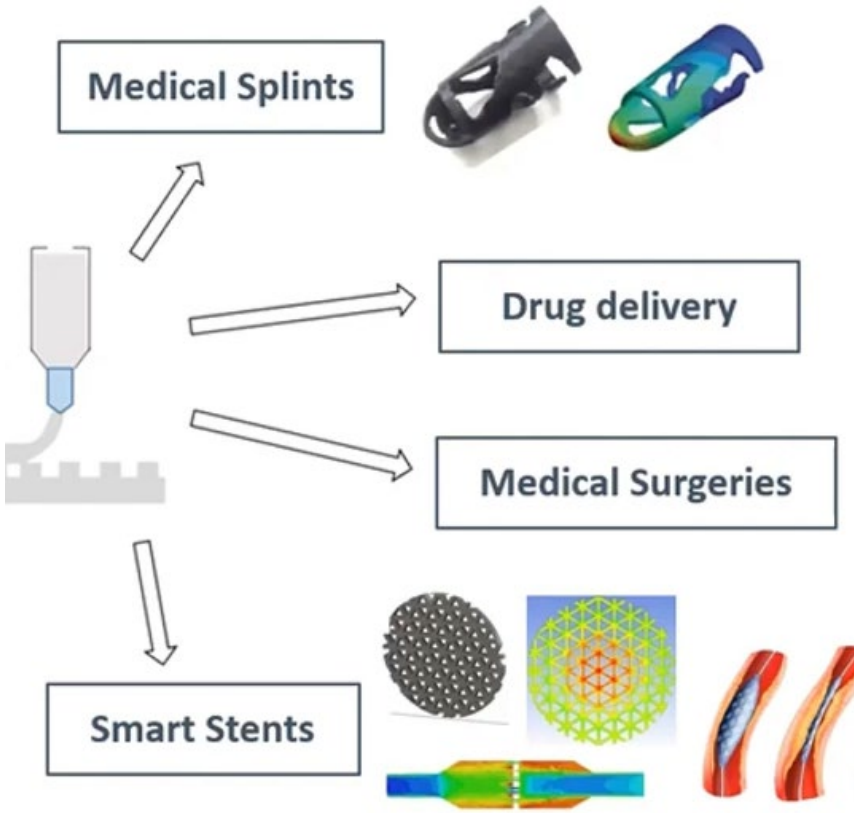




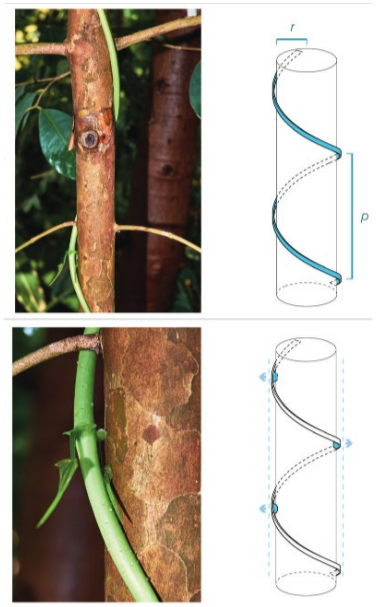




De Marco, Adv. Mat. Tech 2019

# Healthcare



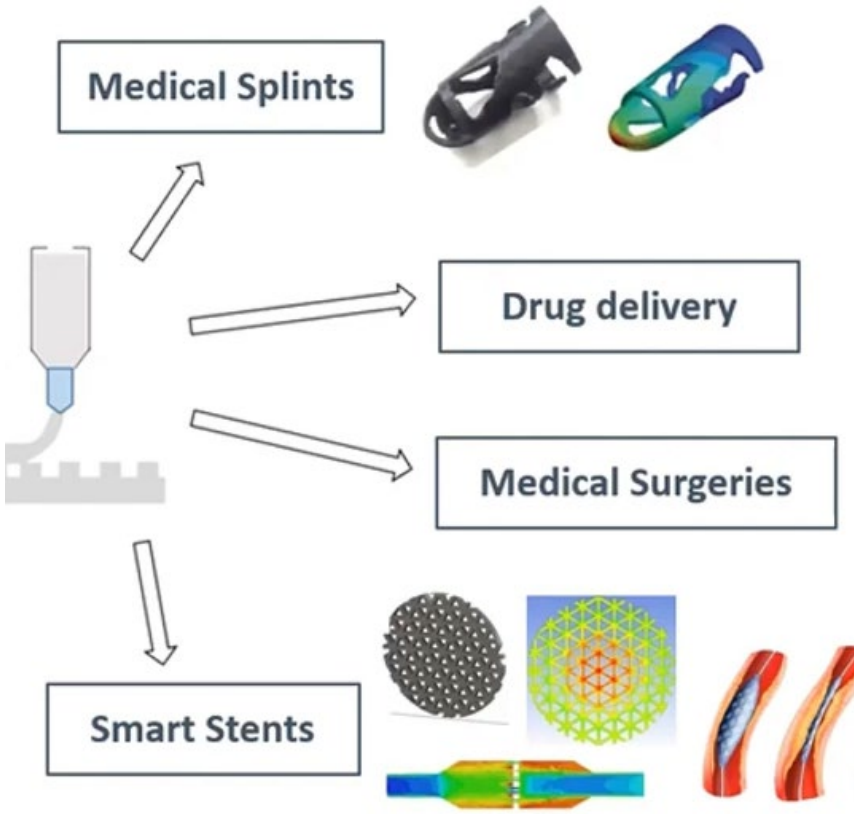

## Functional Orthotic devices



Orthèses

Cheng, Advanced Science 2021

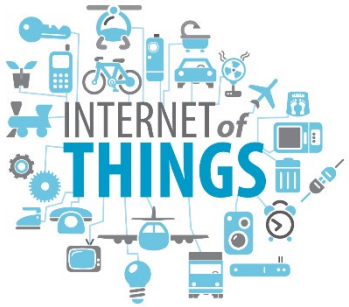
# Healthcare



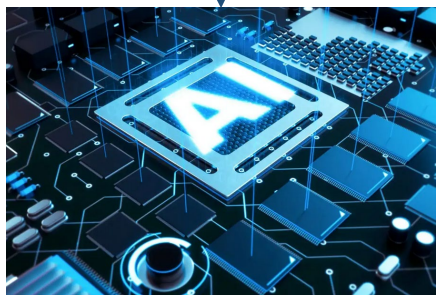

## Drug Delivery


Hu, Nature 2018

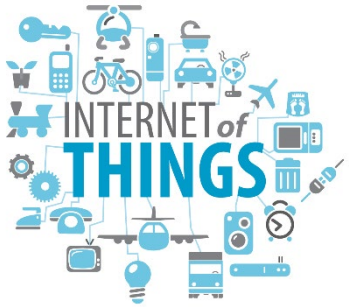
# Wearable and Internet of Things (IoT)-connected technologies

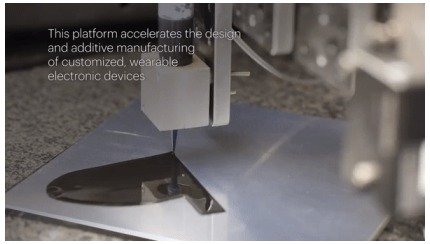



IOT - CONNECTS DEVICES
AI - TAKES DECISIONS



# Wearable and Internet of Things (IoT)-connected technologies



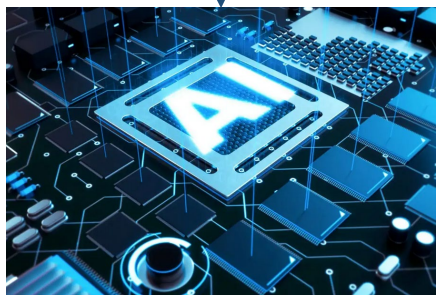



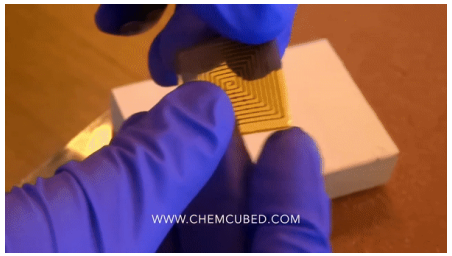

IoT-based 3D Printing

IOT - CONNECTS DEVICES
AI - TAKES DECISIONS

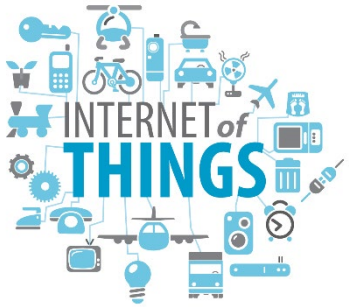
3D printing

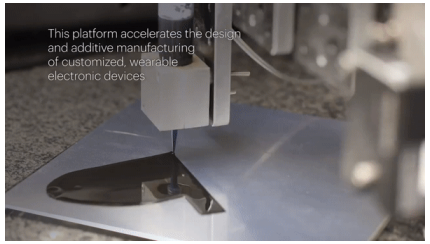
- Subtractive to additive IoT fabrication
- Lower cost/environmental impact
- Flexible Hybrid Electronics
- Wireless powering/communications



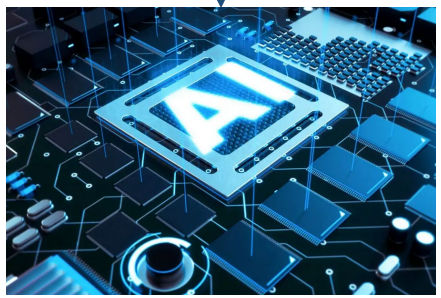
# Wearable and Internet of Things (IoT)-connected technologies




## IoT-based 3D Printing

IOT - CONNECTS DEVICES
AI - TAKES DECISIONS

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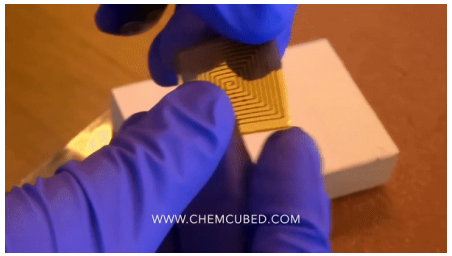
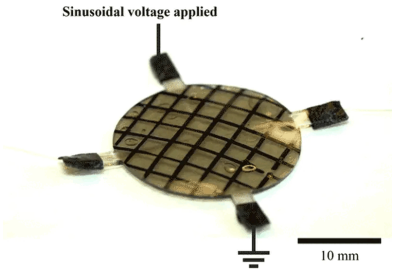
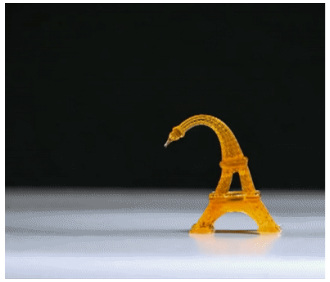


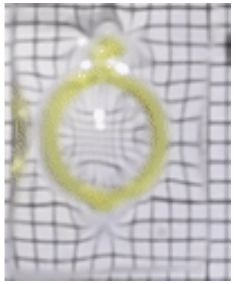

4D Printing

## Actuation



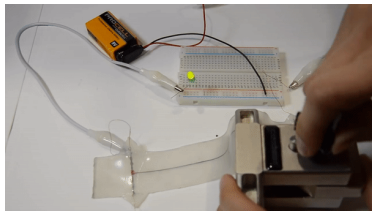

## Shape-shifting & origami-inspired RF structures





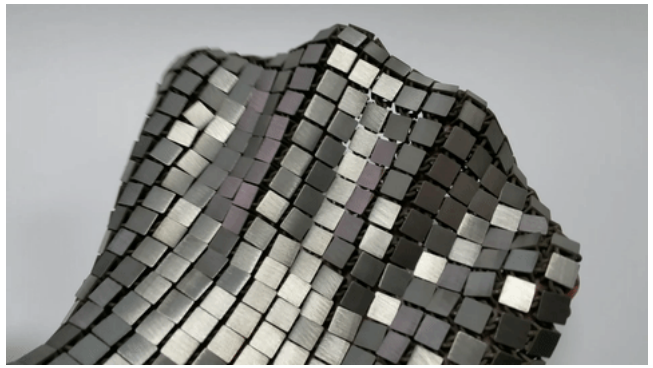
## Energy Harvesting & Self Powering

## Self-healing

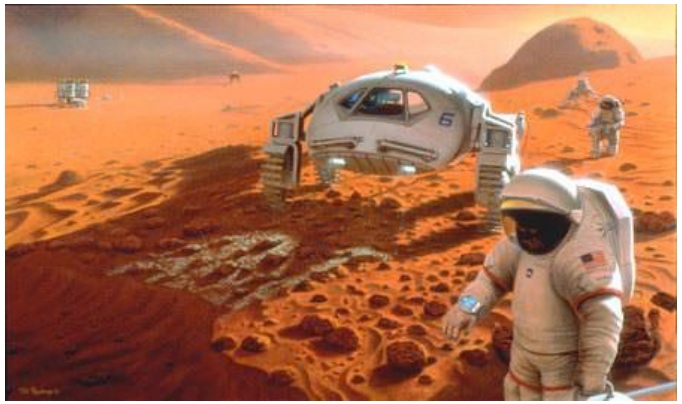


# Spatial

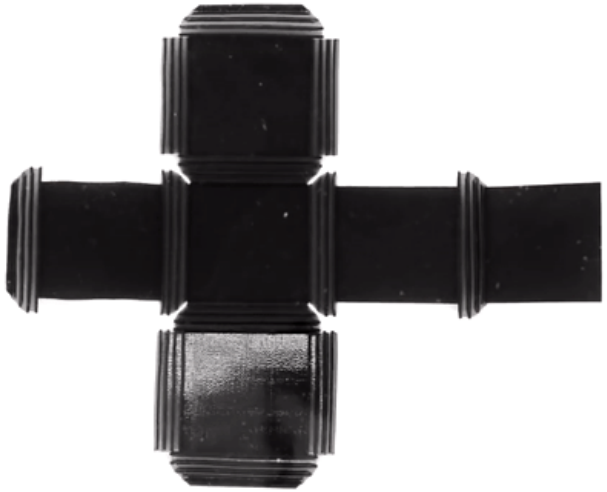
Generative Space Architectures



NASA JPL Jet Propulsion Laboratory

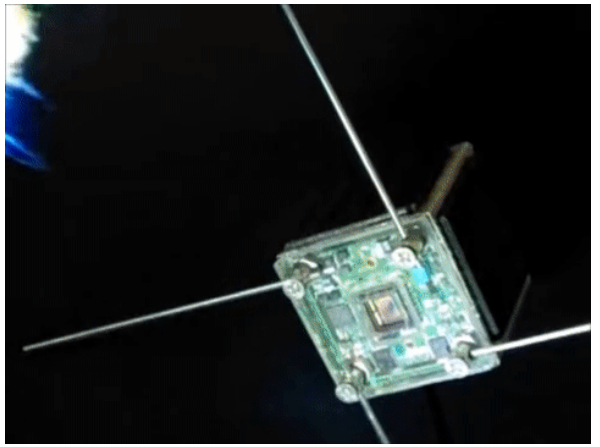


Origami folding



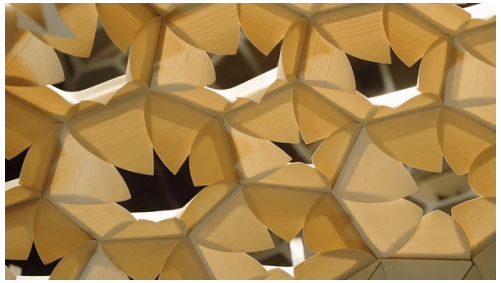
SELF-ASSEMBLY LAB MIT

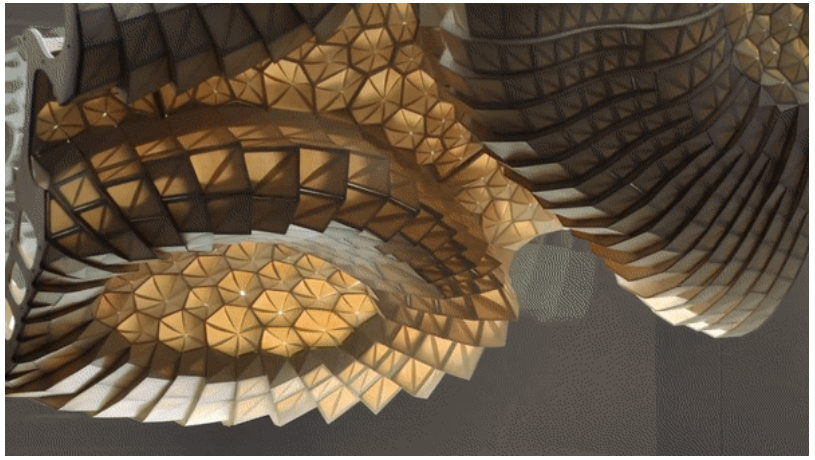
CUBESAT



# Design & Architecture

Climate-responsive architectures

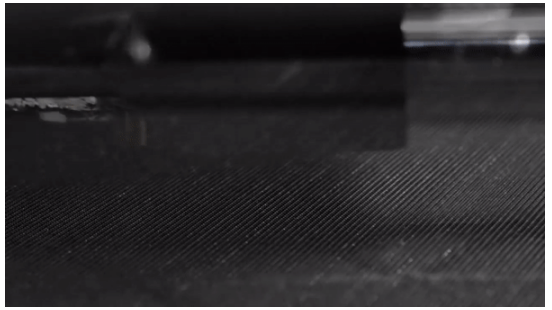


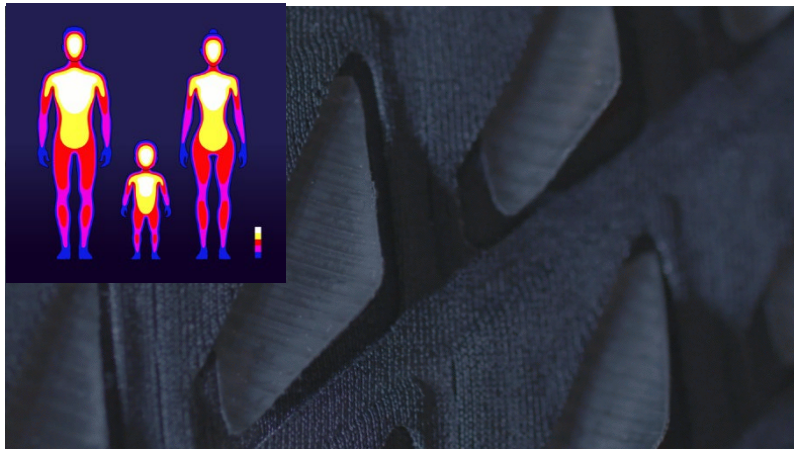


HygroSkin Meteo-sensitive Pavillon

http://www.achimmenges.net/

Responsive textile





https://tangible.media.mit.edu/project/biologic/

Responsive Design



Baromorphs

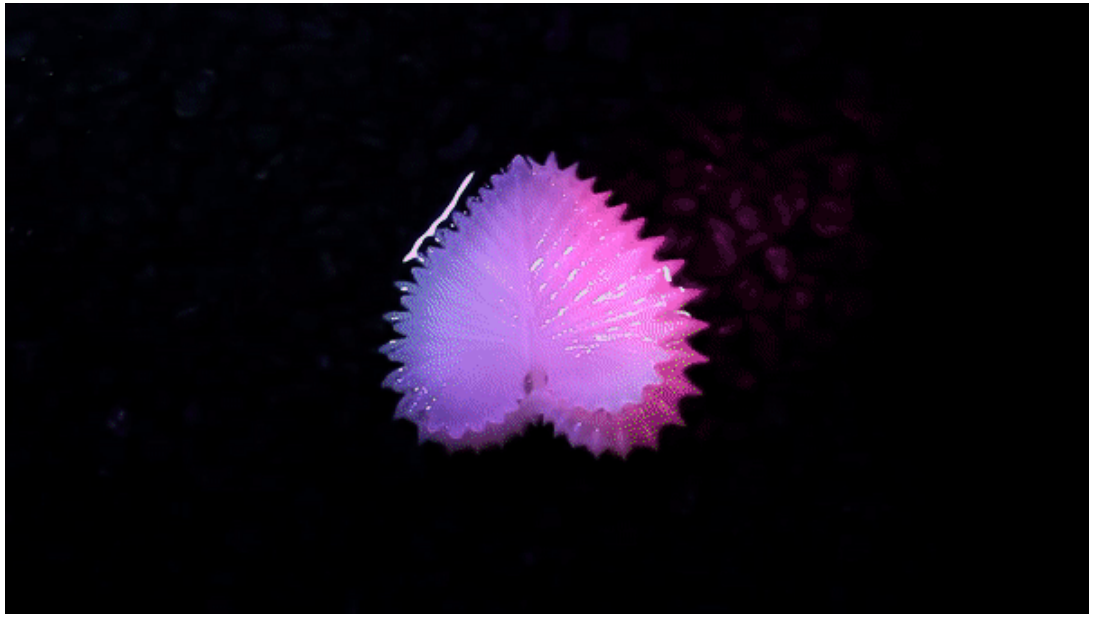



Inflatable structures

Siéfert, Nature Materials 2019

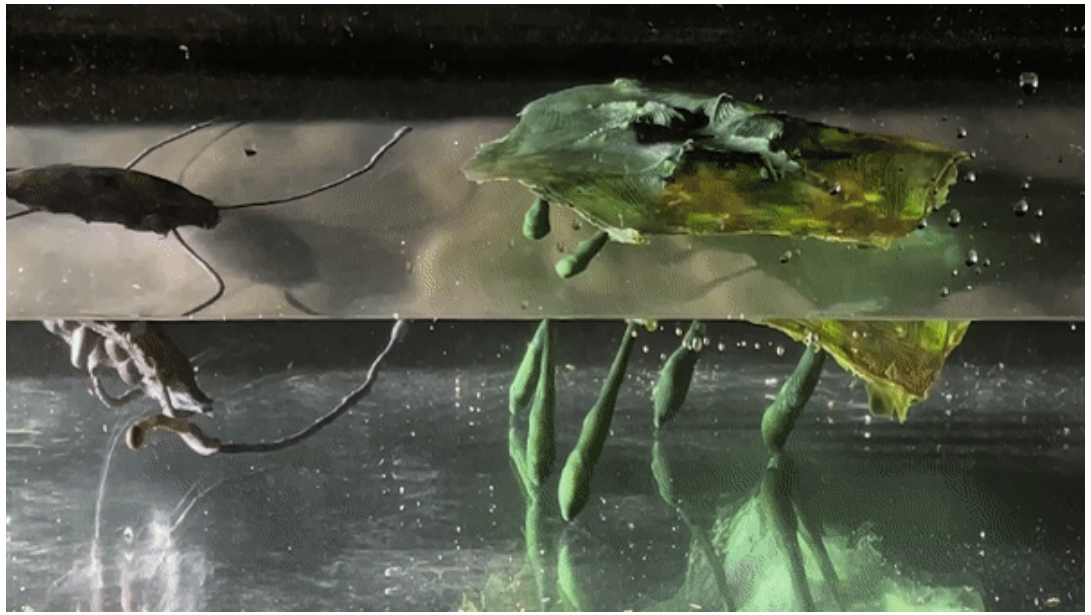
# Art & Science

*Hydrophytes*



https://www.nicolehone.com/hydrophytes

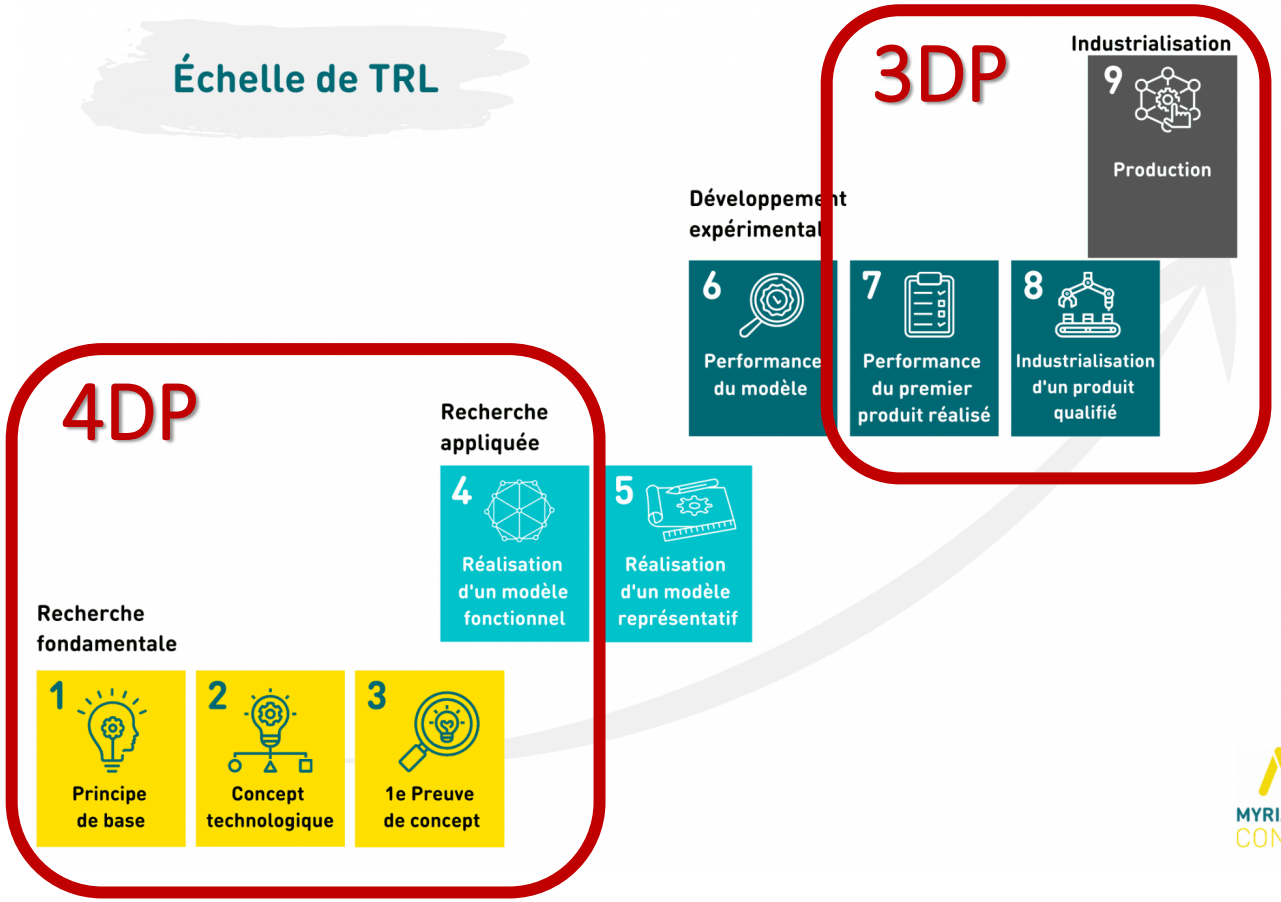
*Zoimorphs*



https://www.youtube.com/channel/UC3WeVDFc14dsUu4n60r3qlg

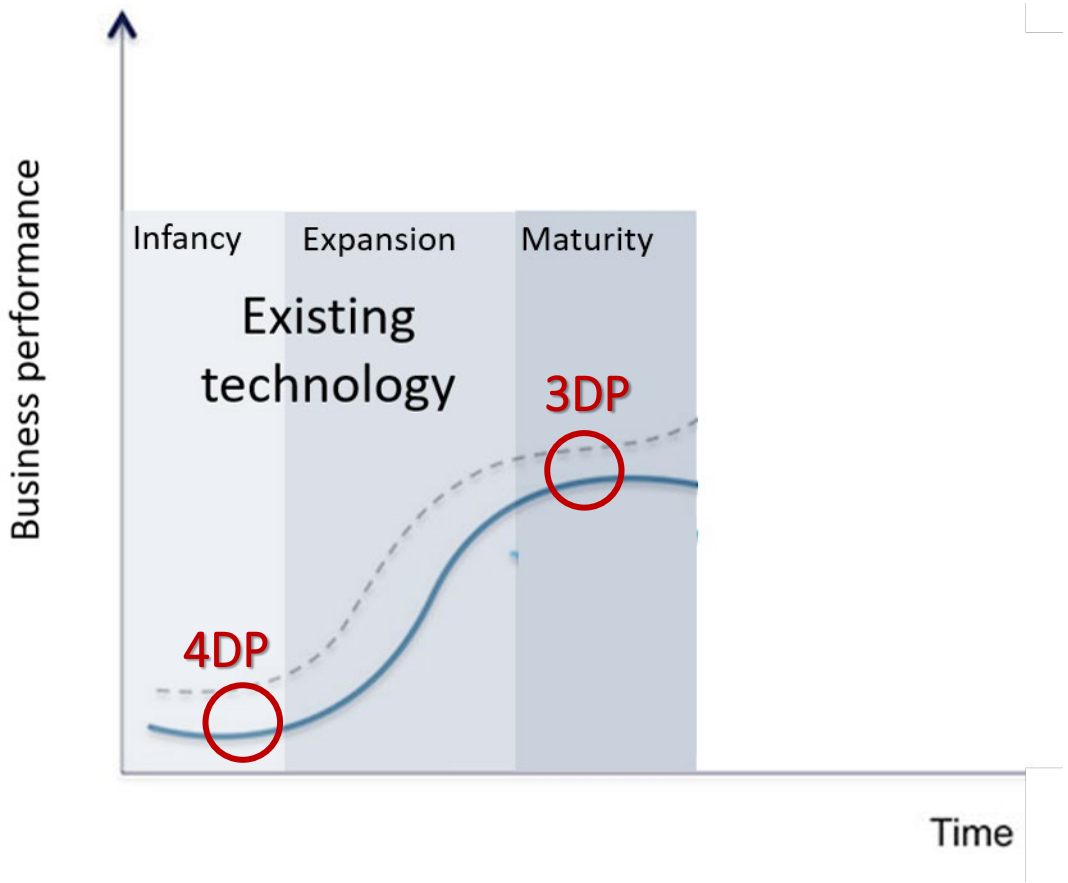
# Global market and perspectives

# Technology Readiness Level

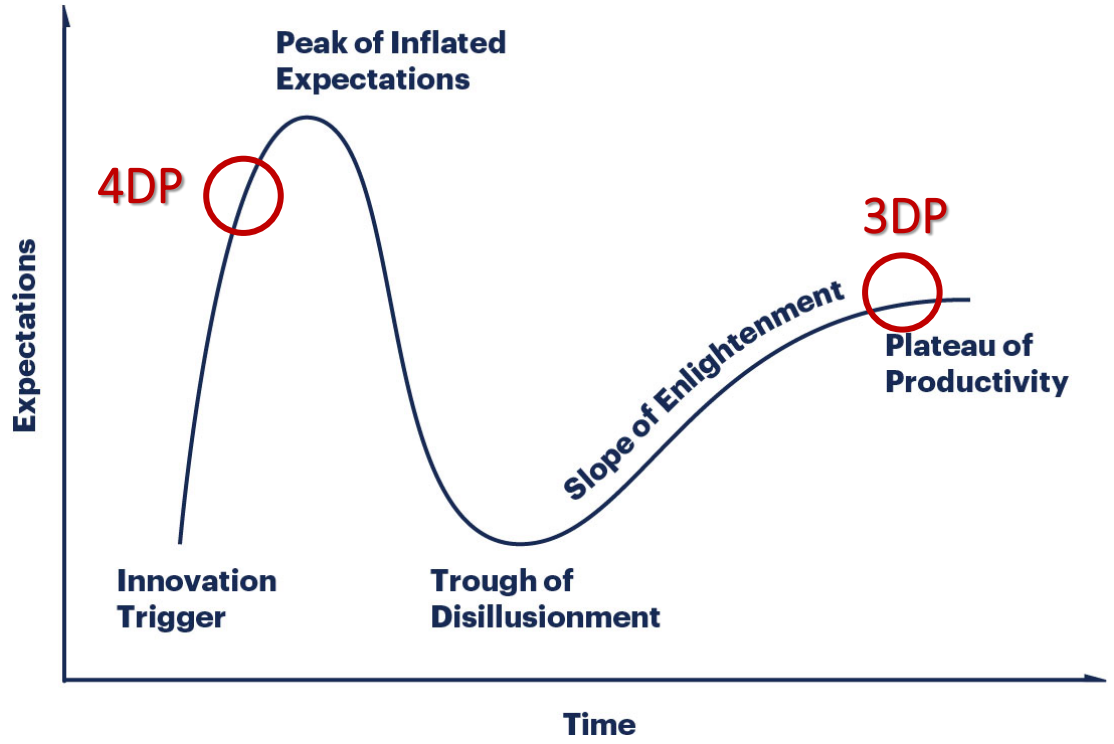



MYRIAGONE CONSEIL

S-CURVE
Bussiness Life Cycle




Gartner Hype Cycle
for Emerging Technologies



## Market Concentration

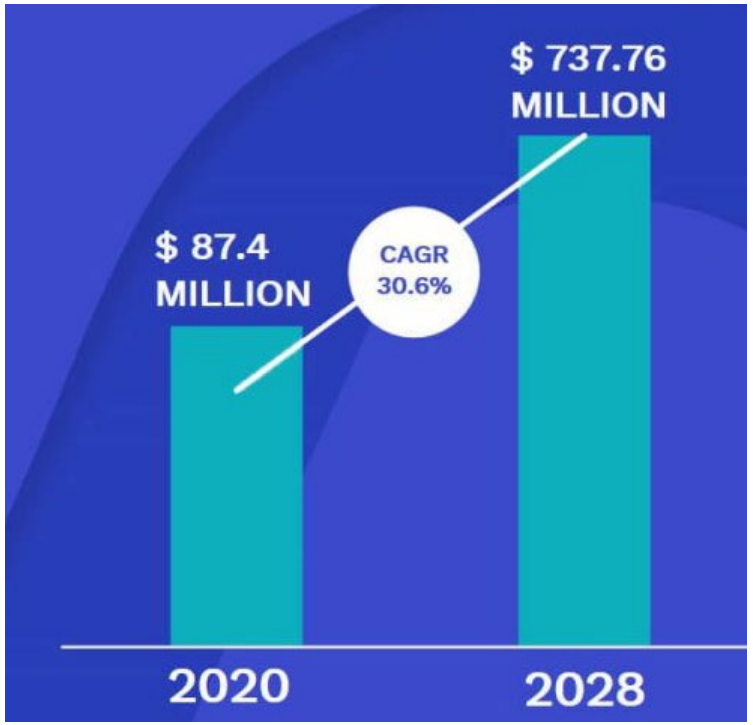
**Consolidated**– Market dominated by 1-5 major players

4D Printing Market

**Fragmented** – Highly competitive market without dominant players

**Source:** Mordor Intelligence

## Global 4DP Market




Taux de croissance annuel moyen



thank you

cea

l'X ÉCOLE POLYTECHNIQUE

IP PARIS