

Brza izrada prototipova i alata

Nastavnik:
Prof. Dr Mladomir Milutinović

Asistent:
Dejan Movrin

Dalji razvoj RP/RT tehnologija

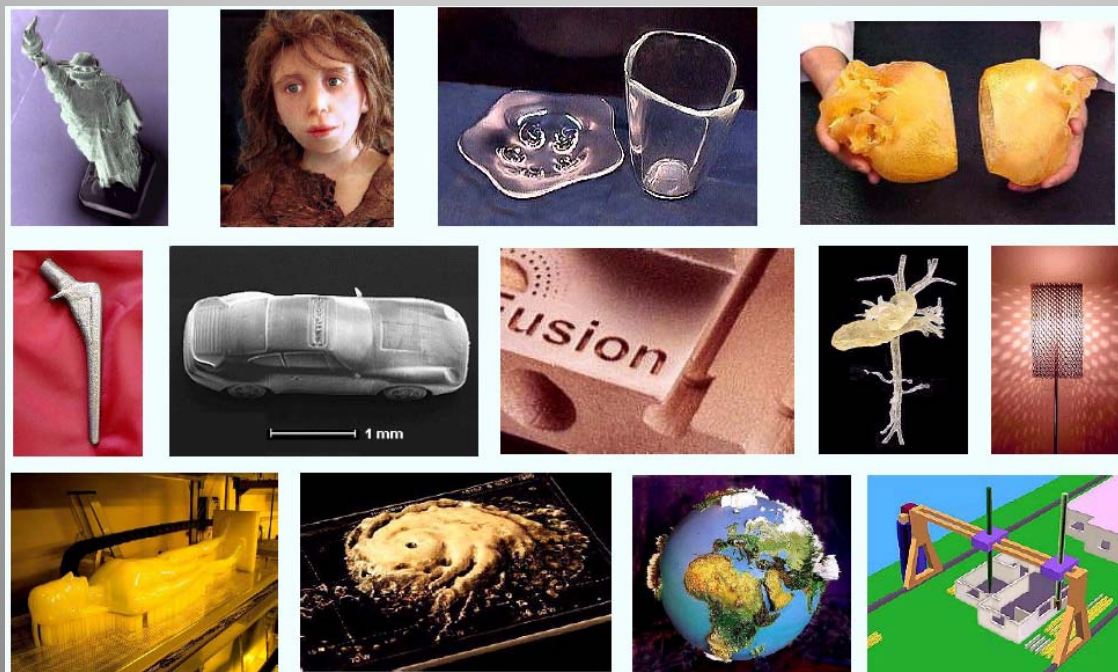
PRINTING THE FUTURE

Tehničke karakteristike:

- a) povećanje brzine izrade modela
- b) povećanje tačnosti modela
- c) novi materijali za RP i RT modele
- d) povećanje dimenzija modela
- e) telegenerisanje proizvoda na zahtev

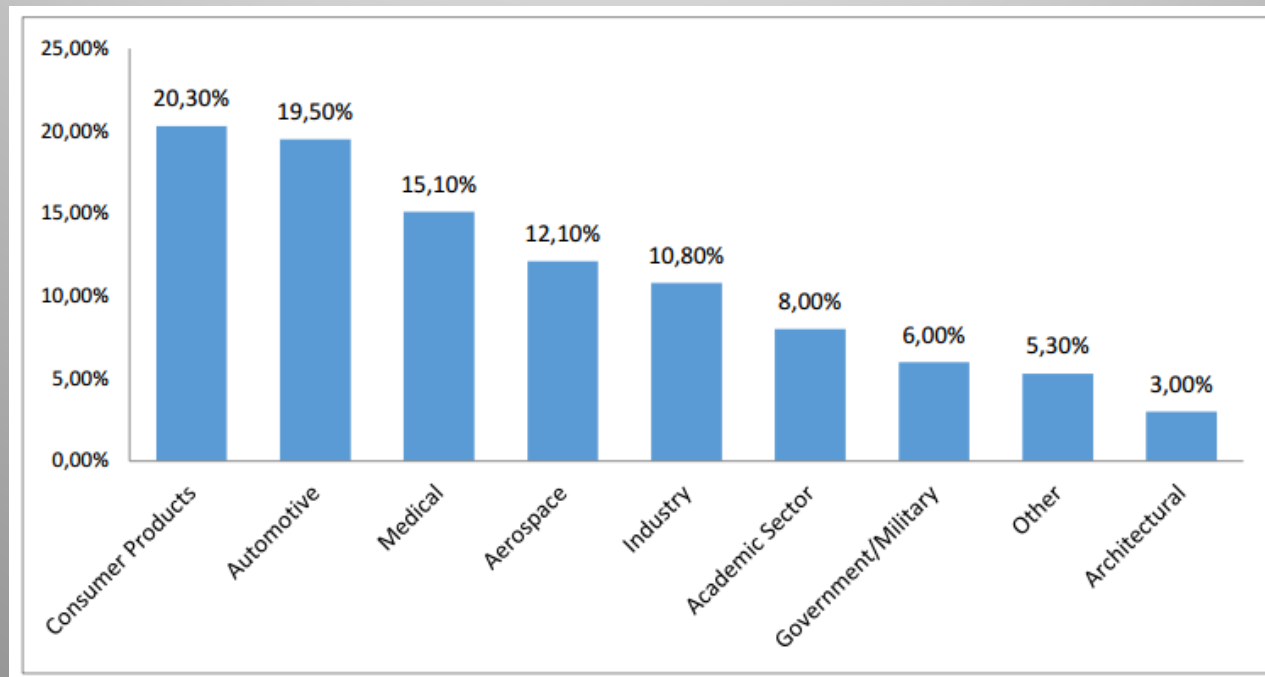
Oblasti:

- a) Medicina - 3D bioprinting
- b) Proizvodnja hrane
- c) Građevina
- d) 3D za kućnu primenu



Razvoj AM sektora

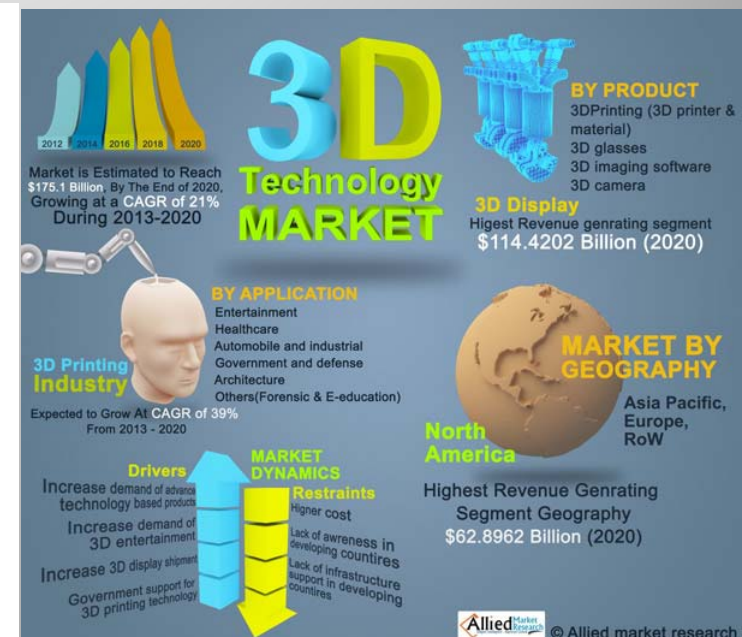
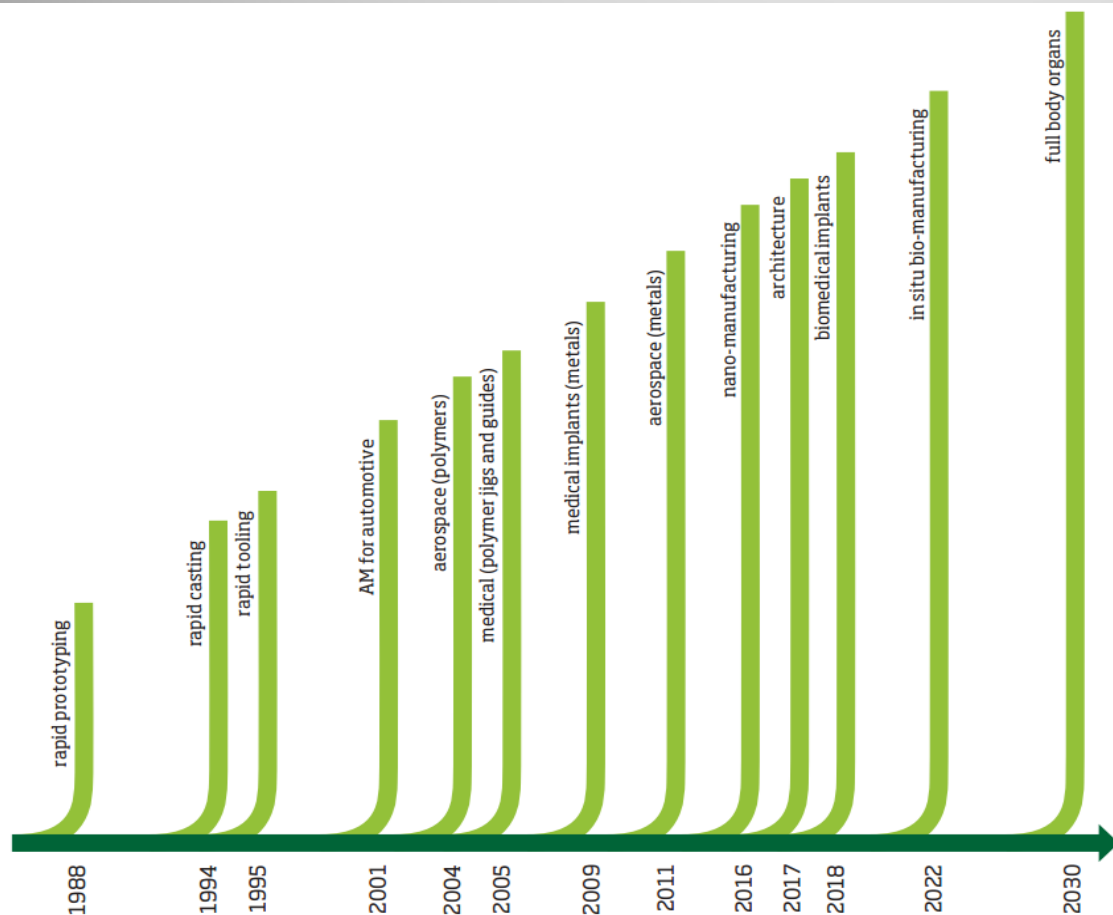
- ▶ Three of the **fastest-growing areas** for AM include the **medical, dental, automotive** and **aerospace** sectors¹
- ▶ In 10 years, **the use of AM for the production of final products** has gone from almost **nothing to 28.3%** of the **total product and services revenue** from AM worldwide.



“3D PRINTING’S POTENTIAL TO REVOLUTIONIZE MANUFACTURING IS QUICKLY BECOMING A REALITY.”

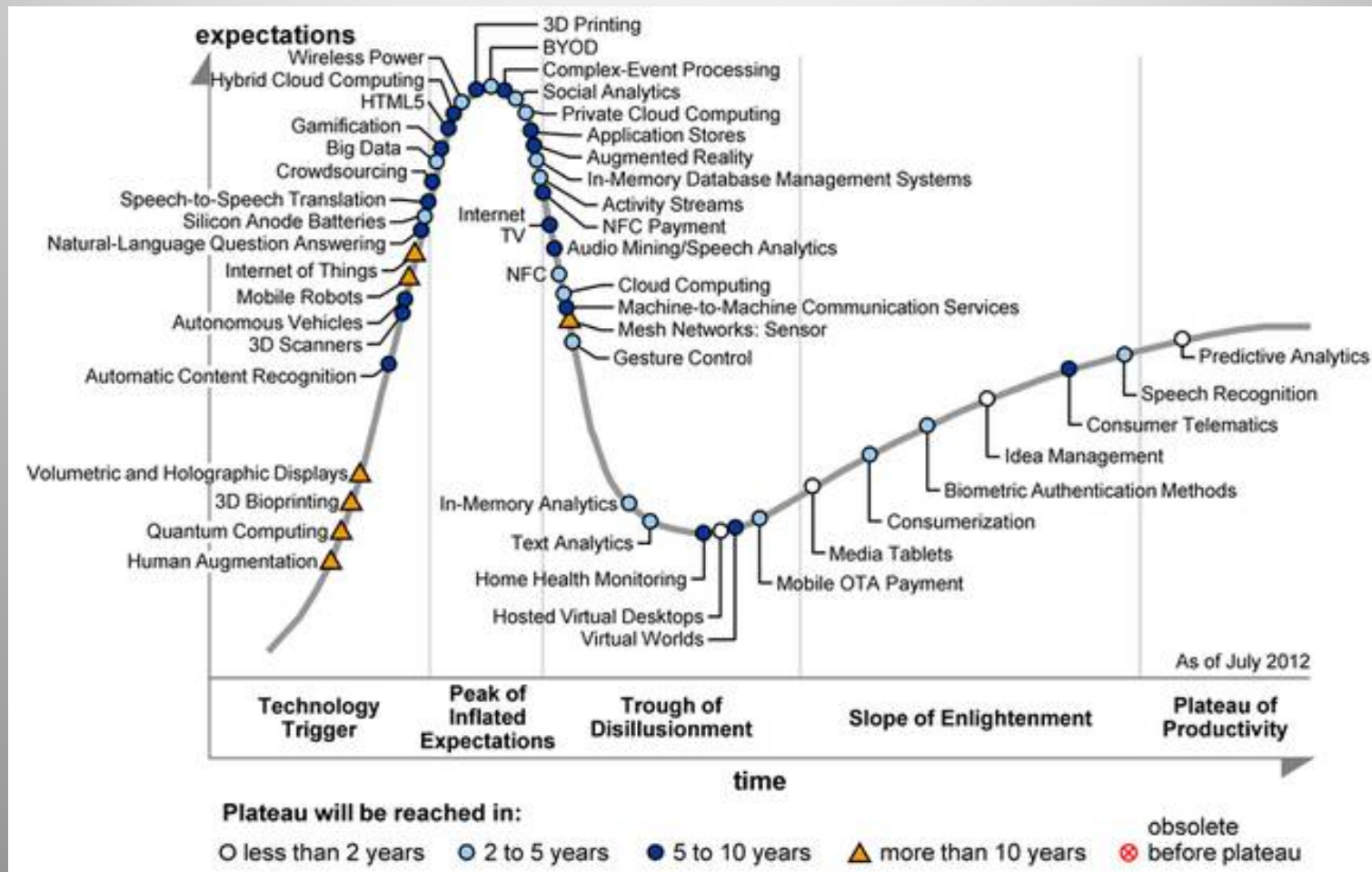
Global 3D printing market
Estimates and forecast of market value to 2018, in USD

Category	2013 estimates	2014 forecast	2018 forecast
Total	\$2.5b	\$3.8b	\$16.2b



A word of caution

Tech Consultancy Puts 3D Printing at Peak of "Hype Cycle"



"Hype Cycle,, - 2016

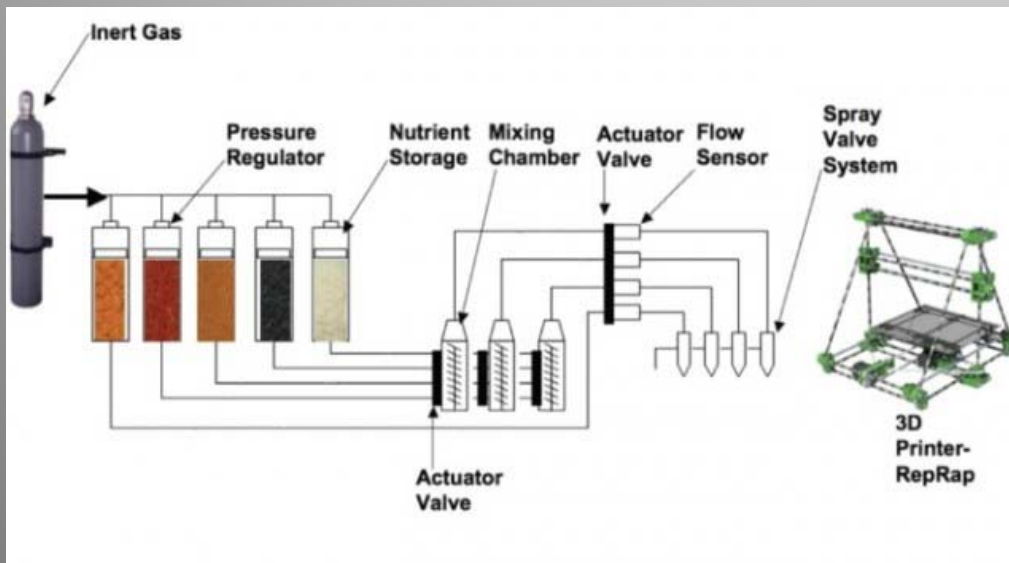


Critical technologies to be considered include: 4D Printing, Brain-Computer Interface, Human Augmentation, Volumetric Displays, Affective Computing, Connected Home, Nanotube Electronics, Augmented Reality, Virtual Reality and Gesture Control Devices.

3D Printing Aims to Deliver Organs on Demand



NASA awarded a \$125,000 grant to develop a process for 3D printing food for astronauts



NASA Funds 3D-Bio-Printer Development to Combat Universal Hunger

Primena 3D Printinga u medicini

- Fabrikovanje tkiva i organa;
- Izrada proteza, implantata, medicinskih pomagala, membrana, anatomskih modela i sl.
- Primena u farmaciji – razvoj novih lekova, novi forme doziranja, novi načini isporuke lekova i sl.

Procedure

X-RAY



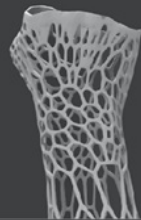
Limb is X-Rayed in order to identify the break and its exact position.

3D SCAN



Arm is 3D scanned in order to define the exact dimension of the limb.

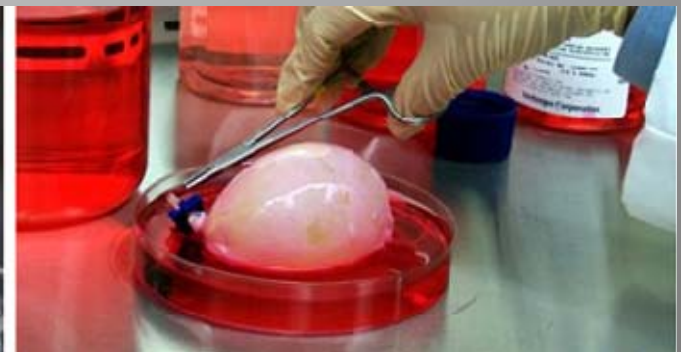
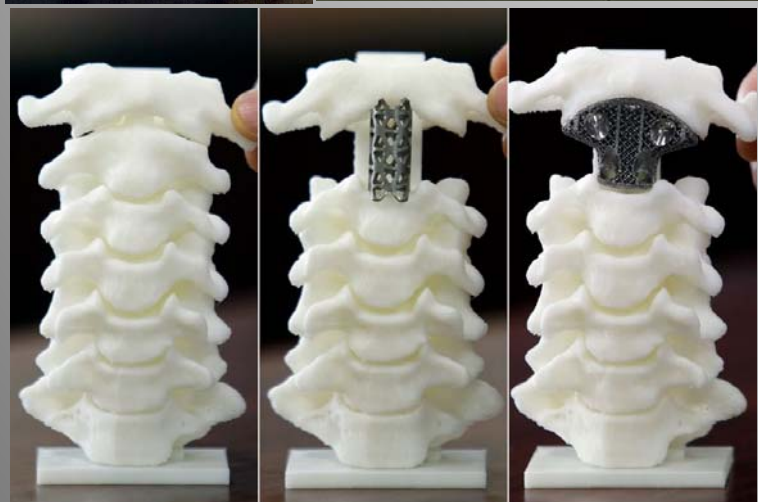
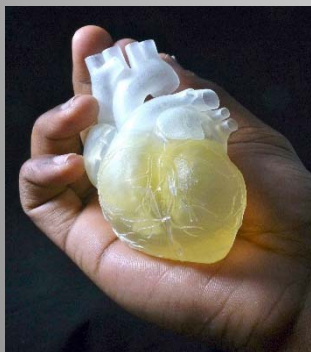
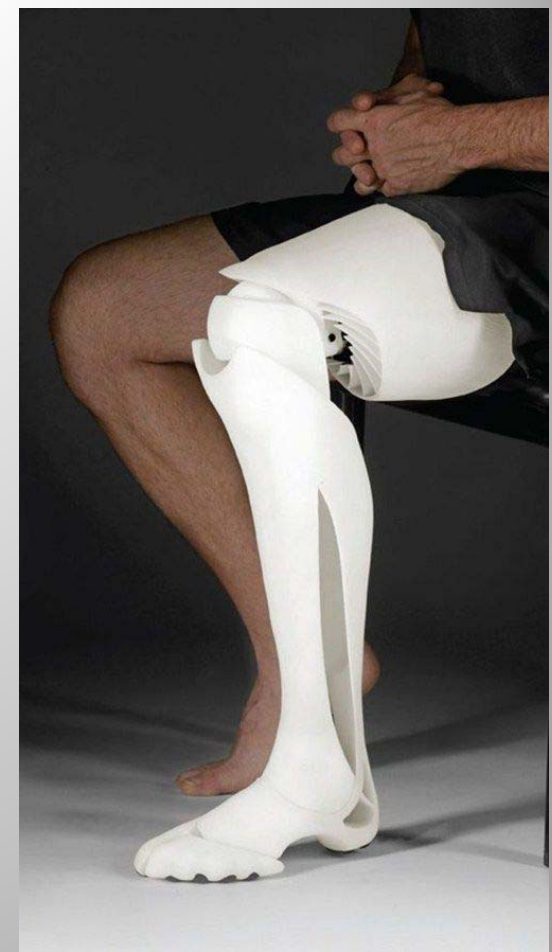
3D PRINT



Dimensions and data are fed into the computer. Cast is generated with optimal support for vulnerable areas and to the exact limb size for a snug fit.



sample illustration, not actual prototype



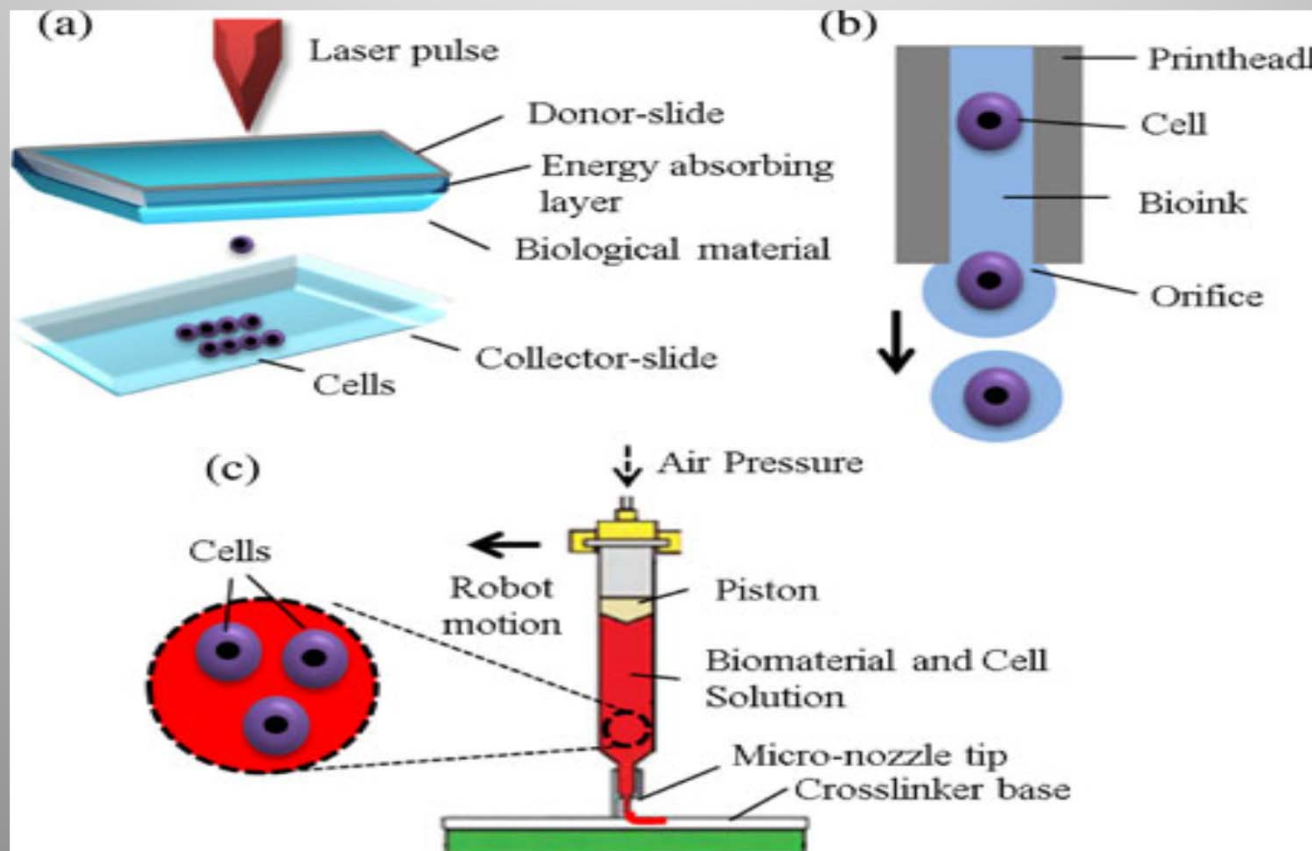
3D Bioprinting

- Kompjuterski vođen bioaditivni proizvodni proces u kome se vrši deponovanje živih ćelija na skeletne strukture (scaffold) na bazi hidro-gela u cilju fabrikacije 3D tkiva i organa.
- It uses bioadditive manufacturing technologies, including laser-based writing , inkjet-based printing , and extrusion-based deposition .
- Bioprinting offers great precision on spatial placement of the cells themselves, rather than providing scaffold support alone.

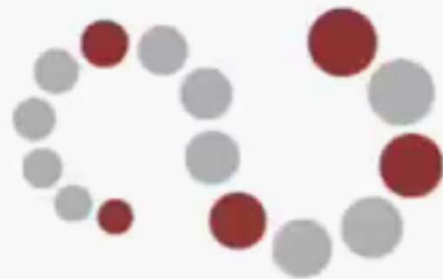
3D Bioprinting

Bioprinting tehnologije obuhvataju:

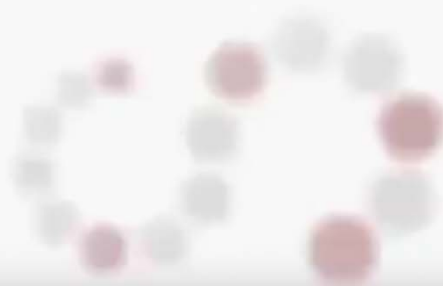
- (a) laser-based writing of cells,
- (b) inkjet-based systems, and
- (c) extrusion-based deposition



3D Bioprinting



ARC Centre of Excellence for
**Electromaterials
Science**



ARC Centre of Excellence for
**Electromaterials
Science**

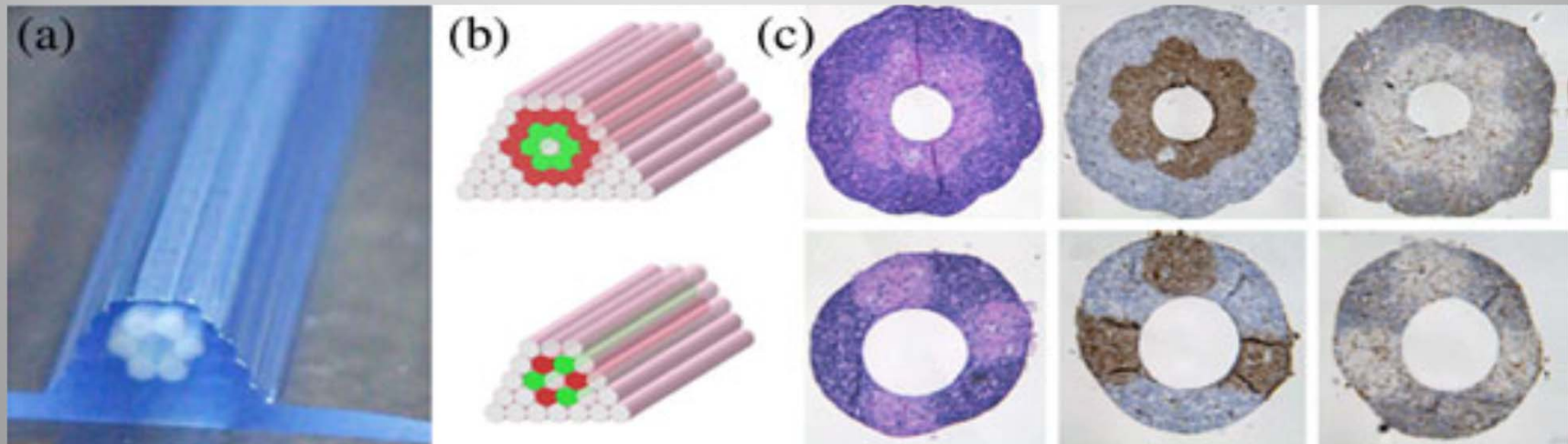
Bioprinting Tissues and Organs

- Organ printing takes advantage of 3D printing technology to produce cells, biomaterials, and cell laden biomaterials individually or in tandem, layer by layer, directly creating 3D tissuelike structures.
- Various materials are available to build the scaffolds, depending on the desired strength, porosity, and type of tissue, with hydrogels usually considered to be most suitable for producing soft tissues.
- Although 3D bioprinting systems can be laser based, inkjet based, or extrusion based, Inkjet based bioprinting is most common.

Procedura 3D Bio -printinga obuhvata sledeće faze (korake) :

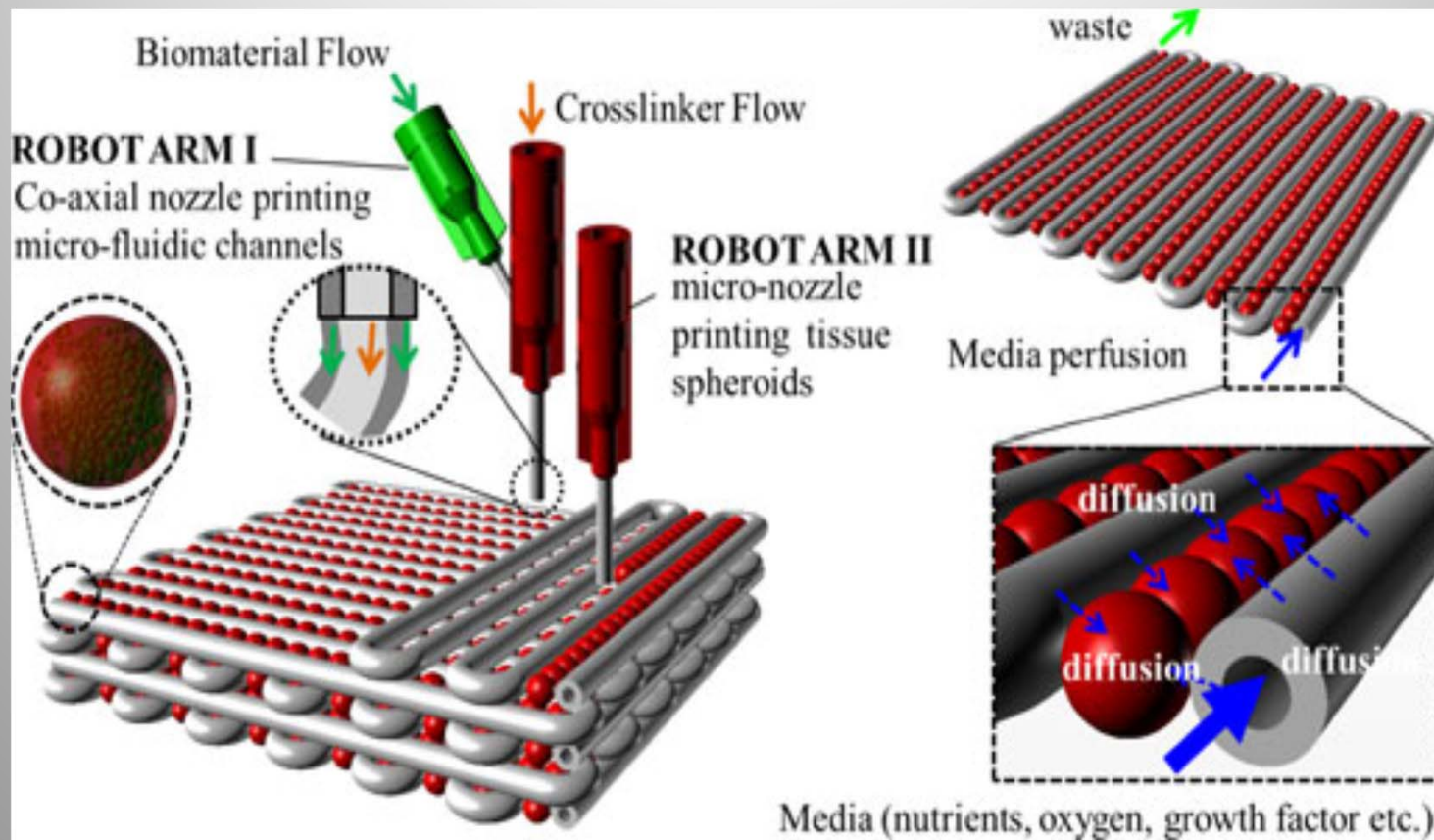
- 1) kreiranje strukture-šeme (blueprint) organa zajedno sa vaskularnim sistemom
- 2) generisanje plana procesa 3D bioprintinga;
- 3) izolacija matičnih ćelija;
- 4) diferencijacija matičnih ćelija u ćelije organa;
- 5) priprema bioink rezervoara sa specifičnim ćelijama organa, ćelijama krvnih sudova i potpornih struktura i pozicioniranje istih u Bio-šampač;
- 6) bioprint;
- 7) postavljanje bio-printovanog organa u bio-reaktor pre transplantacije.

- The precise placement of multiple cell types is required to fabricate thick and complex organs, and for the simultaneous construction of the integrated vascular or microvascular system that is critical for these organs to function.

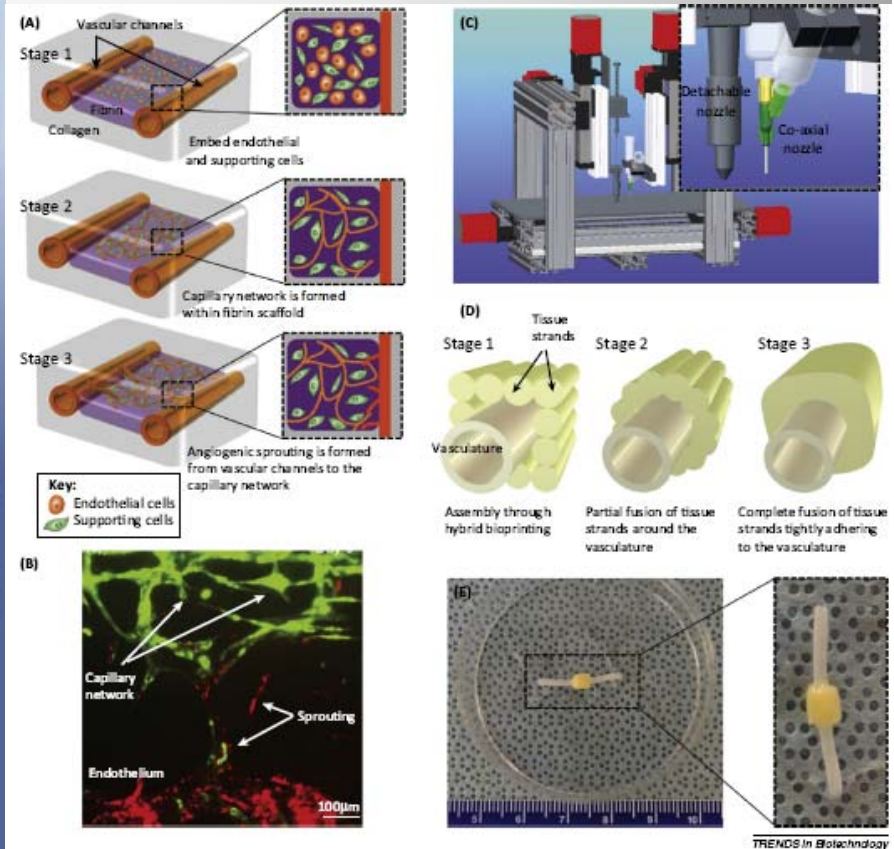
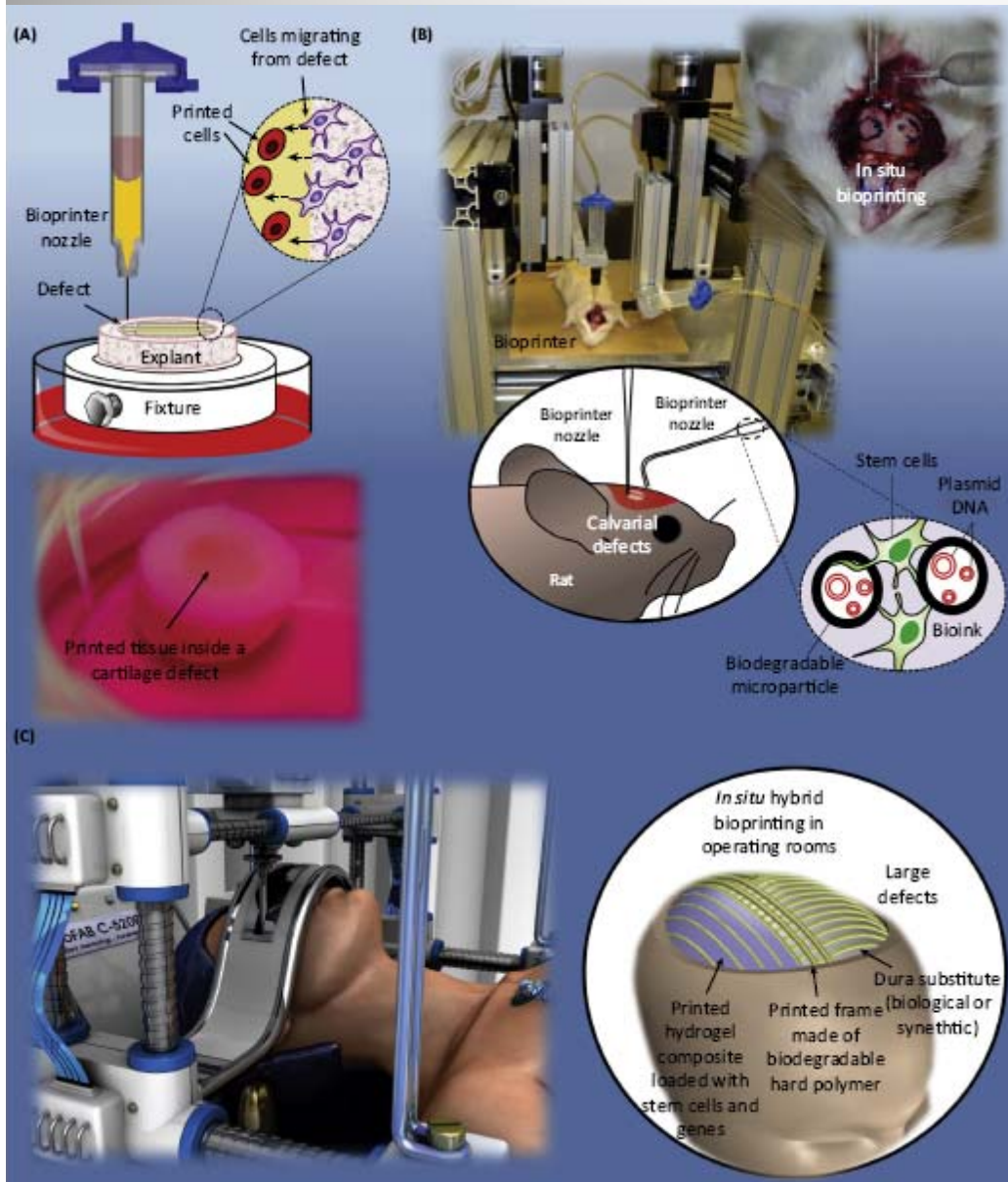


Tissue spheroids for blood vessel printing: (a) Deposition of straight filaments containing a string of tissue spheroids (stained in white) with agarose filaments as support material (stained in blue) both around cellular filaments and inside the core, (b) design for multicellular assembly with (c) printed samples with human umbilical vein smooth muscle cells and human skin fibroblast cells

Concept of 3D organ printing technology



3D Bioprinting



Evolution of Tissue Engineering and Bioprinting

- 1984** Charles Hull invented stereolithography, which enabled a tangible 3D object to be created from digital data. The technology was used to create a 3D model from a picture and enabled testing the design before investing in a larger manufacturing program.
- 1996** Dr. Gabor Forgacs (ONVD founder) and colleagues made the observation that cells stick together during embryonic development and move together in clumps with liquid-like properties, manufacturing program.
- Circa 2000** The first human patients underwent urinary bladder augmentation using a synthetic scaffold seeded with the patients' own cells (engineered, not printed).
- 2003** Thomas Boland's lab at Clemson modified an inkjet printer to accommodate and dispense cells in scaffolds.
- 2004** Dr. Forgacs developed new technology to engineer 3D tissue with only cells, no scaffolds.
- 2009** Organovo creates the NovoGen MMX Bioprinter using Forgacs technology.
- 2009-2010** Organovo prints the first human blood vessel without the use of scaffolds.
- 2011** Organovo develops multiple drug discovery platforms, 3D bioprinted disease models made from human cells.

Today
small-scale tissues for drug discovery and toxicity testing

Tomorrow
simple tissues for implant, (e.g. cardiac patches or segments of tubes, like blood vessels)

Future
lobes or pieces of organs*
*For example, a patient who needs a liver transplant has lost about 80-90% of their liver function, so a full liver is not needed to make a therapeutic impact.

Very Future
full organs

What Has Been Achieved So Far

- Nerve guides - 2009
Blood vessel - 2010
Cardiac sheet or patch - 2011
Lung tissue - 2012

Welcome Let's begin: HOW IT WORKS

Main Components:



Creating the BioInk

1 Cells

Sourced from patient biopsies or stem cells, and grown using standard methods and techniques.



3 Collected

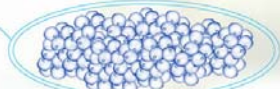
When enough cells are produced, they are collected to make BioInk.

- CELLS ARE THEN**
- formed into spheroids or other shapes
 - loaded into a cartridge to create the BioInk



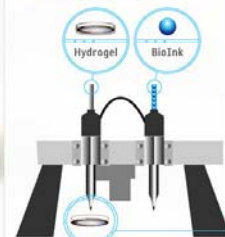
2 Cultured

Cells are cultured in a growth medium, enabling cells to multiply and grow.



Printing Process

NovoGen MMX bioprinter



NovoGen MMX bioprinter is used to:

print a layer of hydrogel (an inert water-based gel), which functions as a space holder for the printed tissue



deposit bioink spheroids into the layer of hydrogel



Hydrogel/spheroid print process is repeated



As layers are built upon, the spheroids naturally fuse together



Maturation

Printed tissue is left in the growth medium for several weeks to grow and mature. During which time, the hydrogel is removed.



Use

Printed tissues can then be used in medical research to discover and test new drugs and investigate causes of human diseases. And, in the future, as therapies.



PRINTING A LIVER

The eventual, longterm goals for bioprinting are to produce full organs. Using today's technology, an average sized liver (1,200cc) and liver lobe (120cc) would take 10 days to print. As technology improves the speed at which human tissue and, eventually, full organs can be printed will vastly improve.



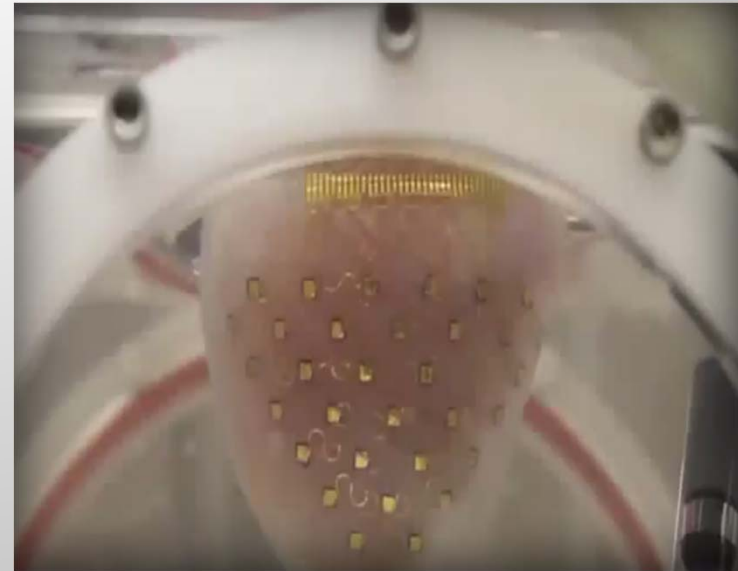
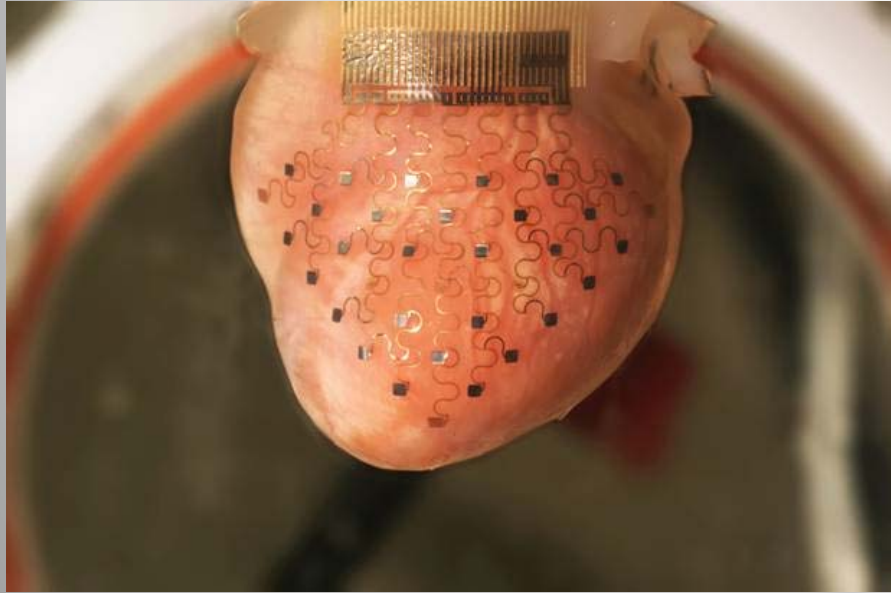
It would take 1,690,912,929,600 hours to print a liver for every member of the human race using today's processes.

3D Bioprinting

Customized Implants and Prostheses

- Implants and prostheses can be made in nearly any imaginable geometry through the translation of xray, MRI, or CT scans into digital .stl 3D print files.
- In this way, 3D printing has been used successfully in the health care sector to make both standard and complex customized prosthetic limbs and surgical implants, sometimes within 24hours. This approach has been used to fabricate dental, spinal, and hip implants.

Customized Implants and Prostheses



Scientists have created a revolutionary new electronic membrane that could replace pacemakers, fitting over a heart to keep it beating regularly over an indefinite period of time. The device uses a “spider-web-like network of sensors and electrodes” to continuously monitor the heart’s electrical activity and could, in the future, deliver electrical shocks to maintain a healthy heart-rate. Researchers used computer modelling technology and a 3D-printer to create a prototype membrane and fit it to a rabbit’s heart, keeping the organ operating perfectly “outside of the body in a nutrient and oxygen-rich solution”.

Anatomical Models for surgical preparation

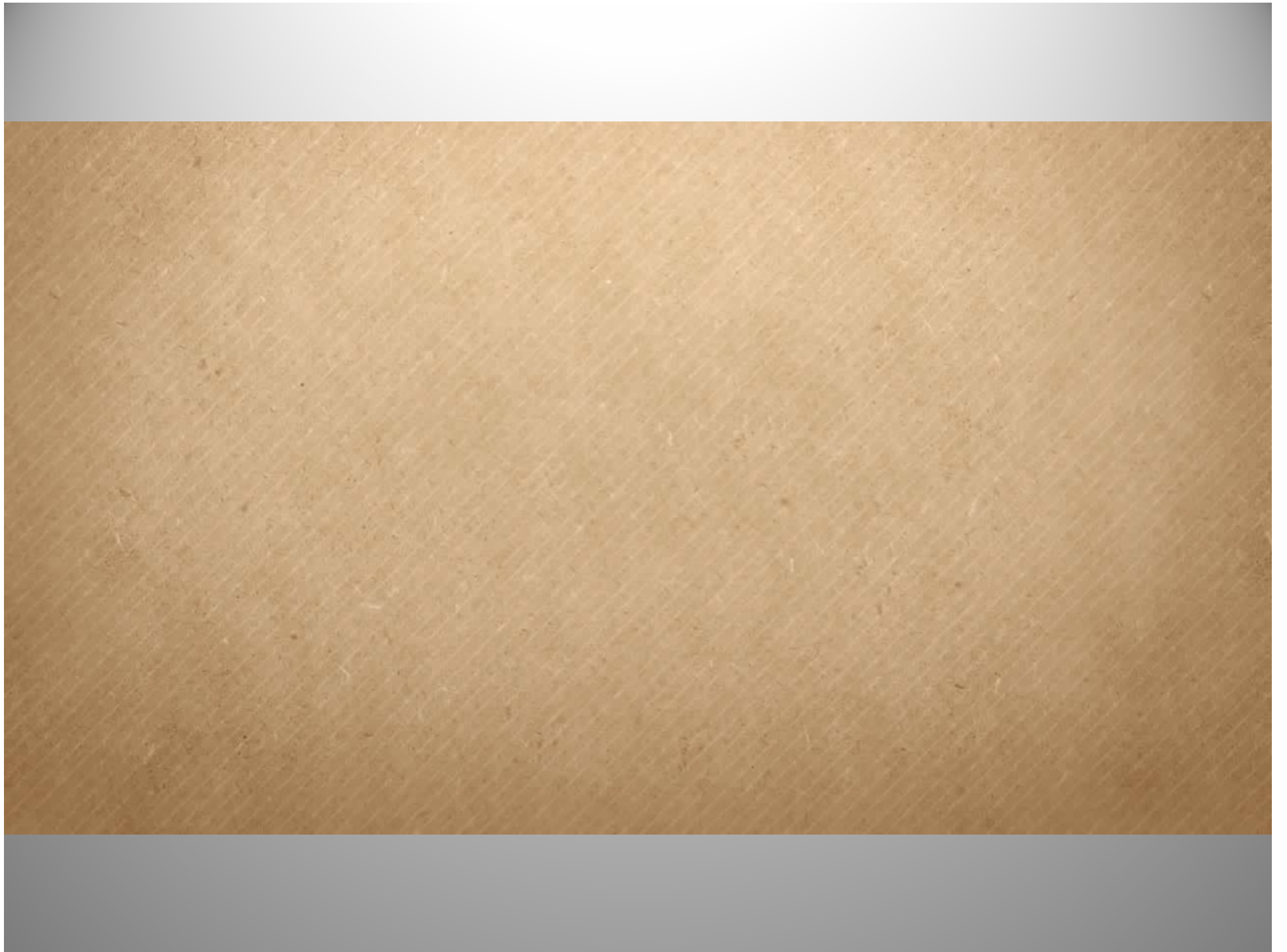
- The individual variances and complexities of the human body make the use of 3Dprinted models ideal for surgical preparation.
- 3Dprinted models can be useful beyond surgical planning.
- 3D printed neuroanatomical models can be particularly helpful to neurosurgeons by providing a representation of some of the most complicated structures in the human body.
- Complex spinal deformities can also be studied better through the use of a 3D model.

Drug Delivery Devices and Personalized Dosage Forms

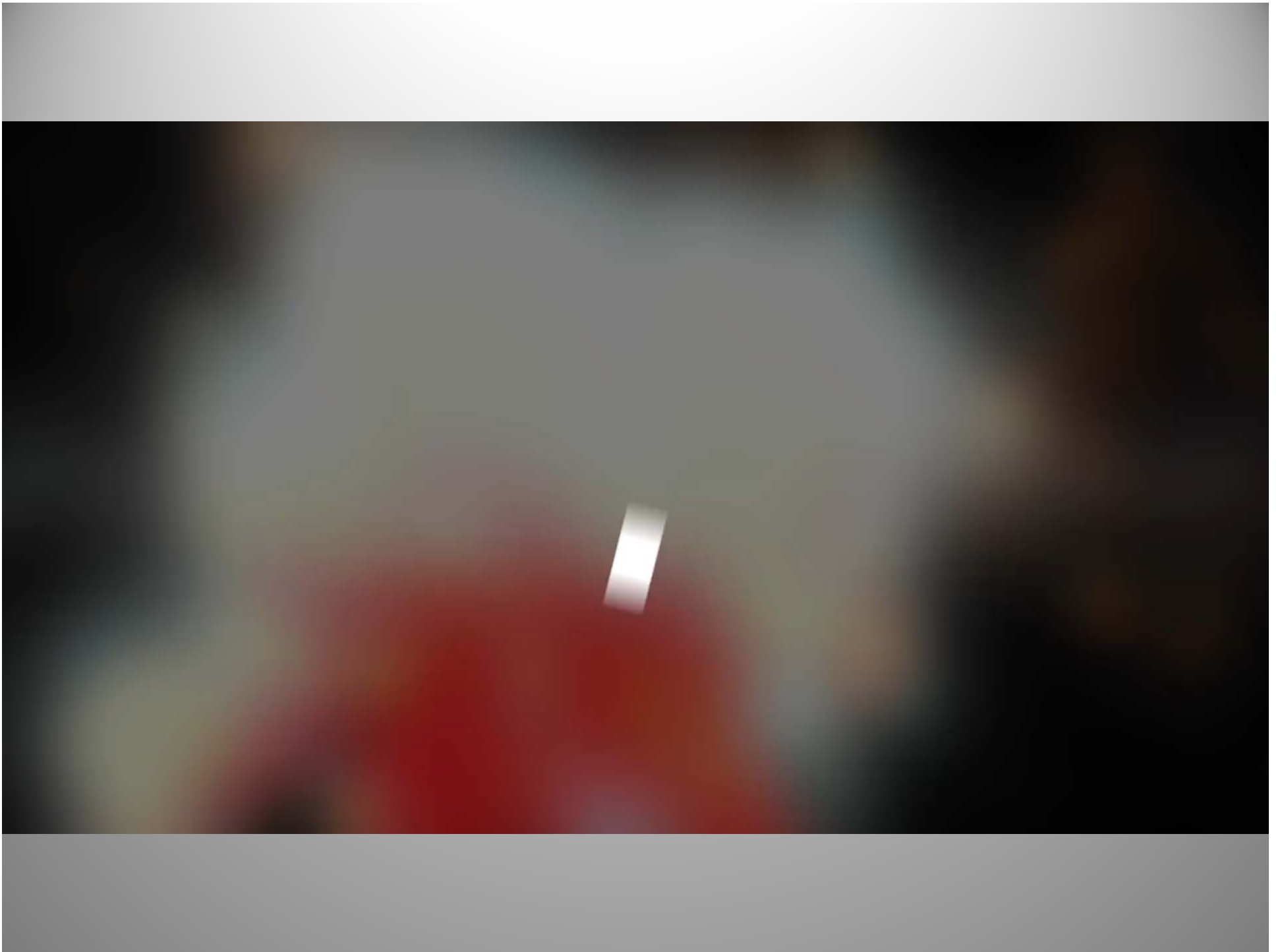
- 3D printing technologies are already being used in pharmaceutical research and fabrication, and they promise to be transformative .
- Advantages of 3D printing include precise control of droplet size and dose, high reproducibility, and the ability to produce dosage forms with complex drug release profiles.
- Complex drug manufacturing processes could also be standardized through use of 3D printing to make them simpler and more viable.
- 3D printing technology could be very important in the development of personalized medicine, too.

- The primary 3D printing technologies used for pharmaceutical production are inkjet based or inkjet powder based 3D printing.
- In inkjet based drug fabrication, inkjet printers are used to spray formulations of medications and binders in small droplets at precise speeds, motions, and sizes onto a substrate. The most commonly used substrates include different types of cellulose, coated or uncoated paper, microporous bioceramics, glass scaffolds, metal alloys, and potato starch films, among others.
- In powder based 3D printing, the inkjet printer head sprays the “ink” onto the powder foundation. When the ink contacts the powder, it hardens and creates a solid dosage form, layer by layer. The ink can include active ingredients as well as binders and other inactive ingredients. After the 3D printed dosage form is dry, the solid object is removed from the surrounding loose powder substrate.

- Personalized 3D printed drugs may particularly benefit patients who are known to have a pharmacogenetic polymorphism or who use medications with narrow therapeutic indices.
- Pharmacists could analyze a patient's pharmacogenetic profile, as well as other characteristics such as age, race, or gender, to determine an optimal medication dose.
- A pharmacist could then print and dispense the personalized medication via an automated 3D printing system.
- If necessary, the dose could be adjusted further based on clinical response.

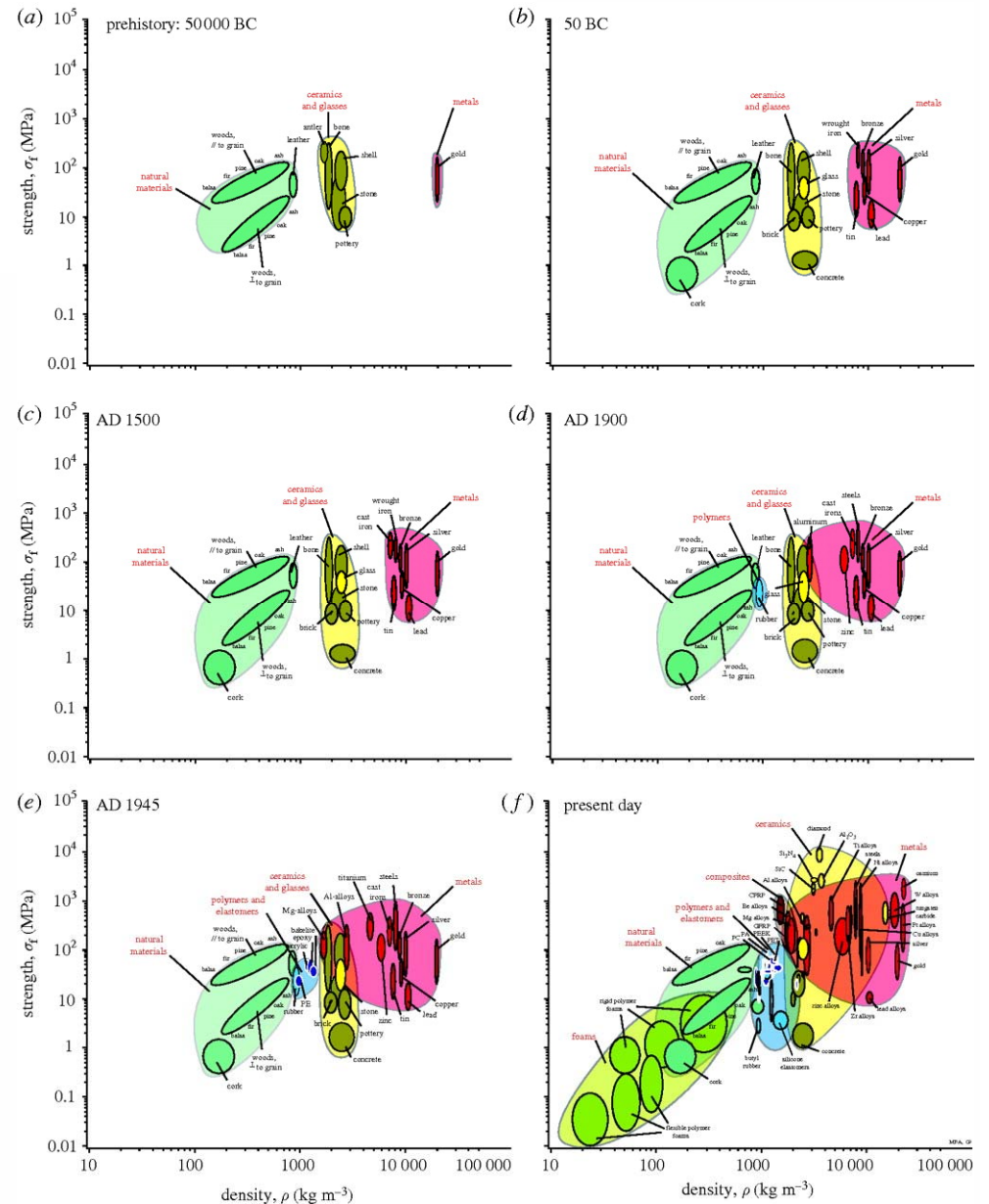
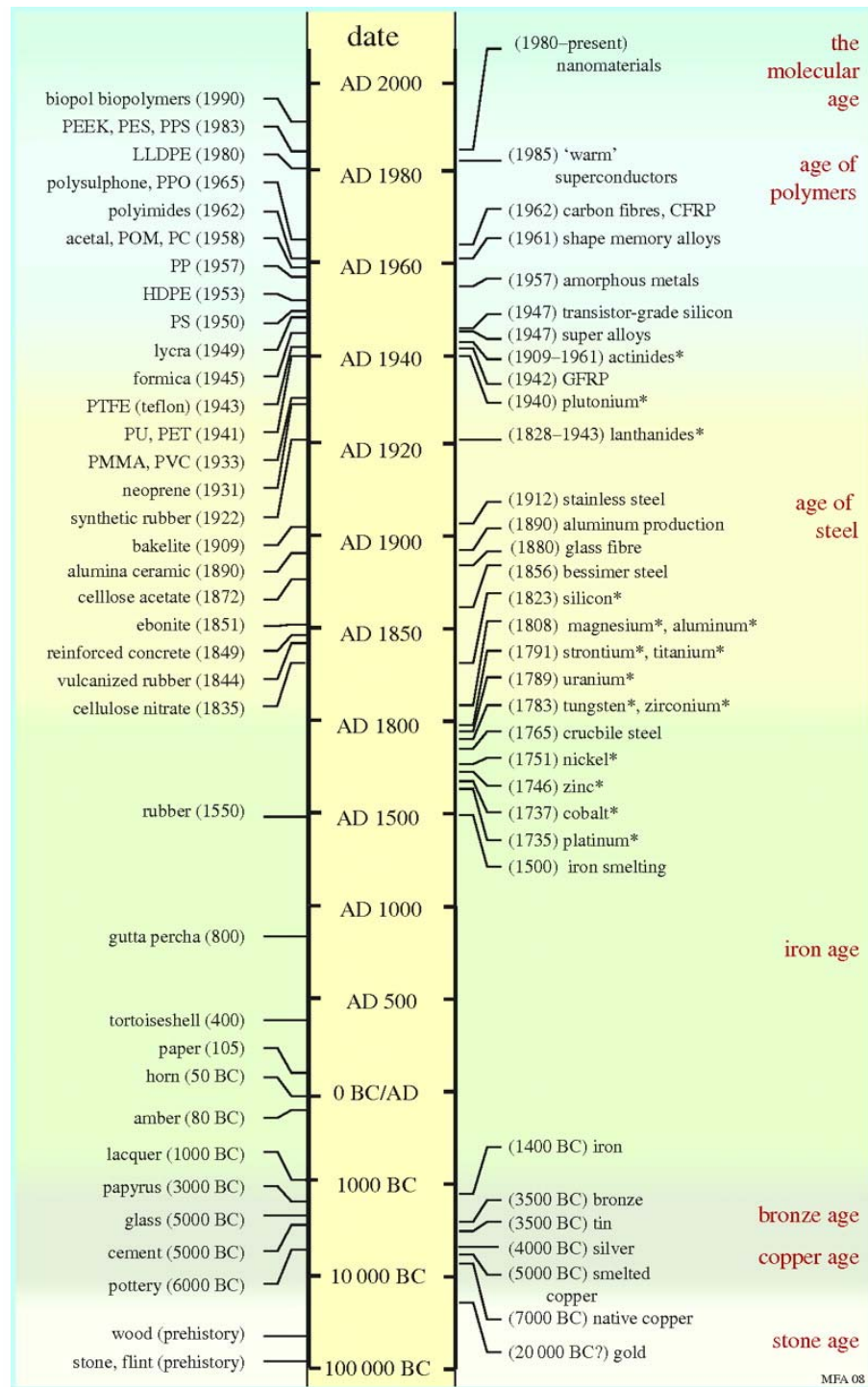




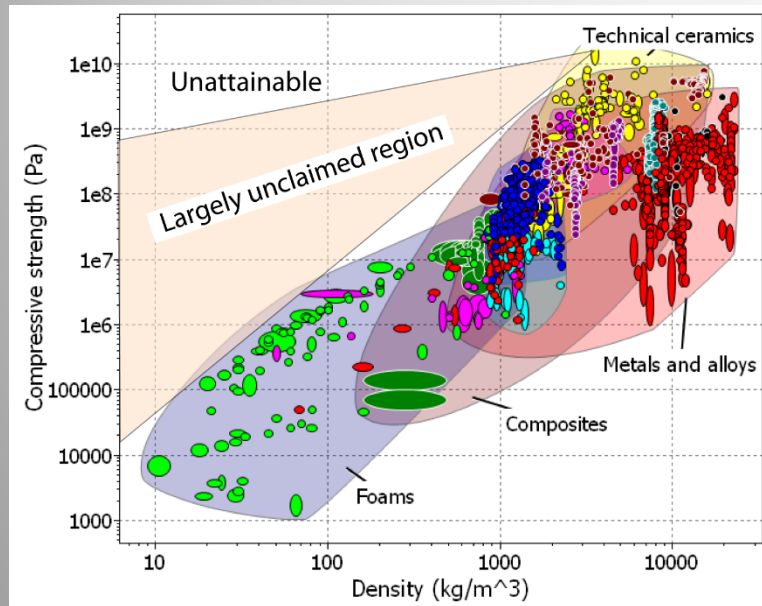


Challenges in AM materials properties predictions

- Most AM processes introduce anisotropy in mechanical properties (z different from x,y)
- Local differences in laser/EB power (e.g., perimeter vs center) introduce heterogeneity in mechanical properties
- Laser fluctuations might result in embedded defects that are difficult to identify
- All existing machines are open-loop: temperature sensors have been introduced in some processes, but the readings are not used to optimize the processing parameters on the fly.



Micro-Architected Materials

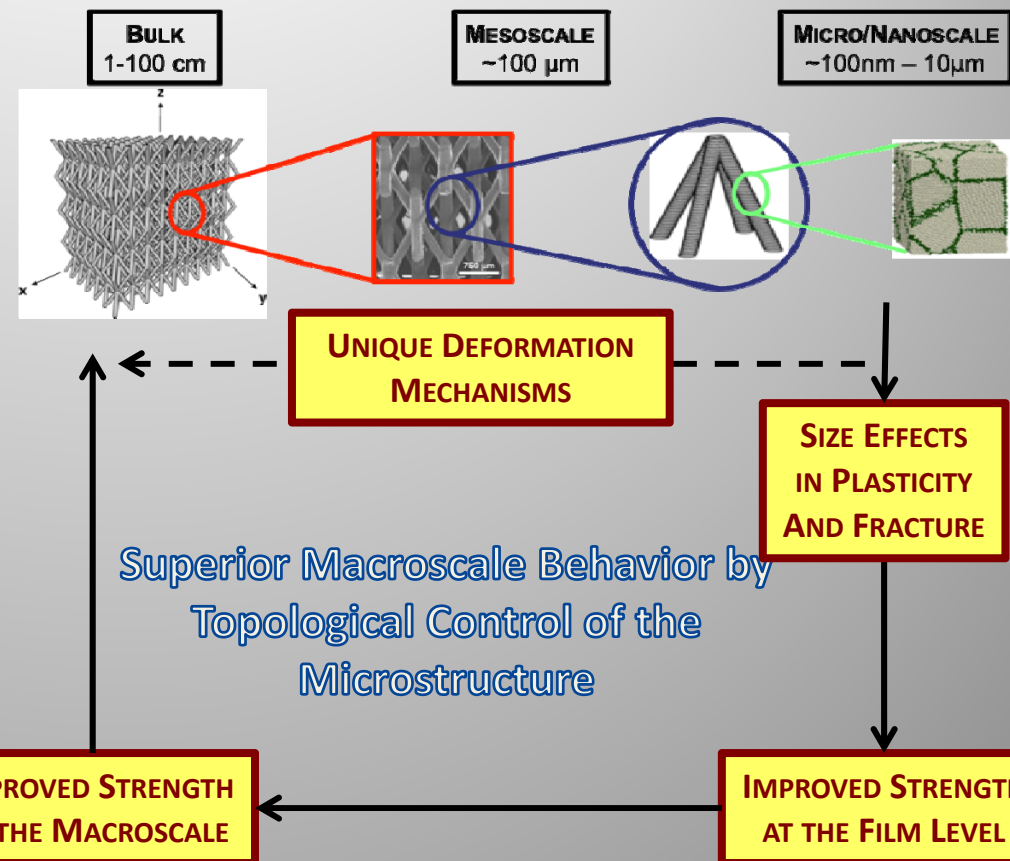


How can we fill unclaimed regions?

- Optimal topology
- Optimal geometry
- **Base material optimization (nm-features)**
- **Hierarchical design**

What do we need?

- Understand multi-scale mechanical behavior (deformation and failure modes)
- Understand processing -> microstructure -> mechanical properties (including size effects)



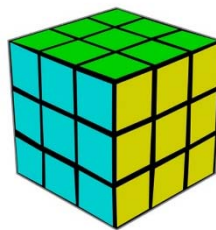
Size-dependent properties

At the nanometer scale, properties become size-dependent.

For example,

- (1) Chemical properties - reactivity, catalysis
- (2) Thermal properties - melting temperature
- (3) Mechanical properties - adhesion, capillary forces
- (4) Optical properties - absorption and scattering of light
- (5) Electrical properties - tunneling current
- (6) Magnetic properties - superparamagnetic effect

 **New properties enable new applications**



sides = 3
surface = $3^2 \times 6 = 54$
volume = $3^3 = 27$

surface/volume = 2



sides = 2
surface = $2^2 \times 6 = 24$
volume = $2^3 = 8$

surface/volume = 3

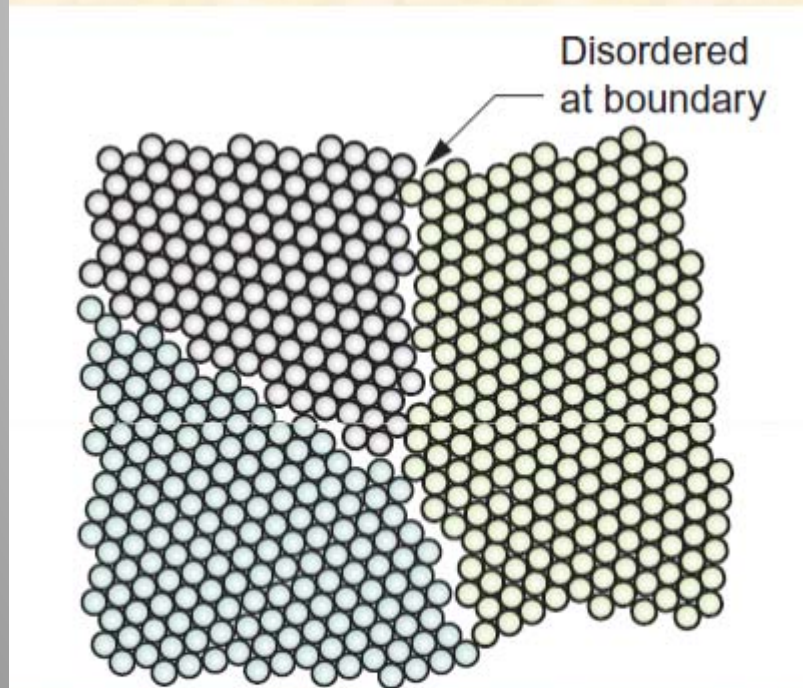


sides = 1
surface = $1^2 \times 6 = 6$
volume = $1^3 = 1$

surface/volume = 6

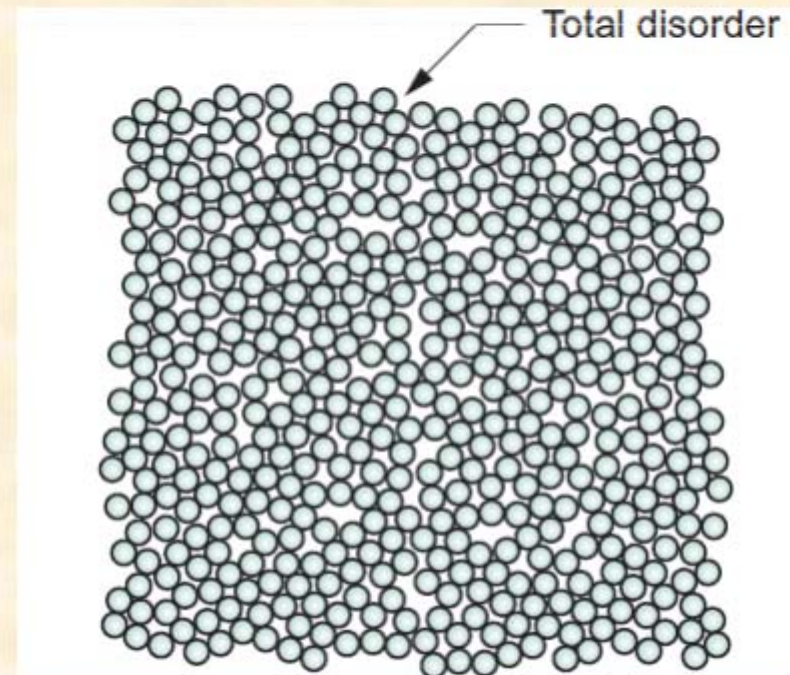
Surface to volume ratio increases with reducing particle size

Materials structures



Most materials are made up of ordered crystals that meet at disordered boundaries; the crystals in nanomaterials are only 100–10,000 atoms across.

Amorphous or “glassy” materials are totally disordered; the only characteristic dimension is that of the atoms or molecules that make them up. They are an extreme form of nanomaterial.



Mechanical Properties

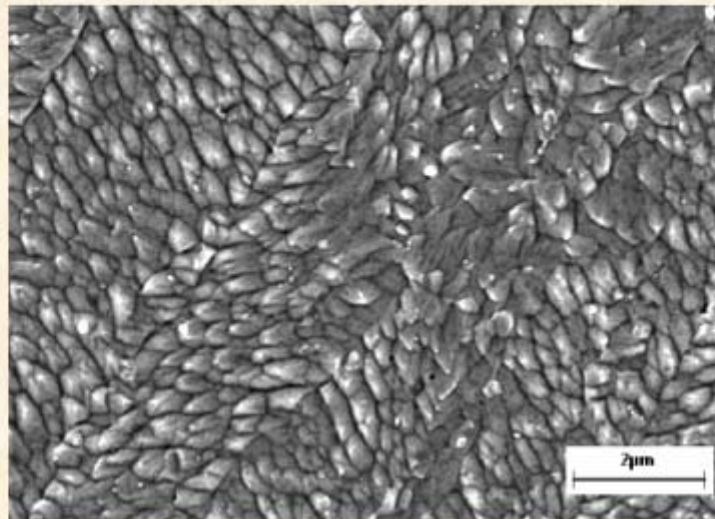
At the nanoscale, surface and interface forces become dominant.

For example,

- (1) Adhesion forces
- (2) Capillary forces
- (3) Strain forces

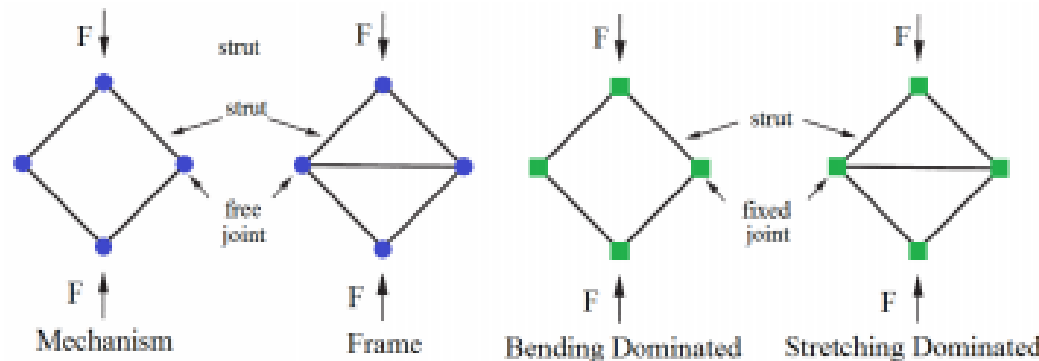


These forces can exceed forces that are normally dominant at macroscopic length scales



How does structure control behavior?

One of the most important properties governing the mechanical behavior of a solid is the density ρ_s . Similarly, one of the critical parameters that governs a lattice material's properties is the **relative density** ($\bar{\rho} = \rho/\rho_s$). This is a geometric parameter that effectively defines the amount of empty space in a lattice. It is a combination of density and deformation mode that govern the bulk material behavior.



Maxwell's Rule:

$$b - 2j + 3 = s - m \text{ (in 2-D)}$$

$$b - 3j + 6 = s - m \text{ (in 3-D)}$$

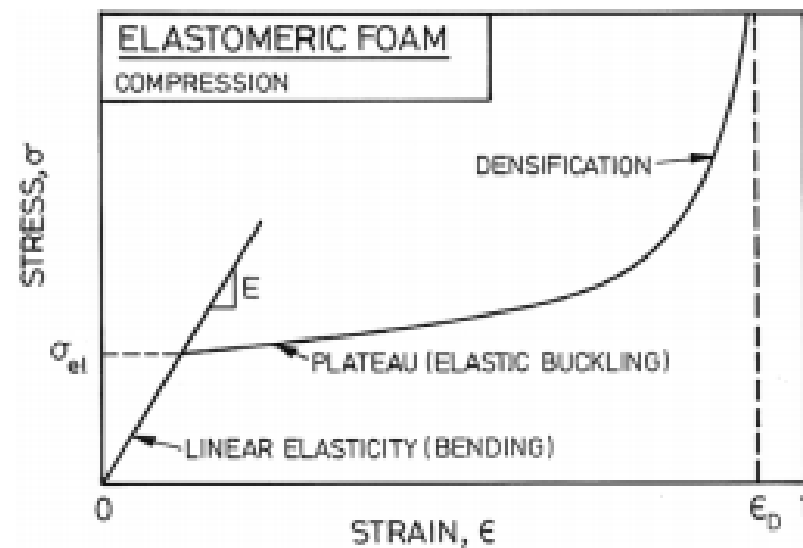
Cellular materials can be divided into two main categories by the deformation mode: bending dominated and stretching dominated structures. The factor that determines which mode occurs is whether or not there are mechanisms in the structure, where the number of mechanisms is determined by Maxwell's rule. For this rule, b is the number of struts, j is the number of frictionless joints, s is the number of self-stress states, and m is the number of mechanisms.

Stochastic Materials (Foams)

Two types of foams:

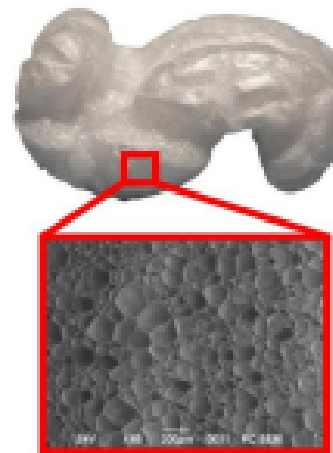
- Open-cell (continuous, inter-connected struts)
- Closed-cell (discrete, discontinuous pockets).

Deformation in foams occurs via bending of the constituent material. Carbon nanotube foams are one example of a material that is able to make use of nanoscale phenomena in deriving its bulk properties.

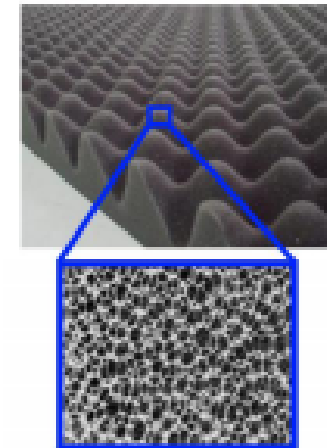


Gibson IJ, Ashby MF. *Cellular solids: structure and properties*. 2nd ed. Cambridge, UK: Cambridge University Press; 1997.

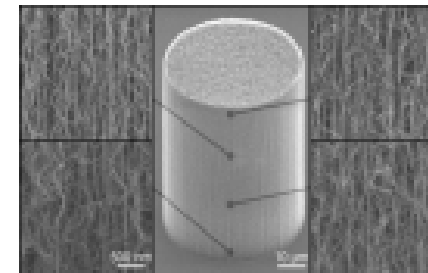
Open-Cell Foams



Closed-Cell Foams



Carbon Nanotube (Open-Cell) Foam



Hutchens, S. et. al. A microstructurally motivated description of the deformation of vertically aligned carbon nanotube structures. *Appl. Phys. Lett.* 100, 121901 (2012)

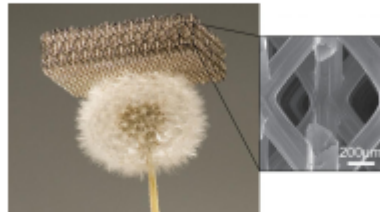
Periodic Materials (Lattices)

Characteristics of periodic lattices:

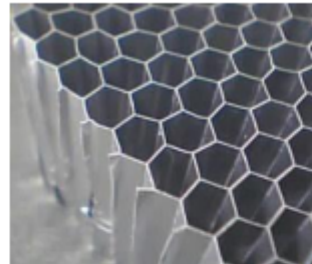
- Single repeating unit cell
- Structure repeats along a set of basis vectors

Periodic lattice structures have been used for a number of years as lightweight structural materials. Deformation occurs by a combination of bending and stretching of the truss members. It is possible to obtain significantly improved strength and stiffness because of the improved material architecture.

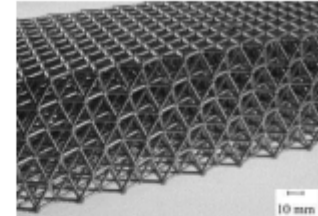
Nickel Microlattice



Honeycomb Structure

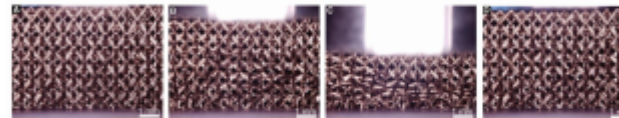


Octet Lattice Structure



Deshpande V.S. et. al. Effective Properties of Octet Truss Lattice Materials. *J. Mech. Phys. Solids* 2001, 49, 1747-1769

Uniaxial Compression of Nickel Microlattice

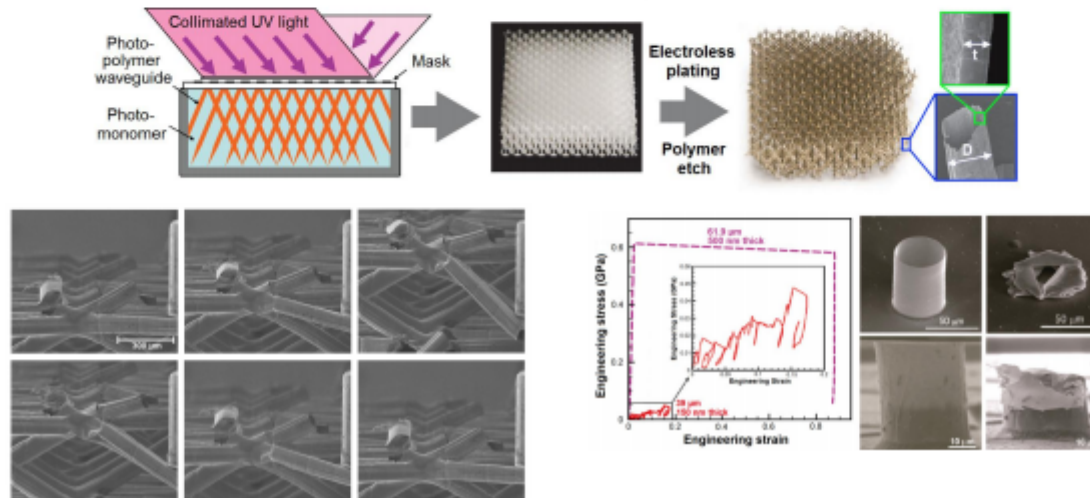


Schaedler, T.A. et. al. Ultralight Metallic Microlattices. *Science* 2011, 334, 962-965

The samples shown above are hollow microlattices, developed and tested in a collaboration between groups at HRL, UIC Irvine, and Caltech. These periodic lattice structures are able to make use of nanoscale phenomena in deriving their properties. The individual members are hollow tubes that are 1 – 4mm in length, 100 – 500μm in diameter, and 100 – 500nm thick. They have properties that include:

- Densities as low as 0.9 mg/cc.
- Full recovery even in excess of 50% strain.
- Novel buckling mechanism at the nodes.
- Vertical axis buckling via small, discrete strain bursts.

The fabrication process and more detailed constituent material behavior is shown in the figures below.



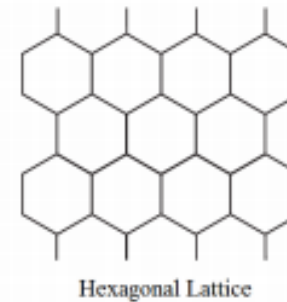
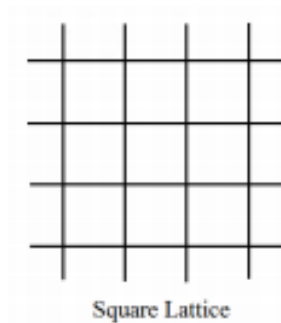
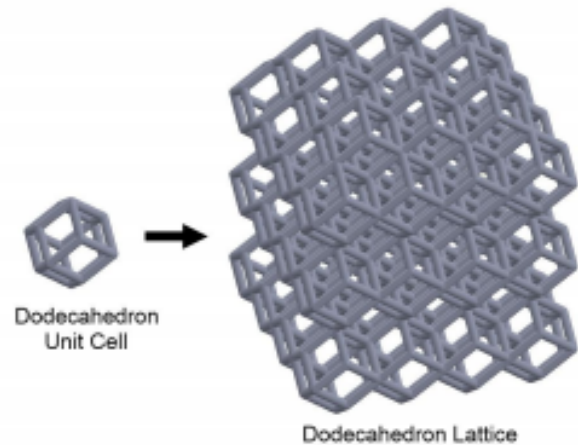
Bending Dominated Structures

- A structure is bending dominated when the number of mechanisms is non-zero ($m > 0$)
- Bending is the **weakest** mode of deformation for any structure.
- All foams, both open and closed-cell, are bending dominated.

For 3D Structures

$$E \approx \bar{\rho}^2 E_s$$

$$\sigma_y \approx 0.3 \bar{\rho}^{3/2} \sigma_{ys}$$



Fleck, N.A., et. al. Micro-architected materials: past, present and future. *Proc. R. Soc. A* 2010 446, 2495-2516

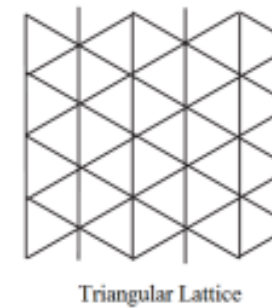
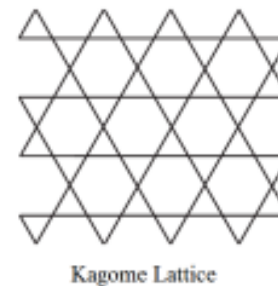
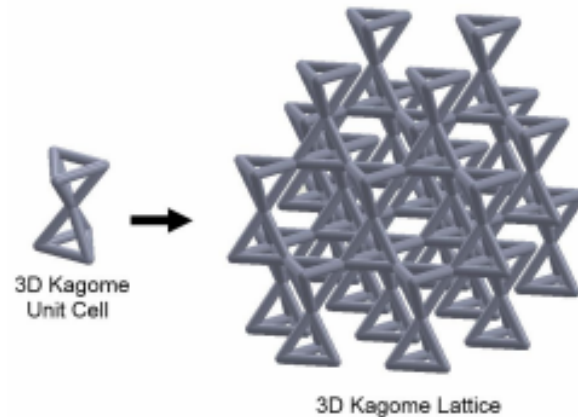
Stretching Dominated Structures

- A structure is stretching dominated when the number of mechanisms is zero ($m = 0$).
- Stretching is the **strongest** mode of deformation for any structure.
- These structures can still have periodic or macroscopic strain-producing mechanisms.

For 3D Structures

$$E \approx \bar{\rho} E_s$$

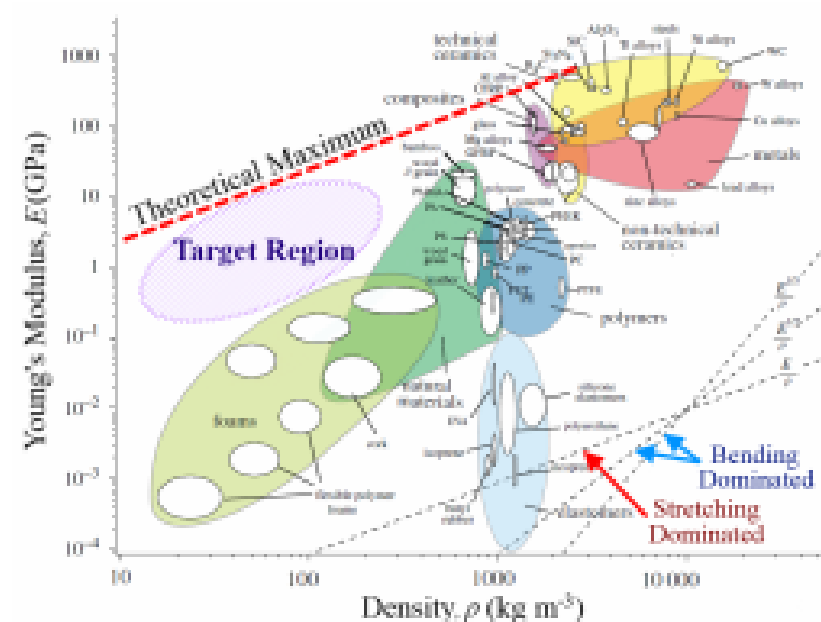
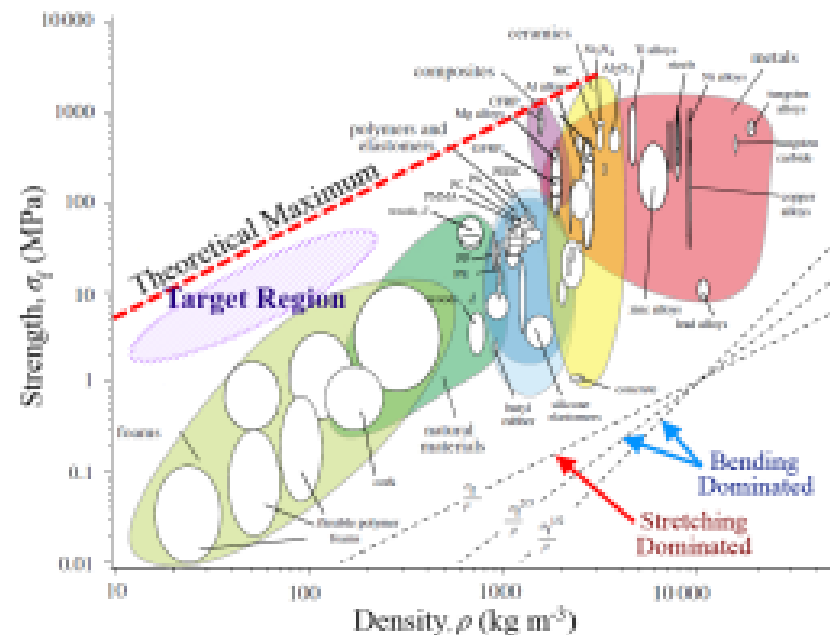
$$\sigma_y \approx 0.3 \bar{\rho} \sigma_{ys}$$



Fleck, N.A., et. al. Micro-architected materials: past, present and future. *Proc. R. Soc. A* 2010 446, 2495-2516

Material Property (Ashby) Charts

There is still a great potential for improving the performance of materials by designing lightweight stretching dominated structures. Shown below are material property plots of strength and stiffness, along with the target region that we are hoping to reach through the design of enhanced nano-architected materials.

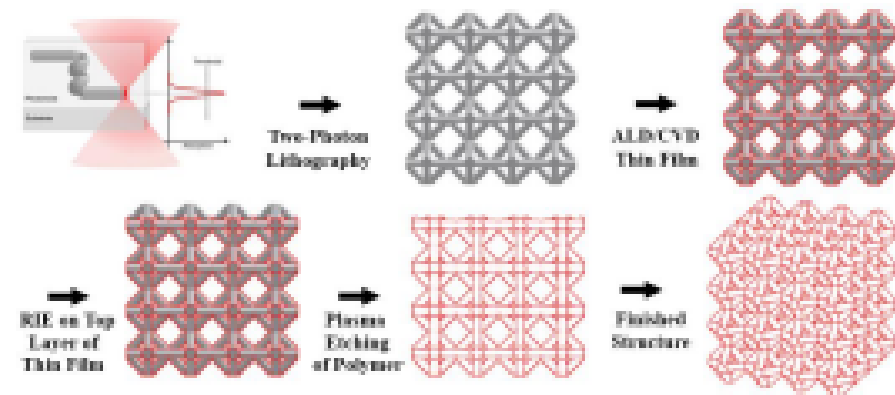


Nanotrusses

Through the advent of new technological advances in two-photon lithography, it is now possible to rapidly reproduce structures with features on sub-micron length scales. Using the commercial two-photon lithography machine created by the German based company Nanoscribe, we have been able to produce the lattice structures with sub-micron constituents.

Fabrication Process:

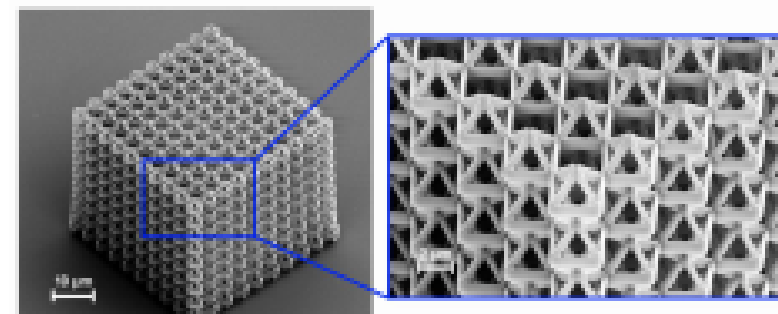
- Two-photon lithography is used to create a polymer sample.
- The polymer is coated using ALD, CVD, or an electroless deposition method to create a thin film on the sample.
- The thin film is partially etched away using RIE.
- The polymer is removed using plasma etching.
- This results in a hollow lattice structure with constituent beam elements on sub-micron length scales.



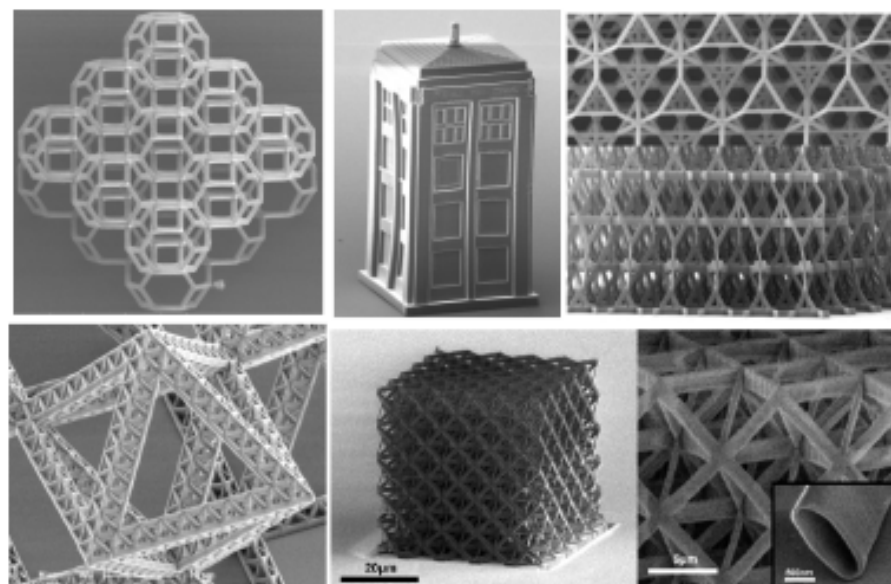
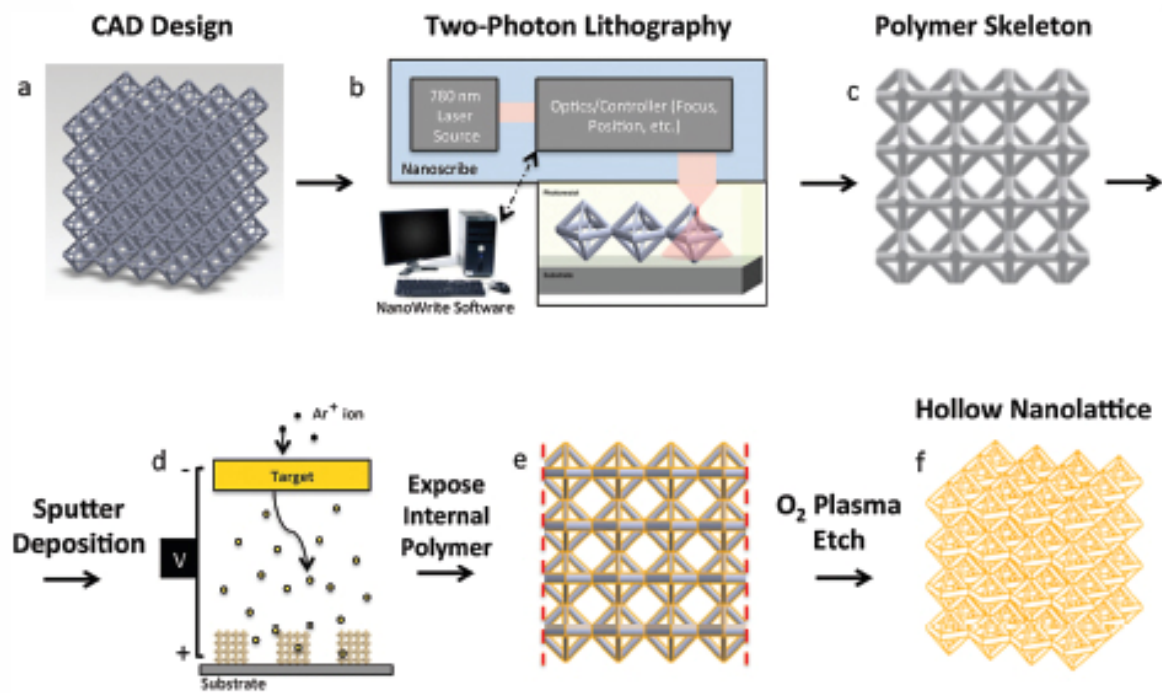
Nanotruss - 5 μ m Unit Cell

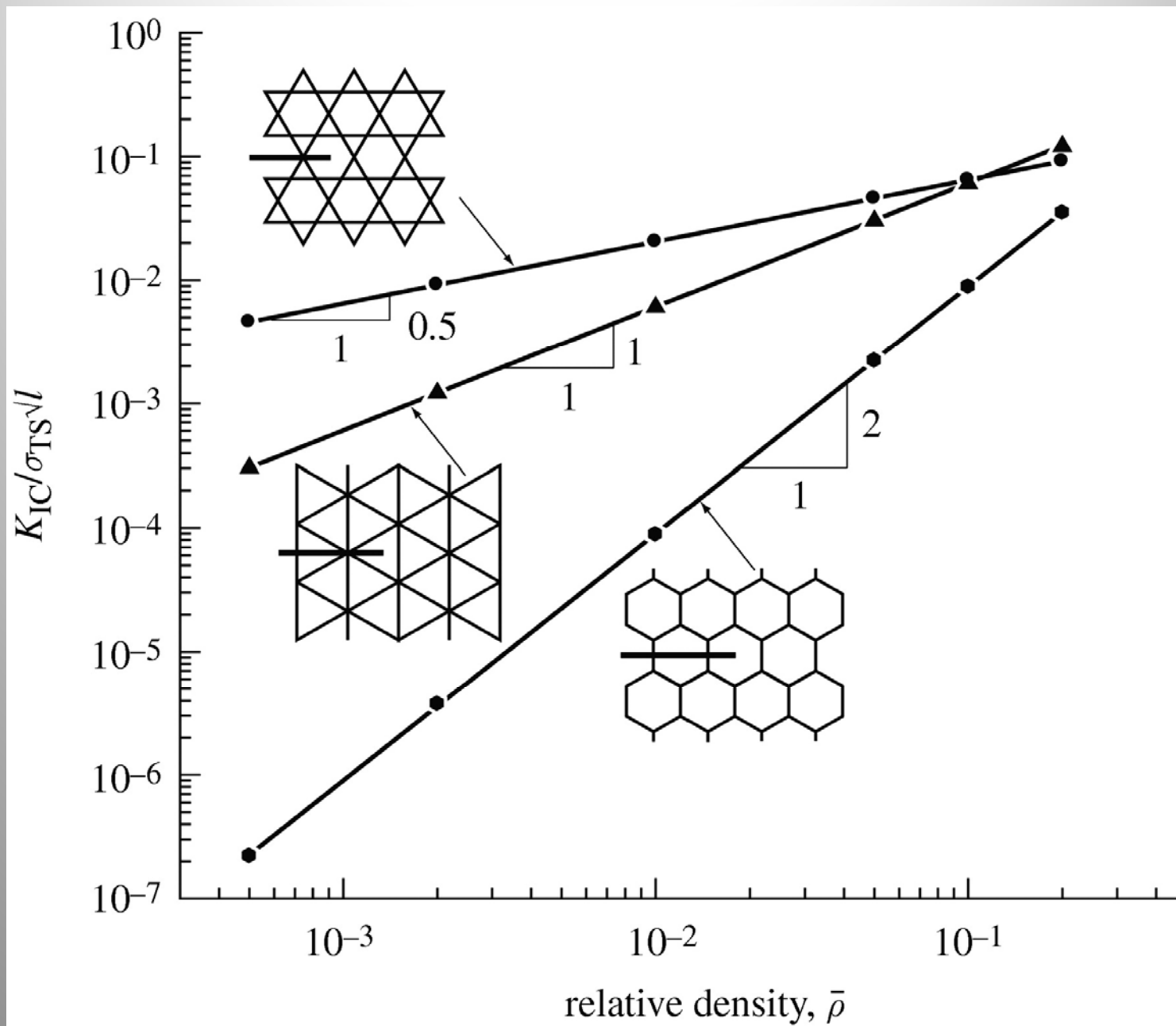
Properties of fabricated structures:

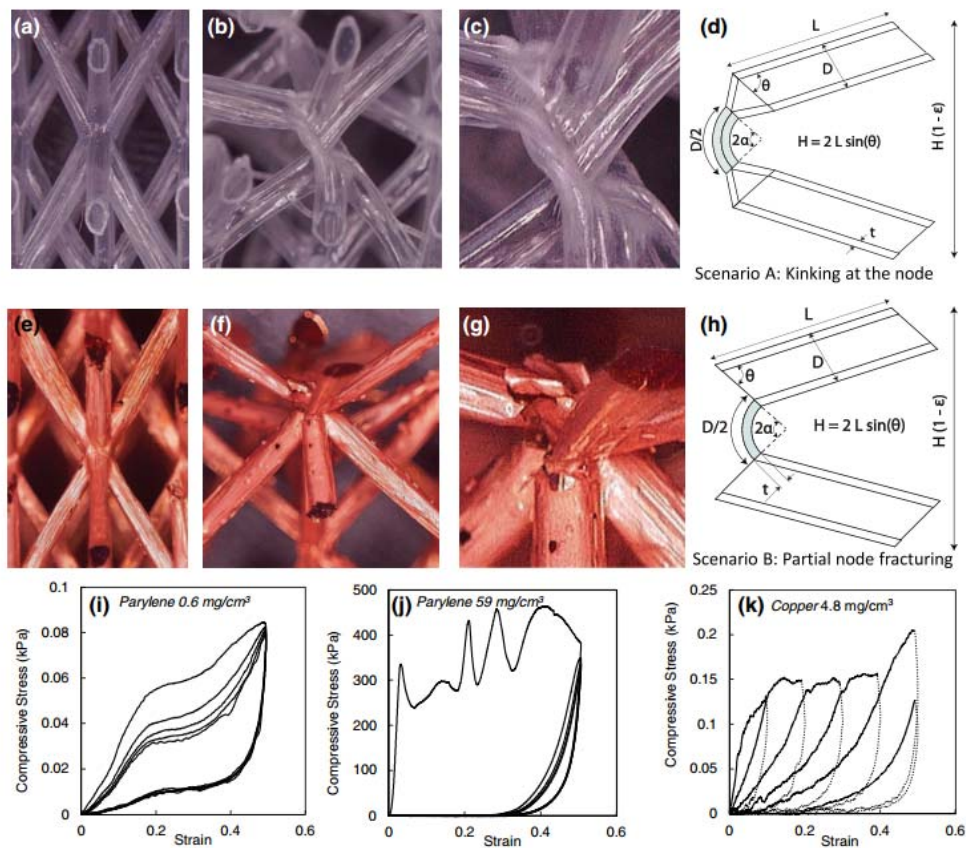
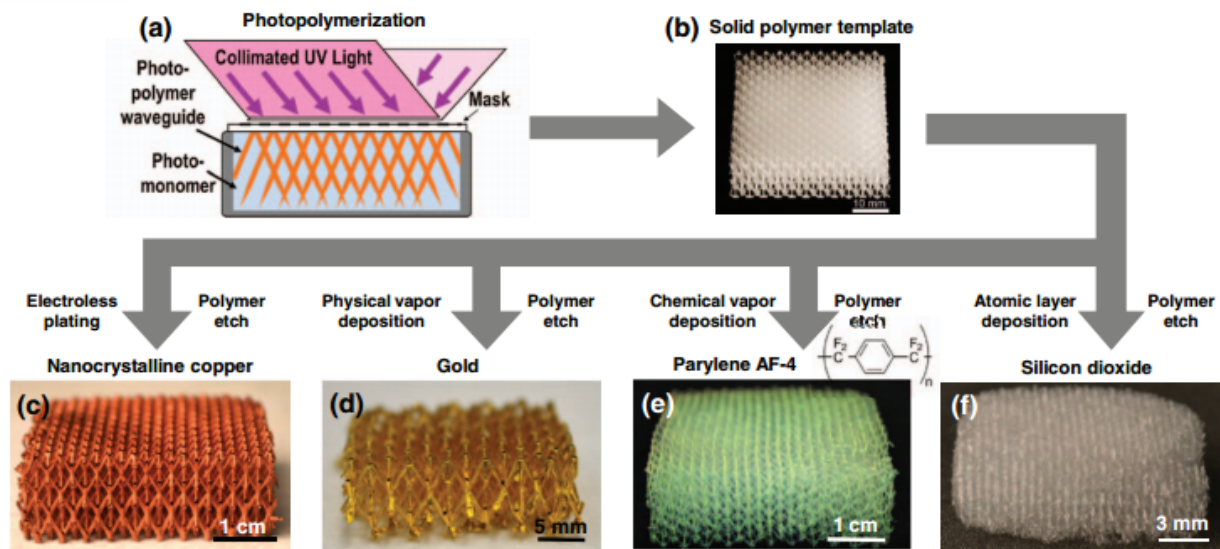
- Unit cell sizes ranging from 2 – 10 μ m
- Beam diameters ranging from 200 – 1000 nm.
- Wall thicknesses ranging from 50 – 150 nm.
- Relative density (ρ/ρ_s) ranging from 0.015 – 0.15

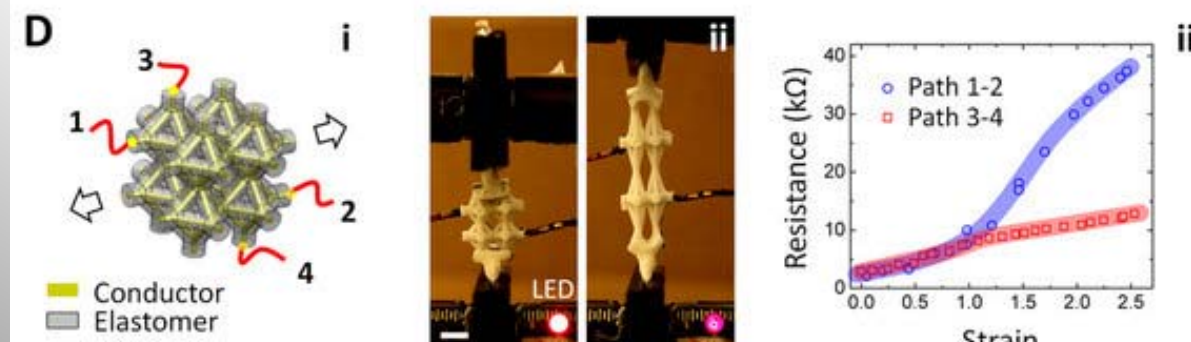
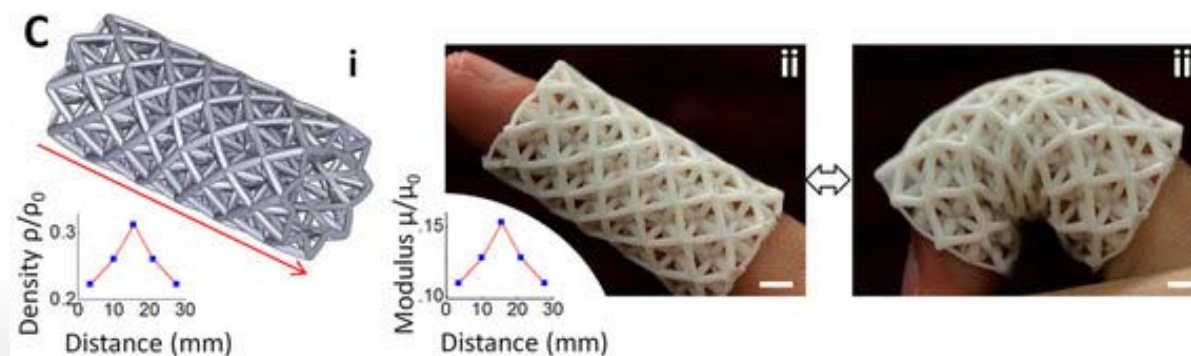
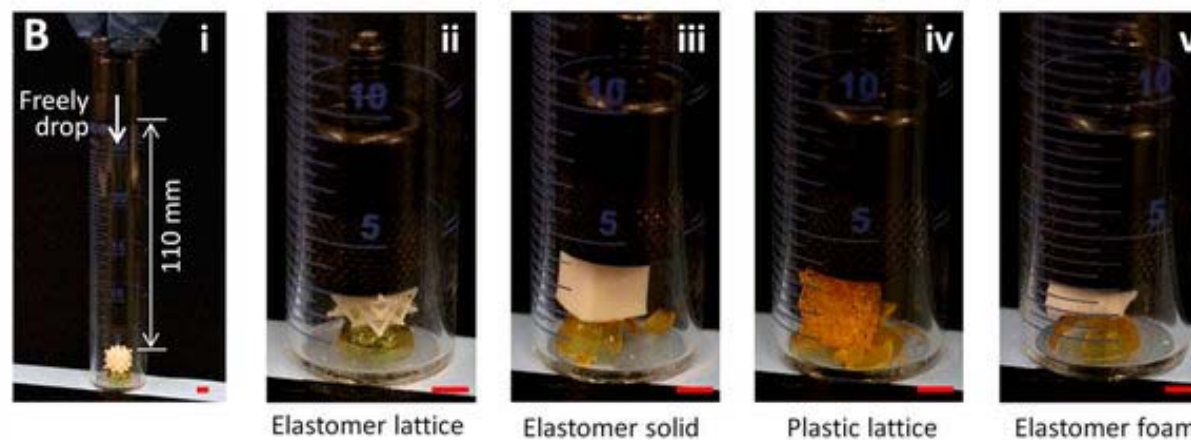


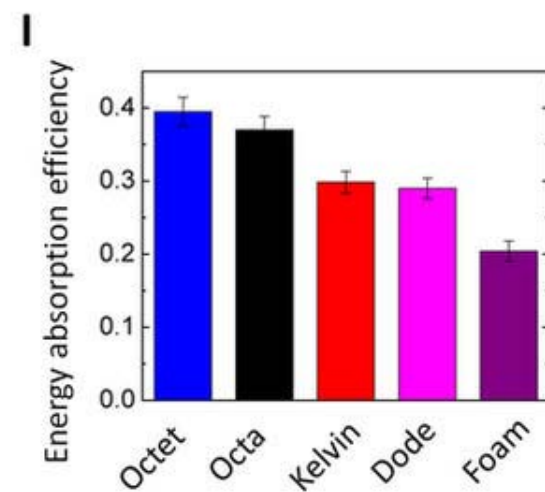
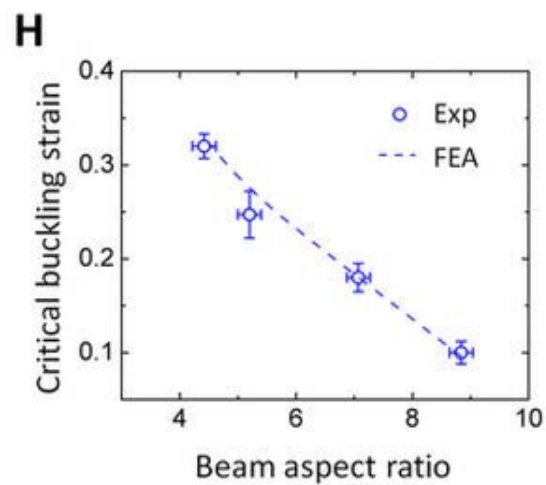
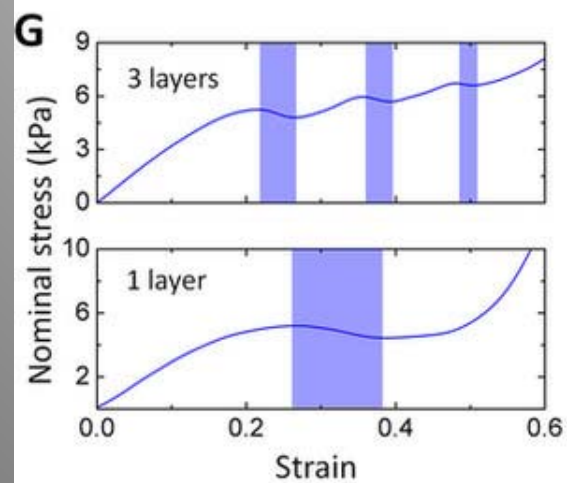
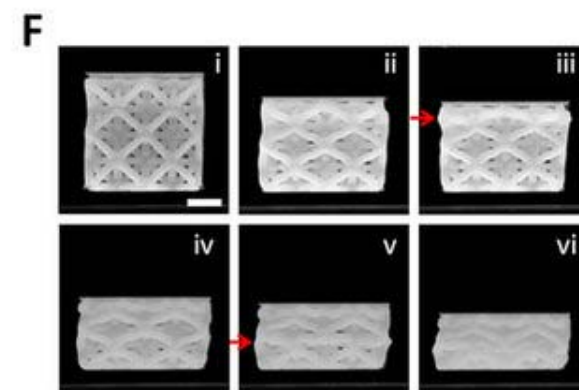
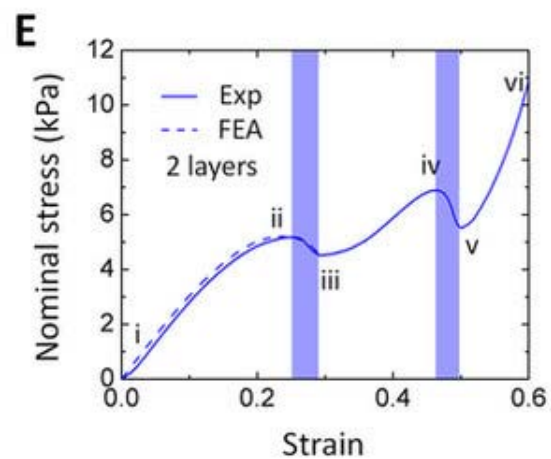
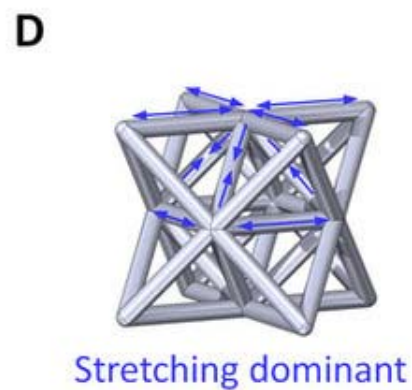
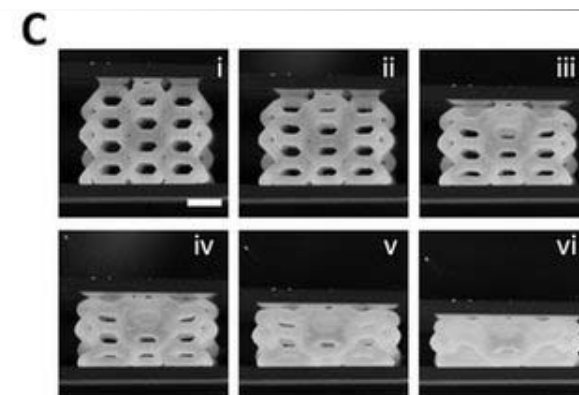
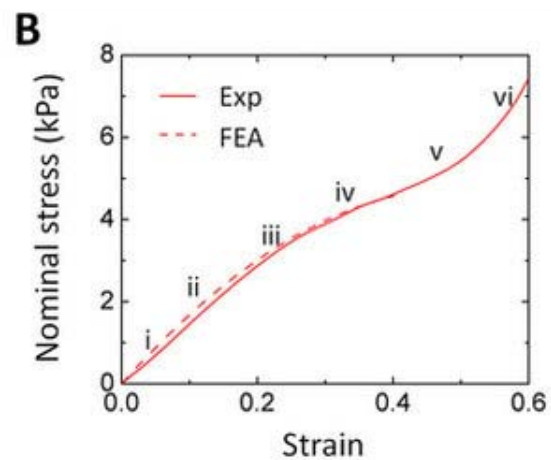
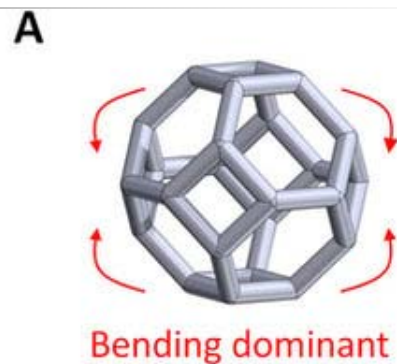
These successful fabrication of these nanotrusses marks a huge step forward in our ability to design materials. Not only is it possible to design arbitrarily complex shapes, it is possible to design features on intrinsic material size scales. Through the use of these nano-architected materials, we hope to be able to break into new regimes of material behavior.





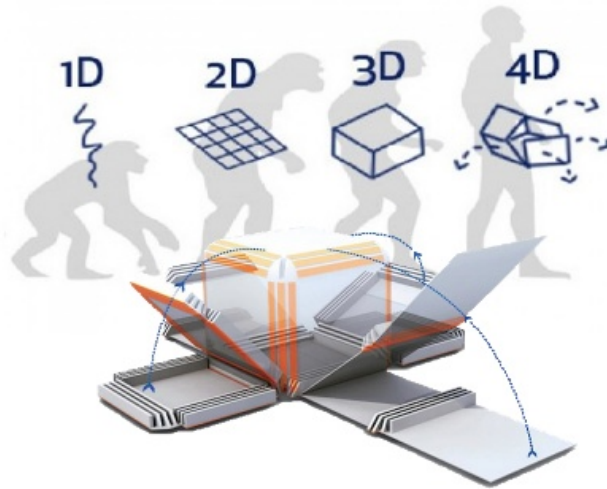




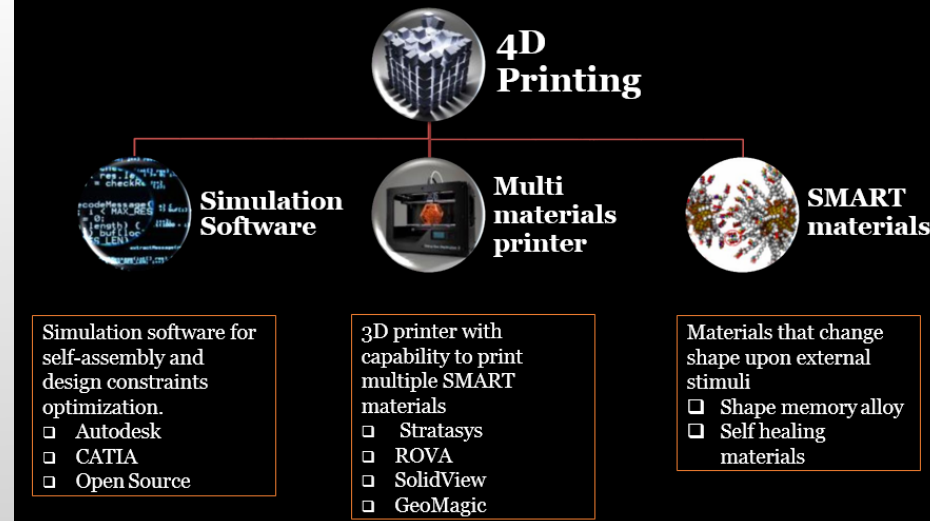


4D PRINTING

Skylar Tibbitts is shaping the next development, which he calls 4D printing, where the fourth dimension is time. This emerging technology will allow us to print **objects that then reshape themselves or self-assemble over time.**



Important Aspects of 4D Printing



Year of Impact (4D printing)

Sectors	Expected Year of Impact									
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Healthcare										
Military										
Infrastructure										
Automobile										
Packaging										
Aerospace										
Manufacturing										

Source: Frost & Sullivan, June 2014

The expected year of widespread/ large-scale adoption of 4D Printing technology has been computed through assessments of technology advances, industry initiatives, challenges, advances in related industries, and market potential

Further Applications of Smart Materials



