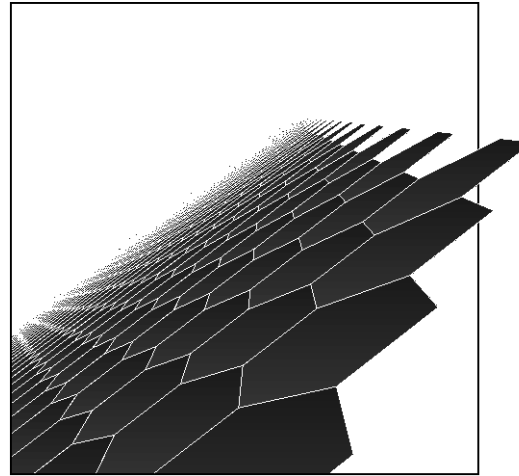


# Towards self-reproducing robots

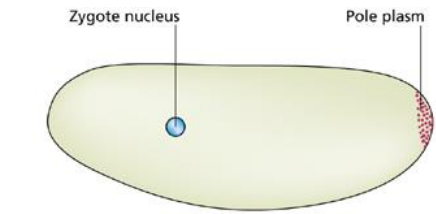


# What you will learn in this class

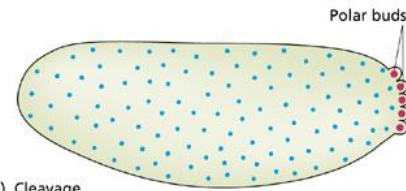
- Self-reproduction by growth and by self-assembly
- Self-assembly by robots
- Programmable self-assembly
- 2D multi-cellular robots: *in silico* evolution and hardware assembly
- 3D multi-cellular robots: hardware design and assembly
- Evolution of self-reproduction by growth *in silico*
- *In silico* evolution, *in vivo* self-assembly of multicellular organisms
- *In vivo* kinematic self-replication

# Self-reproduction: Divide and Grow

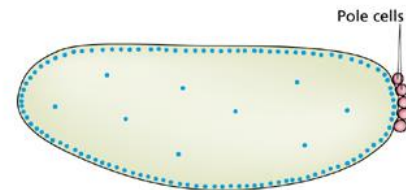
Organisms self-reproduce by a mechanism of cell division, specialization, and migration



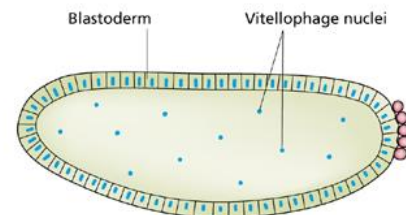
(a) Zygote



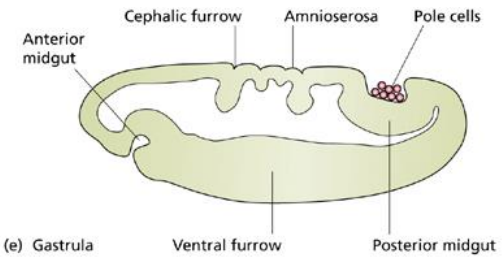
(b) Cleavage



(c) Syncytial blastoderm



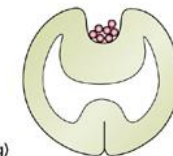
(d) Cellular blastoderm



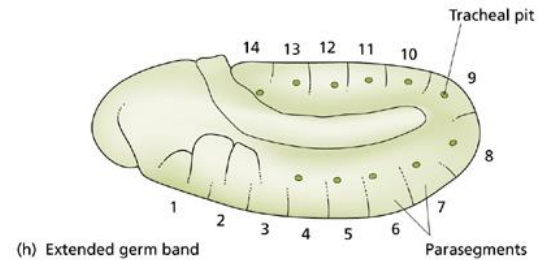
(e) Gastrula



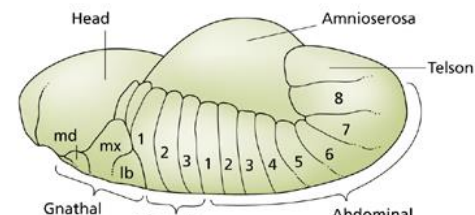
(f)



(g)



(h) Extended germ band



(i) Retracting germ band

Early development of *Drosophila* [Slack 2006]

# Self-reproduction by self-assembly

At sub-cellular level, self-replication happens by self-assembly of existing materials (see first lecture on “From DNA to Proteins”)



Von Neumann (1966), *Theory of self-reproducing automata*, A.E. Burks (Editor), University of Illinois Press

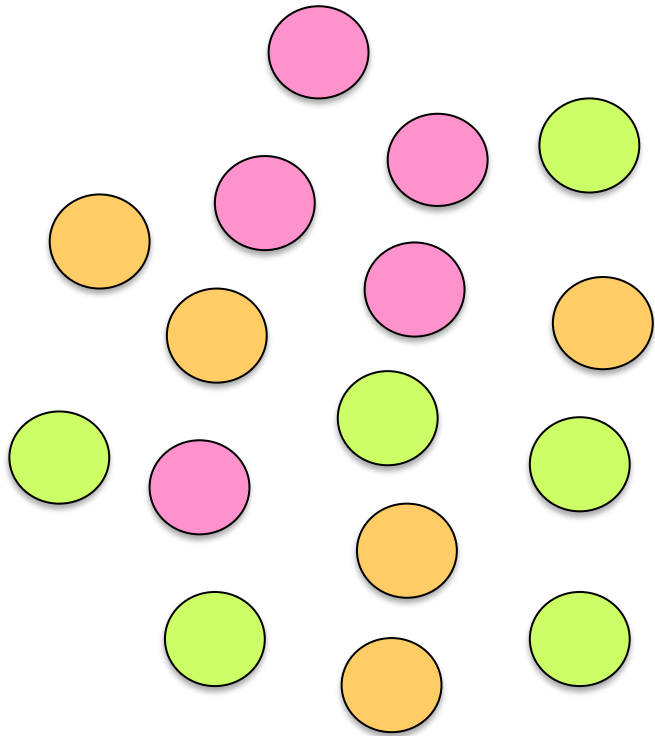
“Self-reproducing robots by self-assembly are possible if a reservoir of specialized cells is available in the environment”

He considered a floating environment with millions of elementary “cells” of approximately 20 types:

- sensor cell
- muscle cell
- cutting cell
- fusing cell
- neuron-like cell
- ...

## *2 requirements for self-assembly*

A population  
of diverse cells



Intrinsic and/or extrinsic  
energy potential



**Galton Laboratory**

**University College**

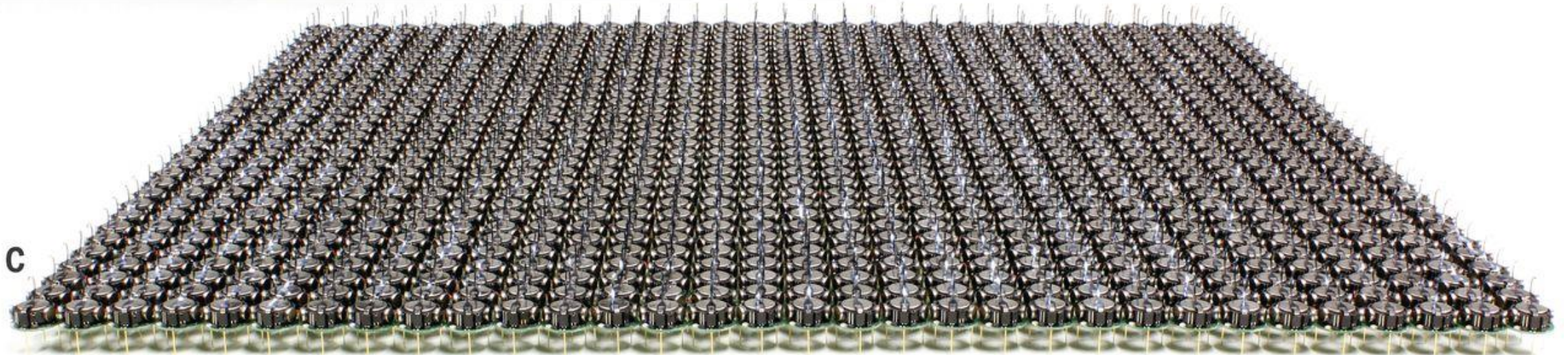
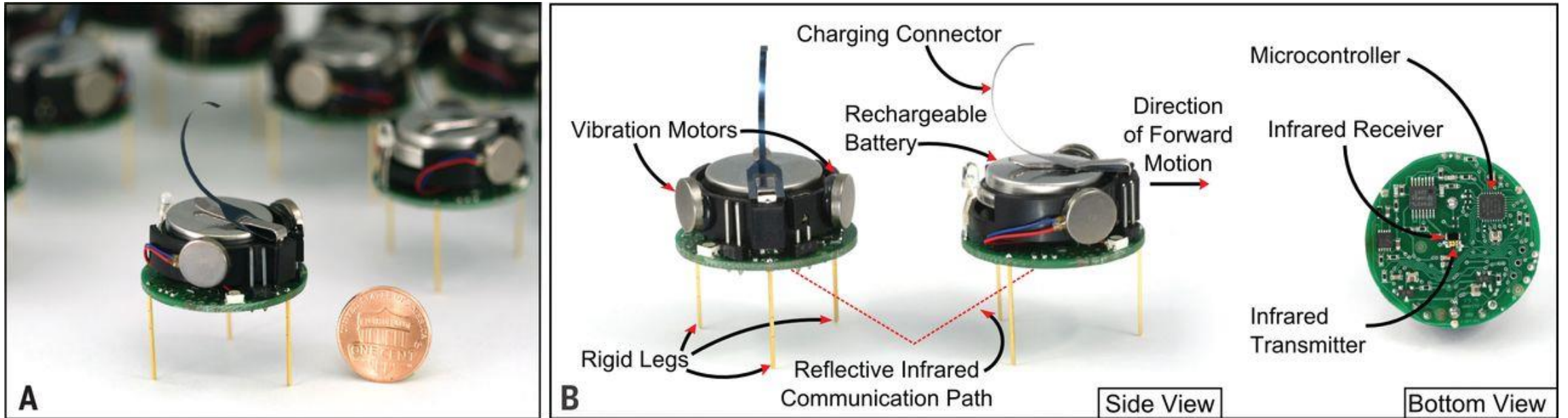
**London**

*presents*

—

Penrose, L. S. & Penrose, R. *Nature* **179**, 1183 (1957).

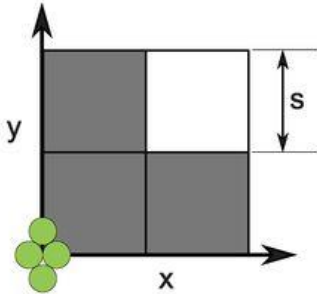
# Self-assembling Kilobots



# Self-assembly Algorithm

## User-specified shape

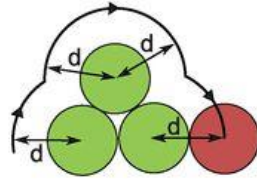
The desired shape is given to all robots in the form of a binary bitmap. Four pre-localized seed robots (green) define the origin and orientation of the coordinate system.



The desired shape is aligned with the coordinate system and scaled by the input parameter 's'.

## Edge-following

A robot (red) moves by maintaining a fixed distance 'd' to the center of the closest stationary robot (green).



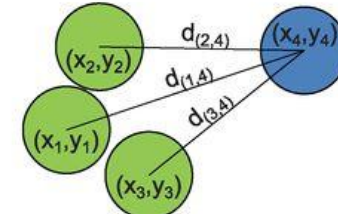
## Gradient formation

Each robot sets its gradient value to 1 + the minimum value of all neighbors closer than distance 'g'. The source robot (green) maintains a gradient value of 0.



## Localization

A robot (blue) determines its position in the coordinate system by communicating with already localized robots (green).

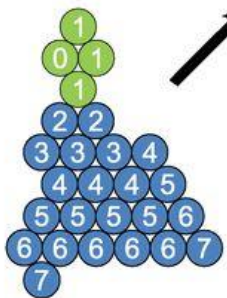


$$(x_4, y_4) = \min_{x_4, y_4} \left( \sum_{i=1}^3 |d_{(i,4)} - \alpha_i| \right)$$

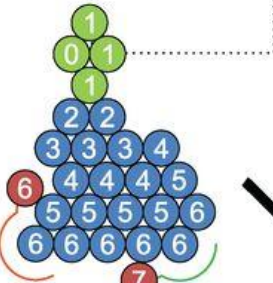
$$\text{where } \alpha_i = \sqrt{(x_i - x_4)^2 + (y_i - y_4)^2}$$

## Self-assembly algorithm

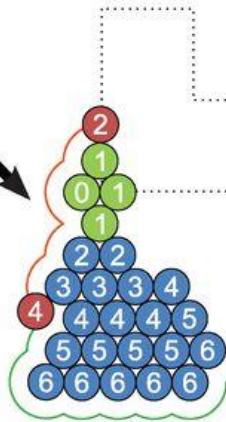
Starting position of the initial group (blue robots), and seed robots (green). Gradient value displayed on robots.



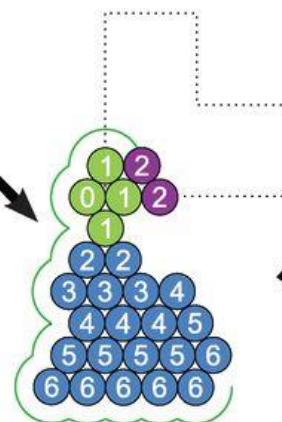
Robots start edge-following (red). Internal representation of desired shape is shown as dotted line.



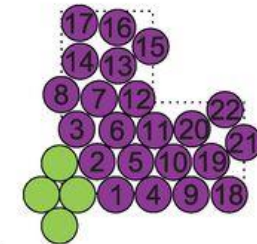
First edge-following robot enters desired shape, as determined by its location in the coordinate system.



Second robot stops and joins the assembly when next to a stationary robot with the same gradient value.



A robot (purple) stops and joins the assembly as it is about to exit shape.



Completed shape after all robots have joined the assembly, with numbers showing the order in which robots joined.

# Self-Organizing Systems Research Group

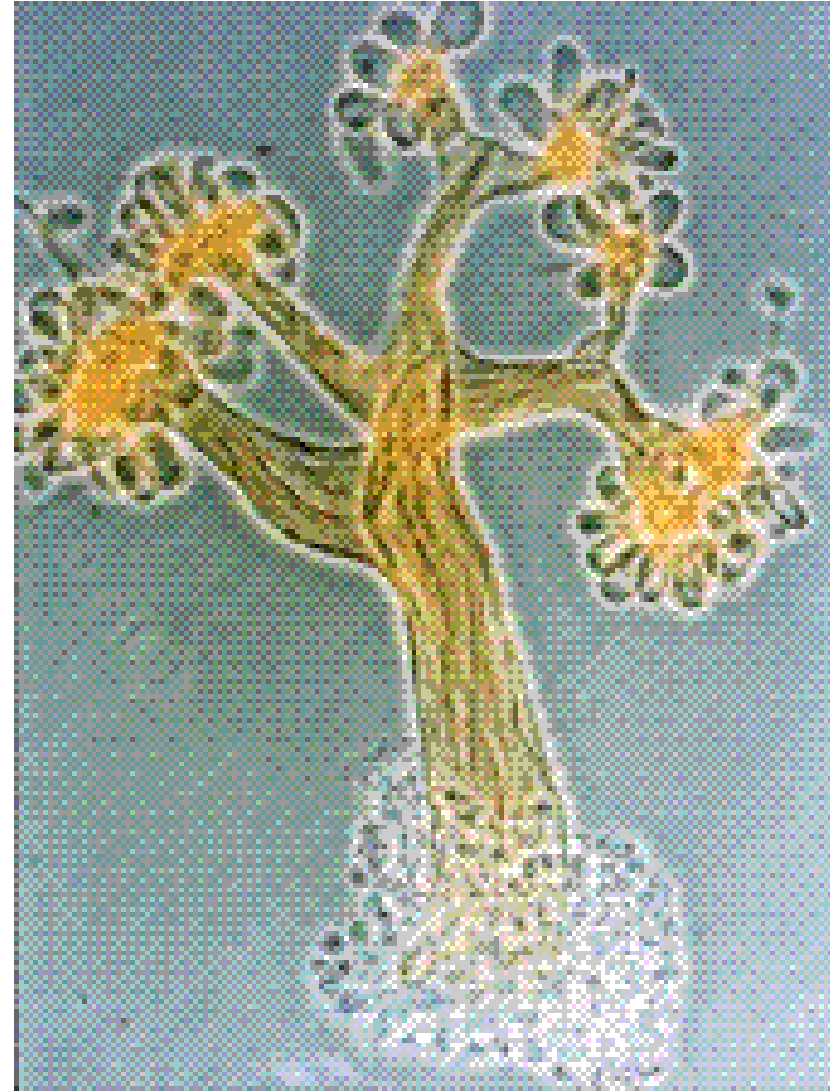


Harvard University  
School of Engineering and Applied Sciences  
Wyss Institute for Biologically Inspired Engineering

# *Cells in Multicellular Organisms* *stiffness, specialization, connectivity*



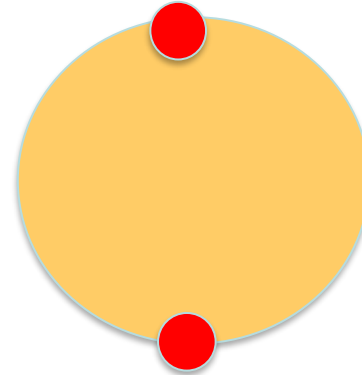
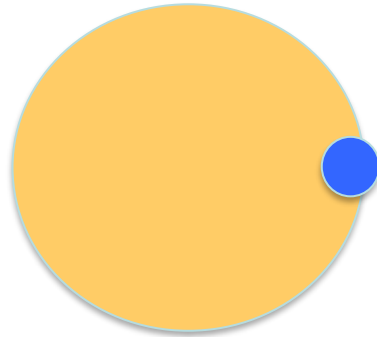
Cyanobacteria



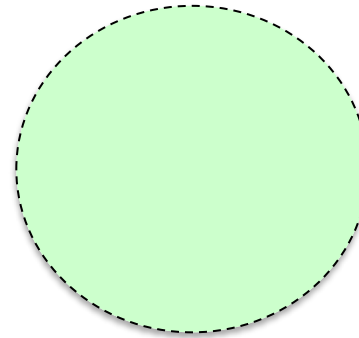
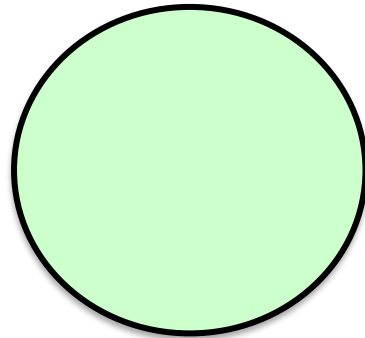
Myxobacteria

# *Cell diversity*

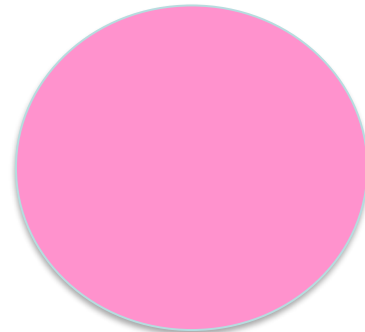
Variable  
connectivity



Variable  
stiffness



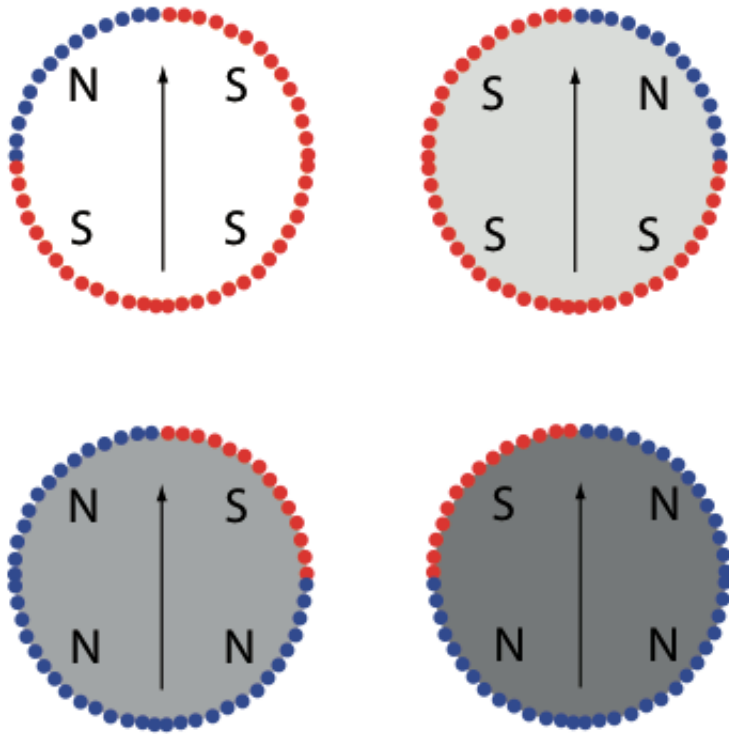
Passive /  
actuated



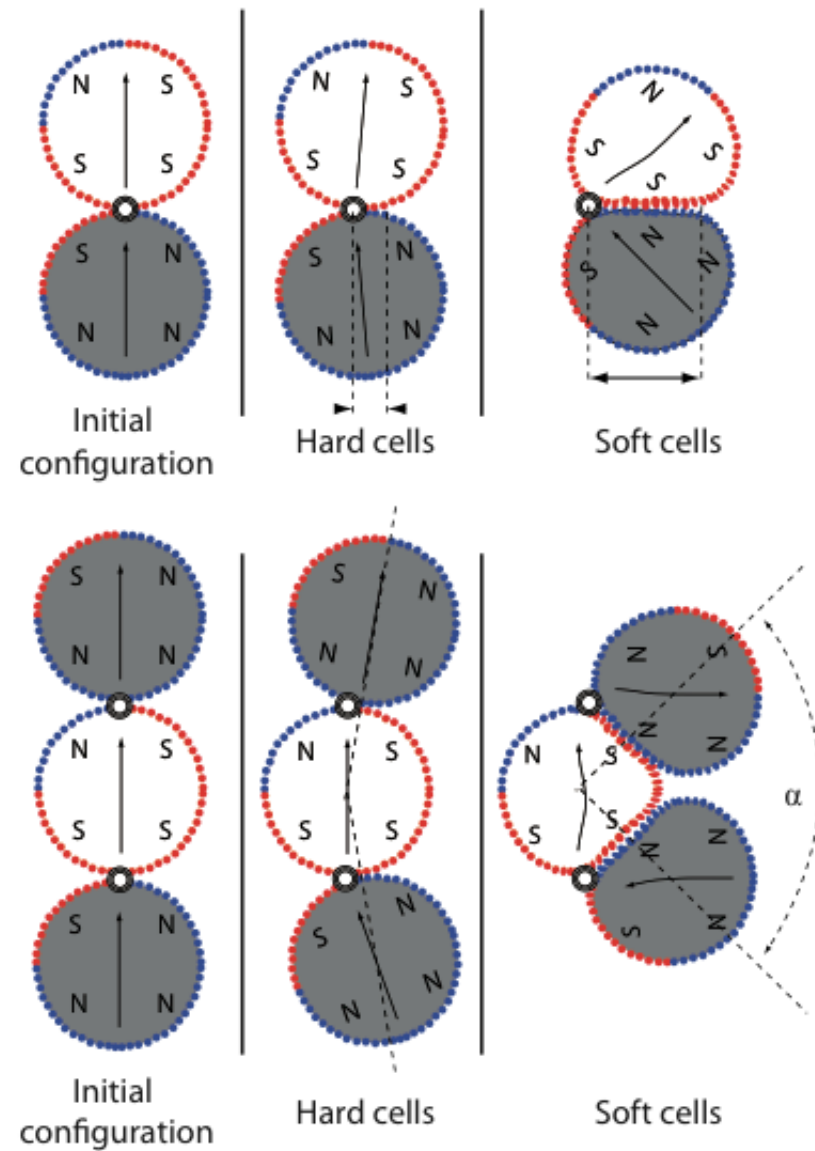
**MORPHOLOGY**

**FUNCTION**

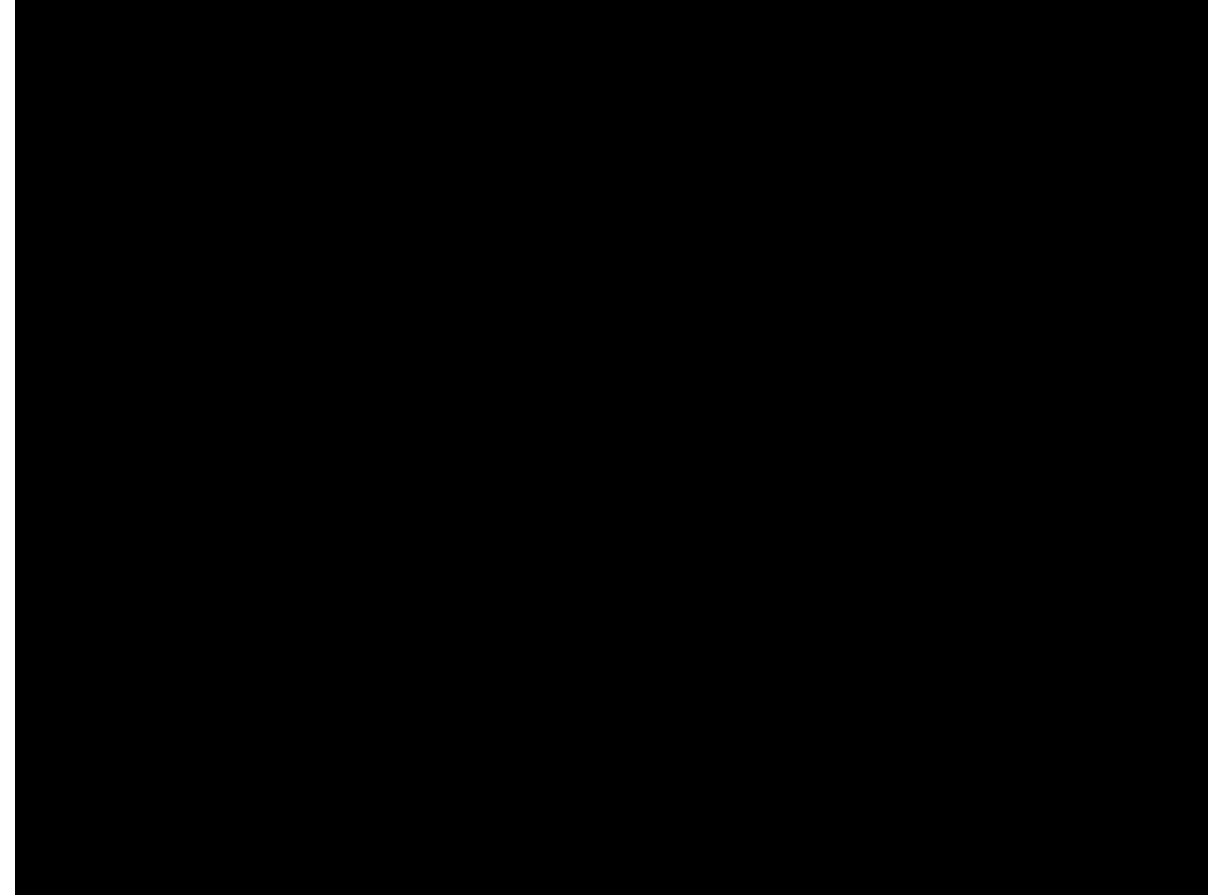
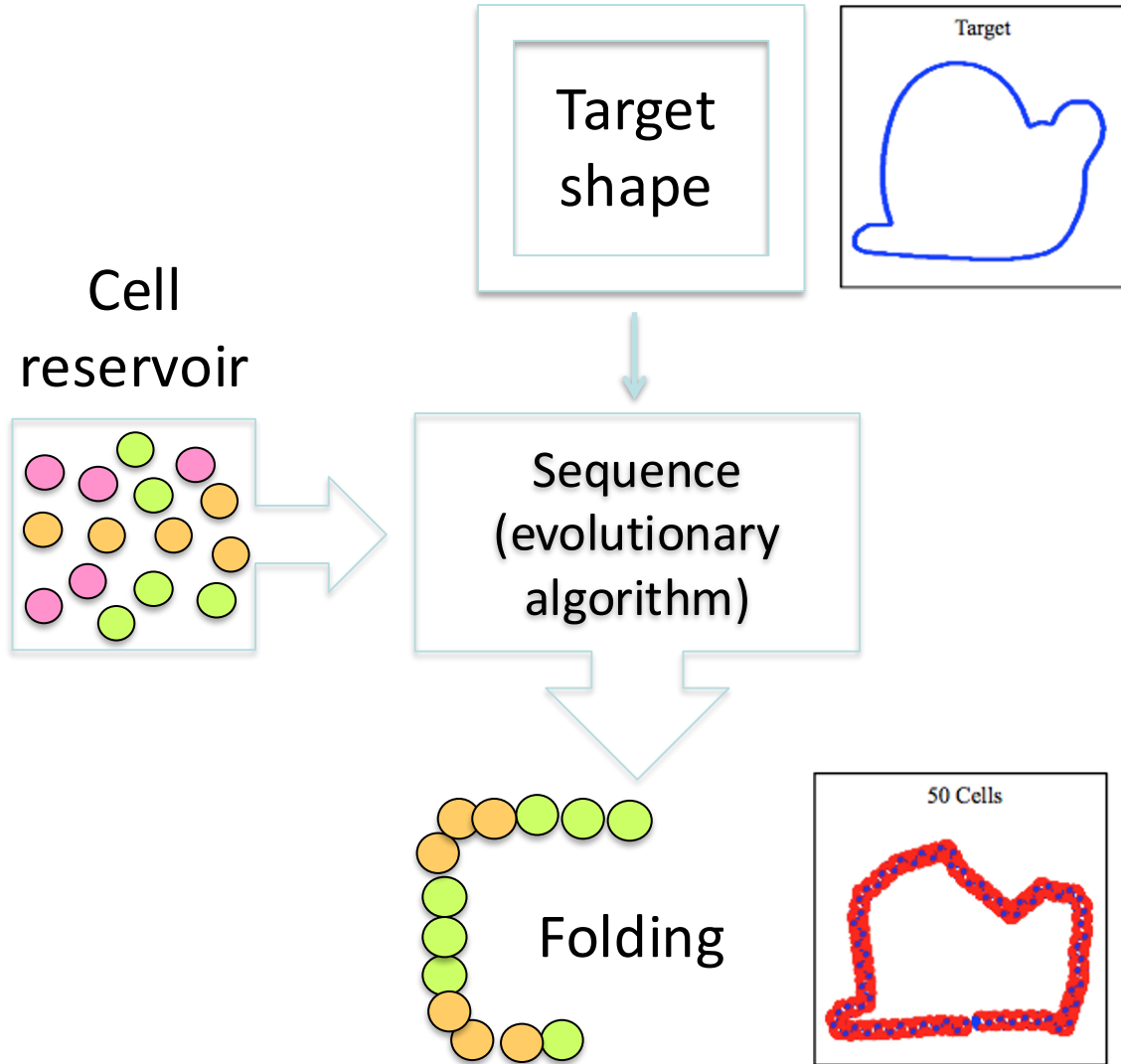
# Softness affects folding angle



Germann et al (2014)  
*Soft Robotics*



# Programmable Self-Assembly

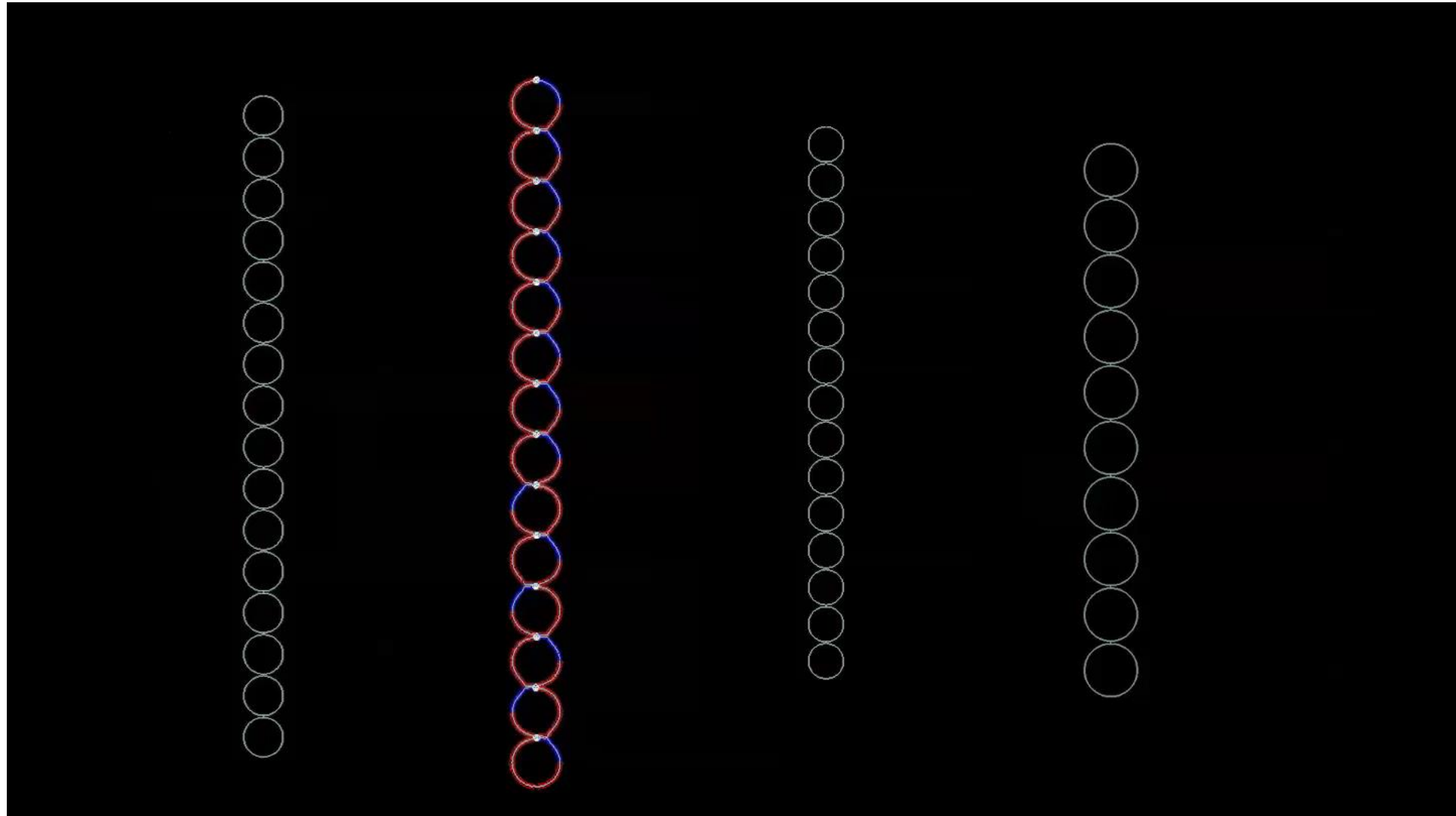


S. Griffith (2004), Growing Machines,  
MIT PhD thesis

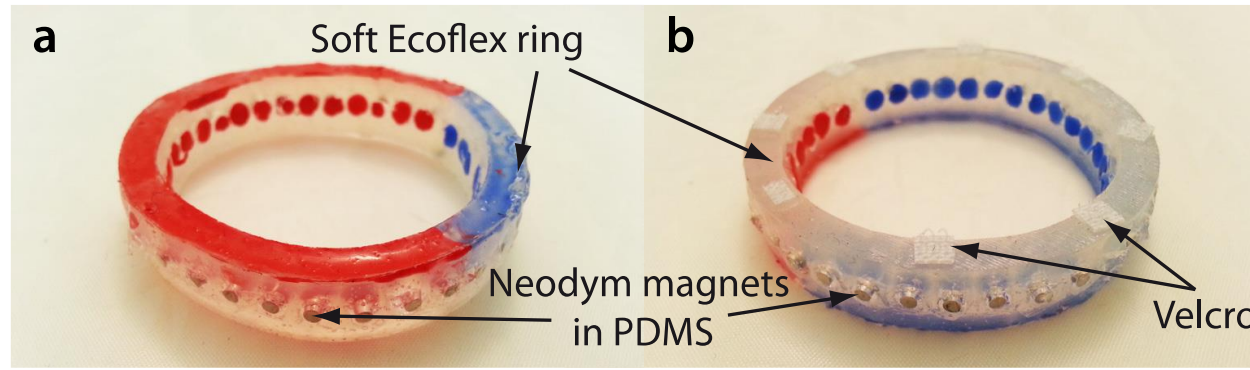
# Programmable self-assembly in silico



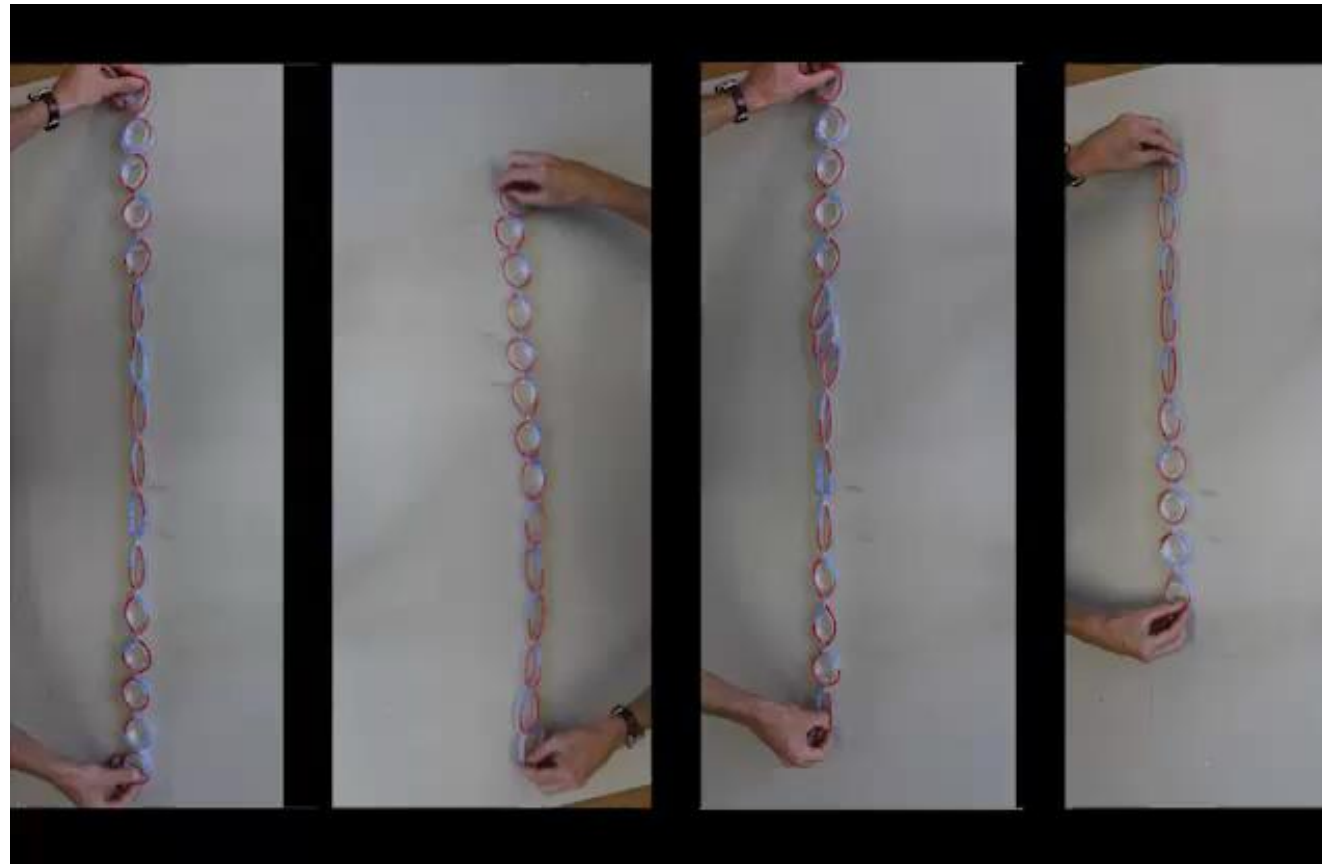
Germann et al (2014) *Soft Robotics*



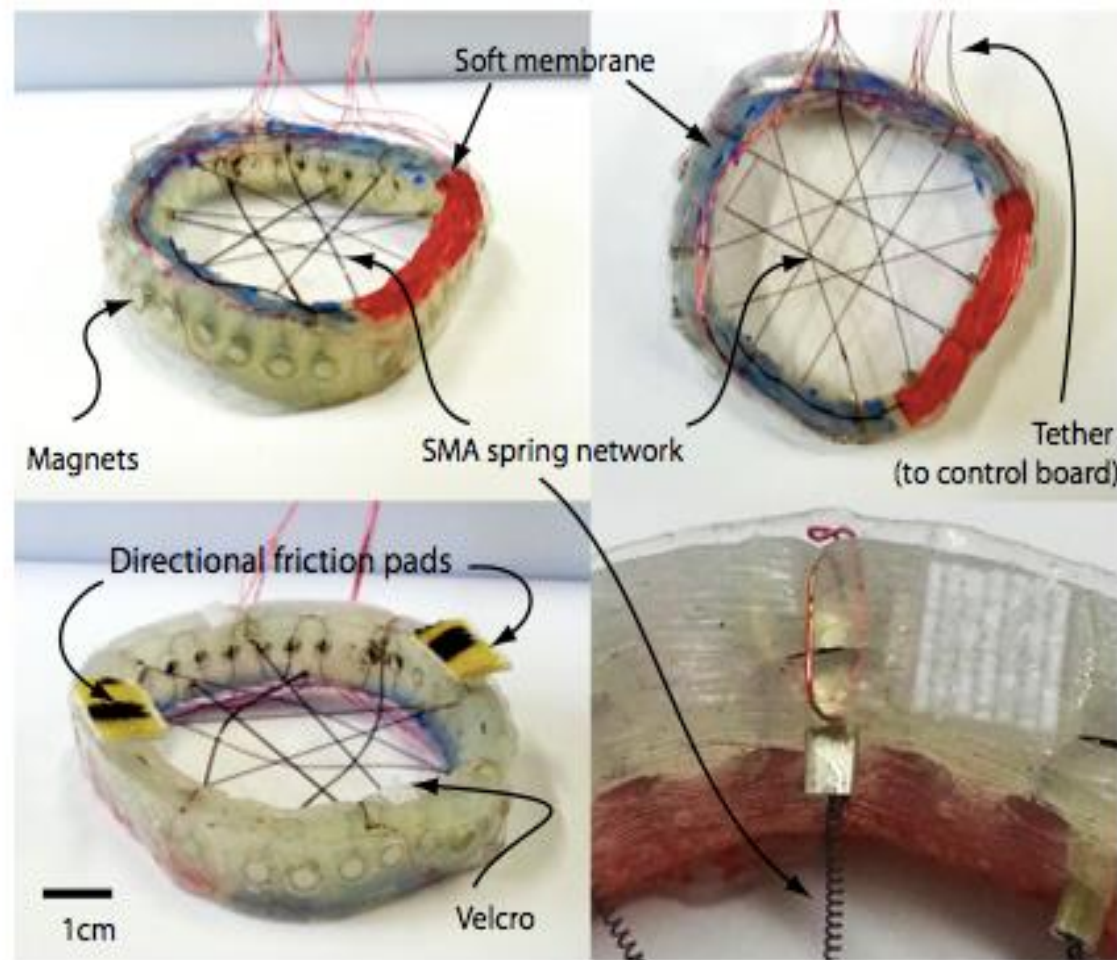
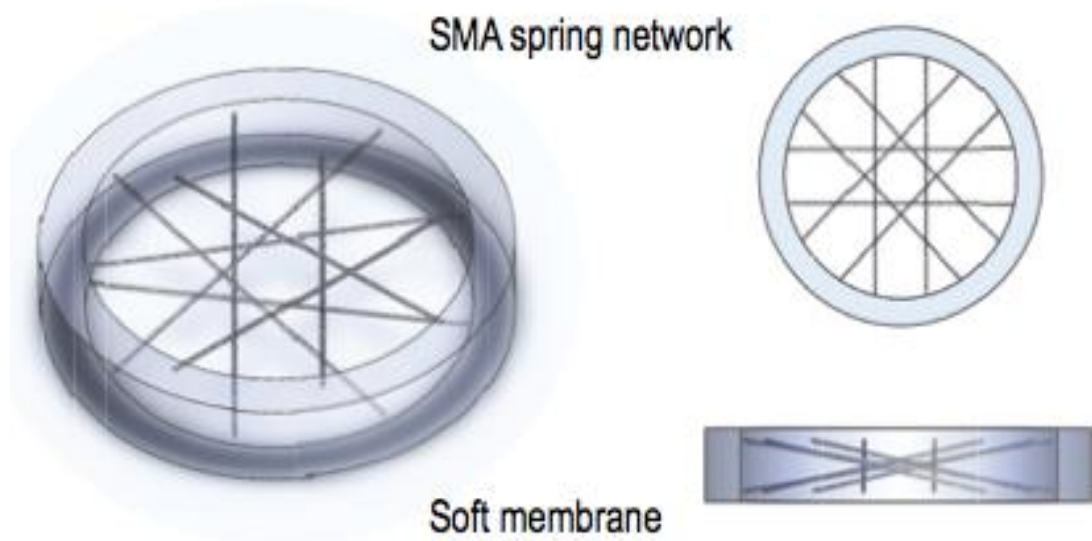
# Programmable self-assembly in hardware



Germann et al  
(2014) *Soft Robotics*

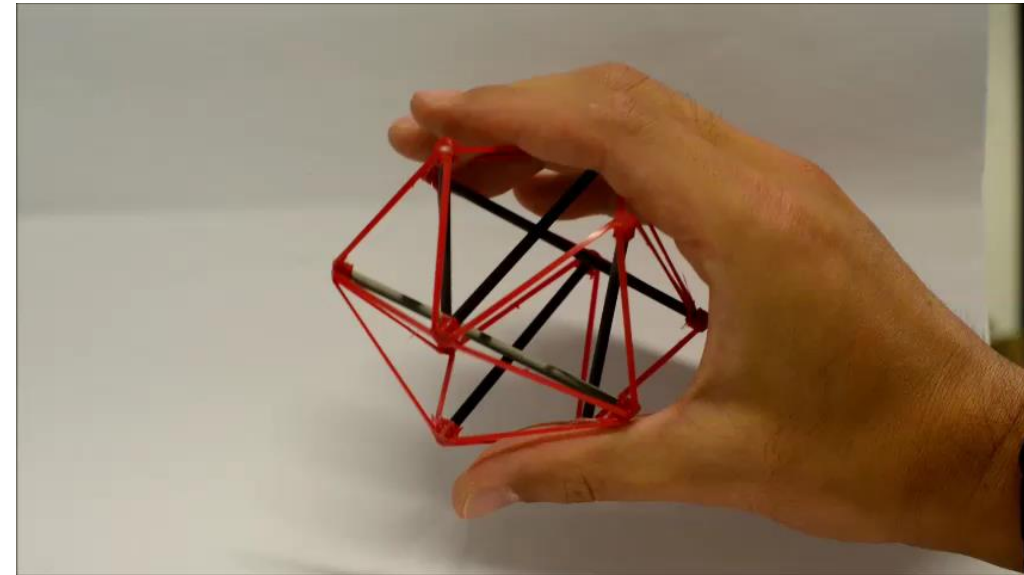
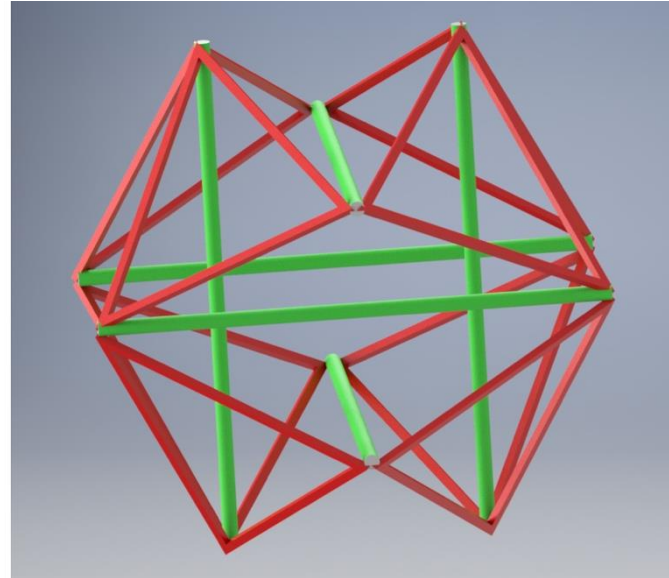
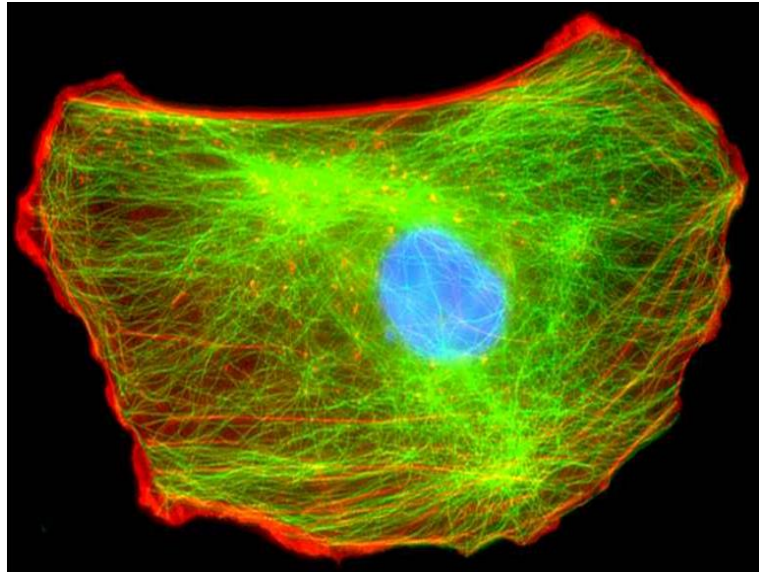


# Adding muscle cells



# **Soft Modular Worm**

# From 2D to 3D: Tensegrity robotic cells



Actin filaments



Pre-stretched cables

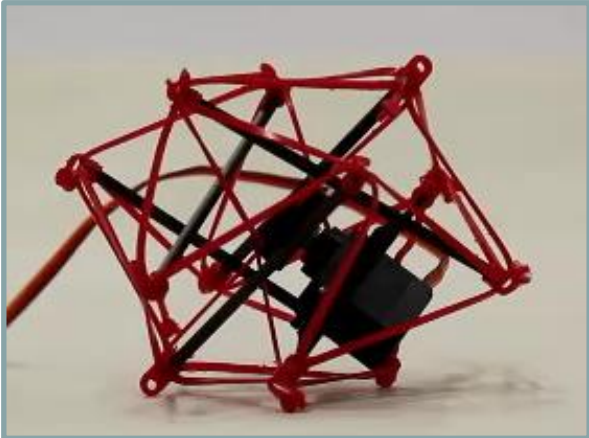
Microtubules



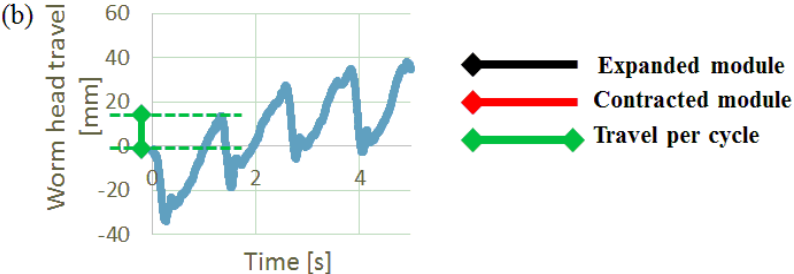
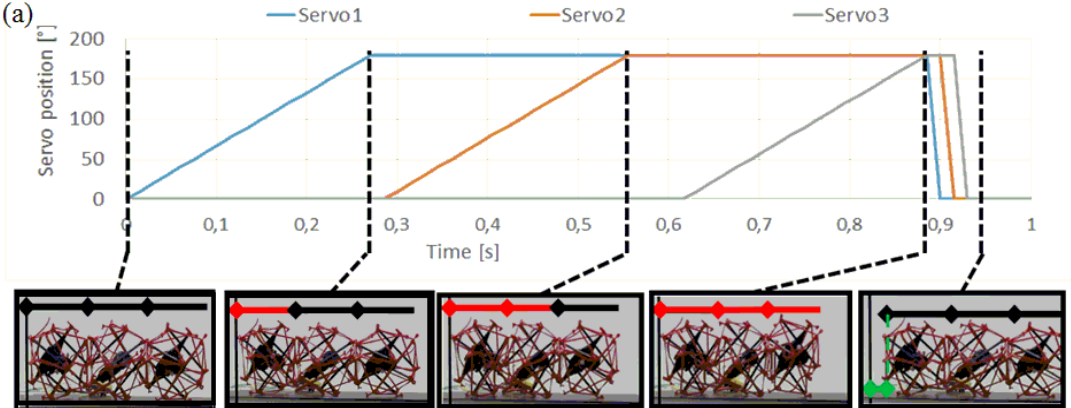
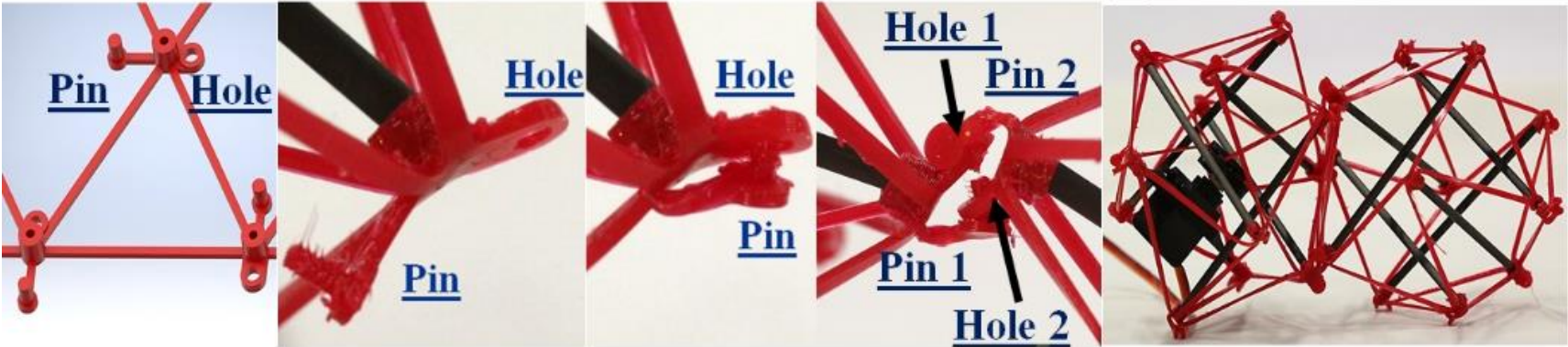
Struts

# 3D multicellular worm

A contracting module



3D printed hole-pin latching

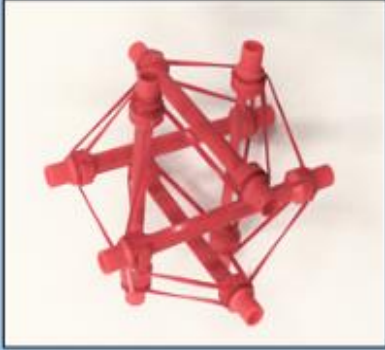


D. Zappetti, S. Mintchev, J. Shintake, e D. Floreano (2017) «Bio-inspired Tensegrity Soft Modular Robots», in *Biomimetic and Biohybrid Systems*, 497–508

# Different types of tensegrity cells

a

Passive Icosahedron



b

Brain module



Microcontroller and battery



c

Junction connector



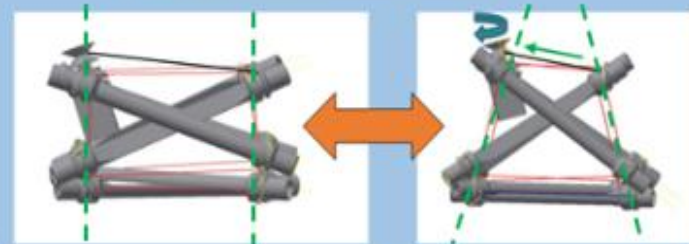
d

Passive three-box-prism module

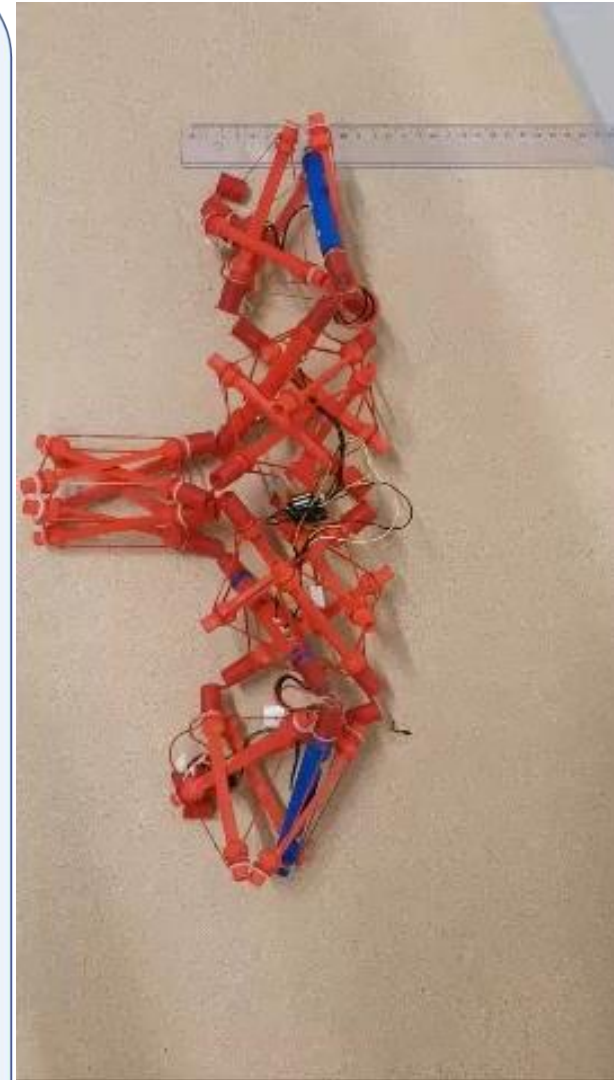
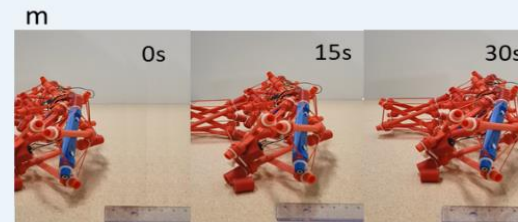
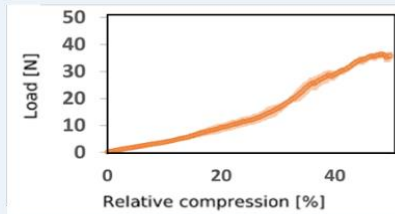
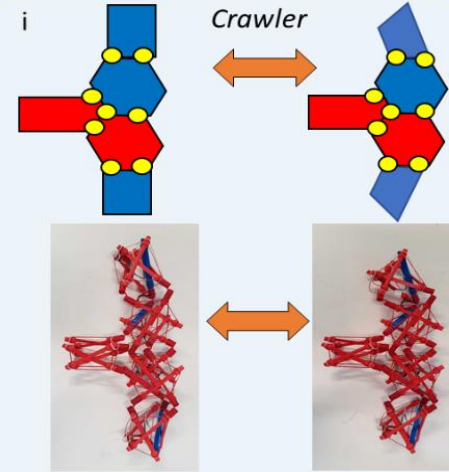
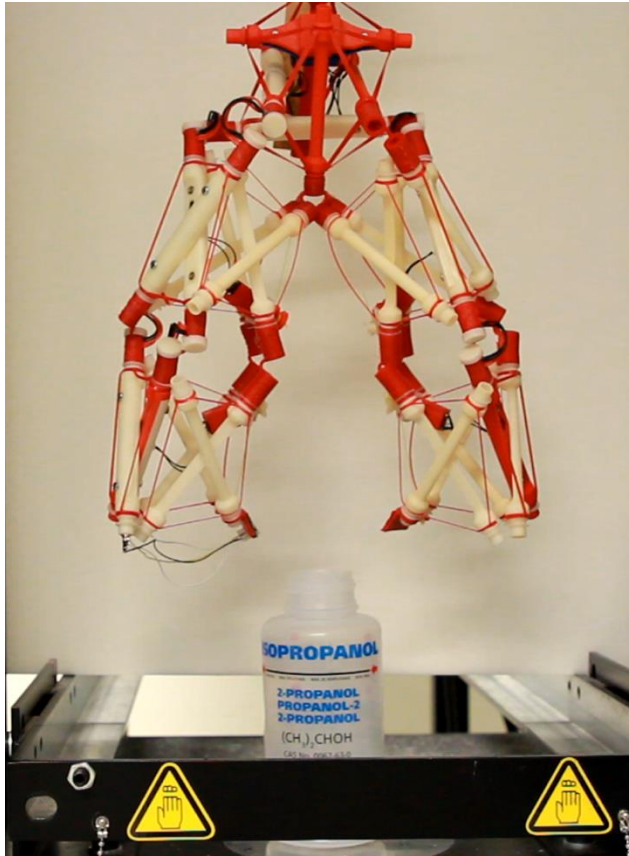
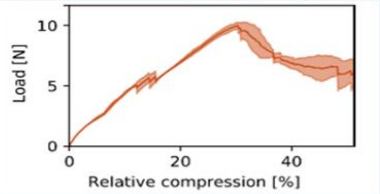
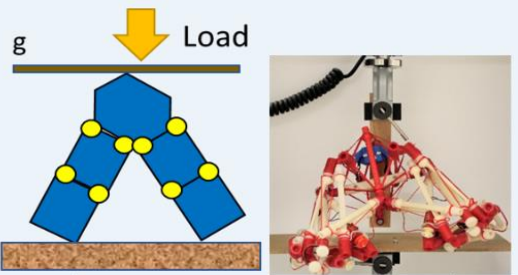
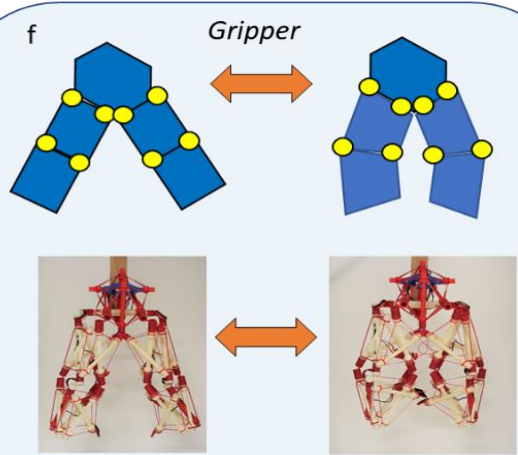


e

Bending module

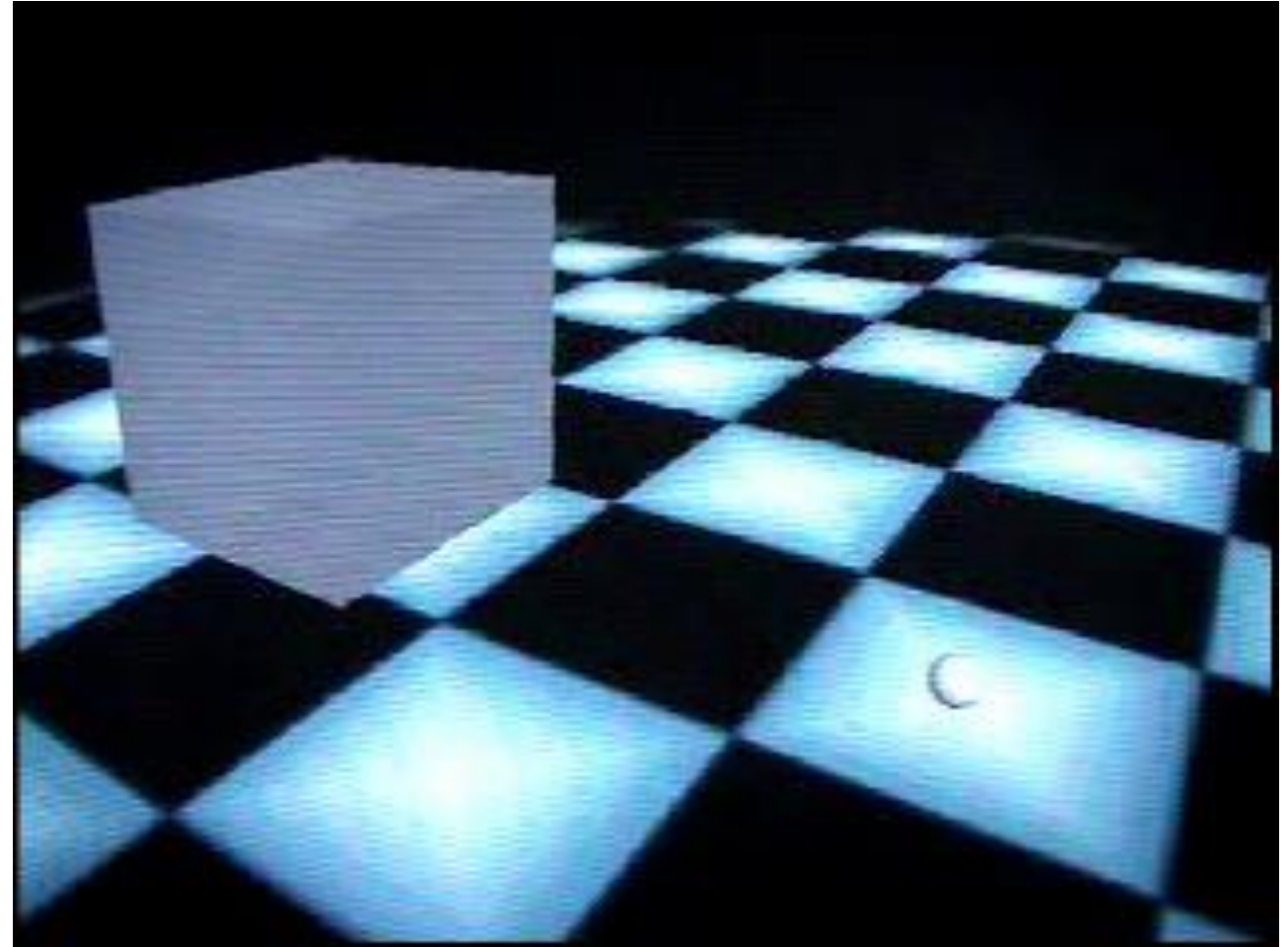
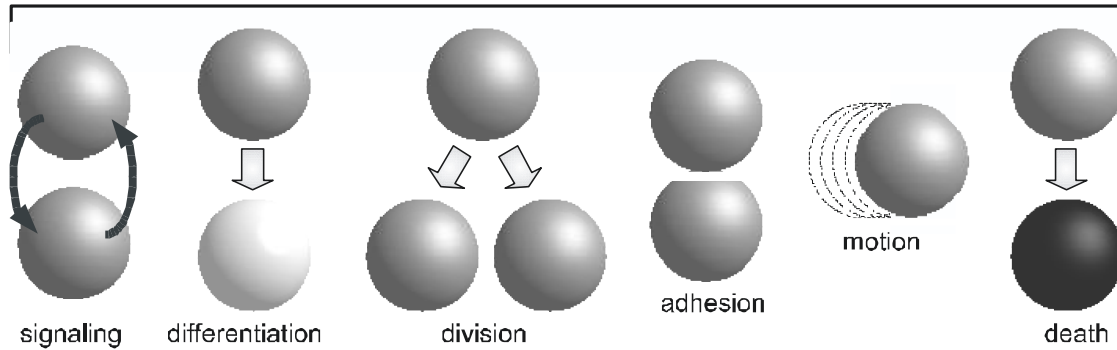
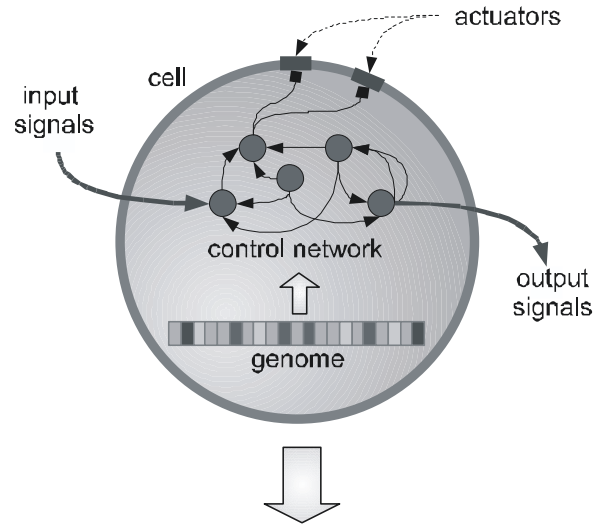


# Multicellular tensegrity robots

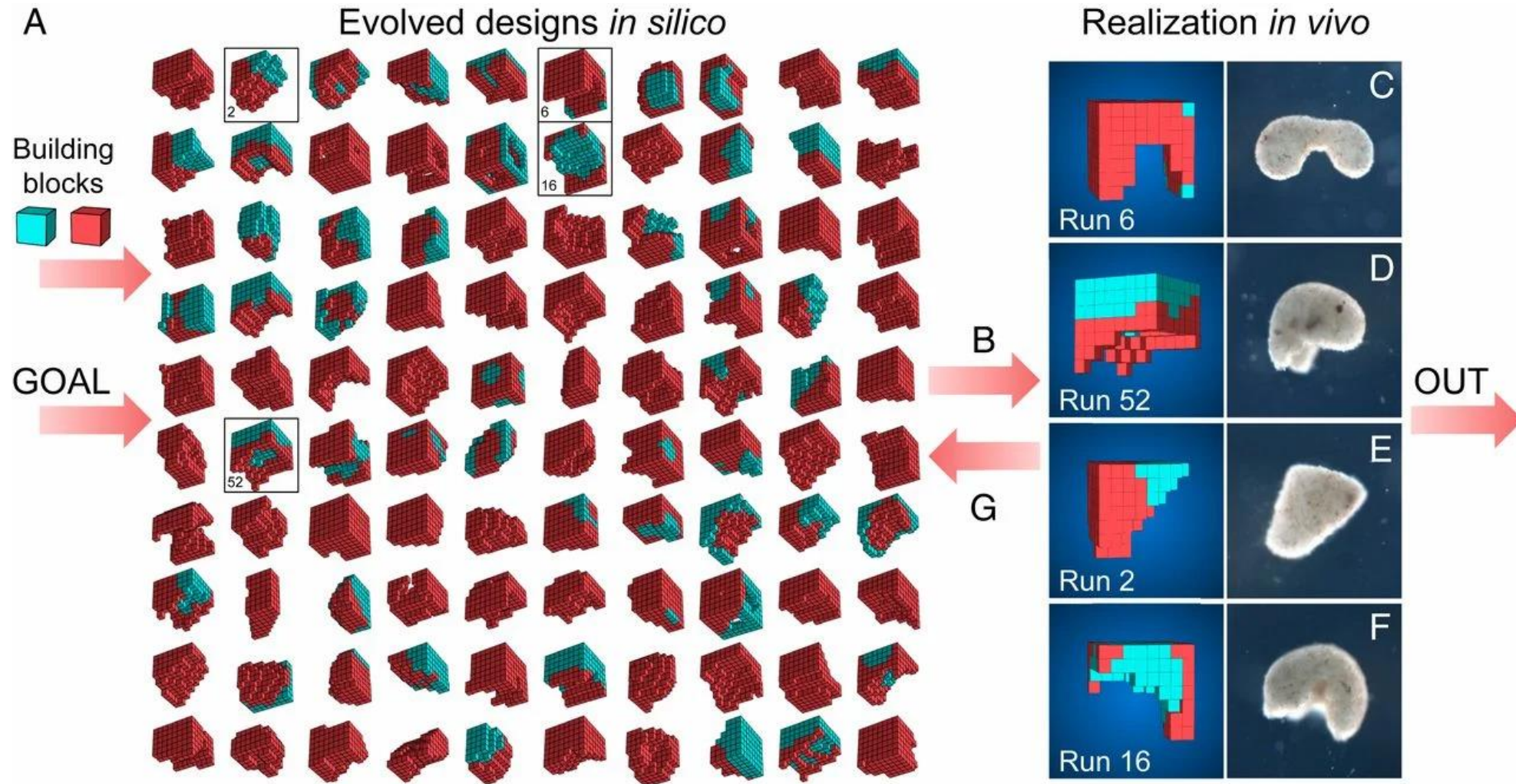


# Artificial Ontogeny (Bongard and Pfeifer, 2001)

*Evolutionary developmental process to synthesize artificial multicellular "creatures"*



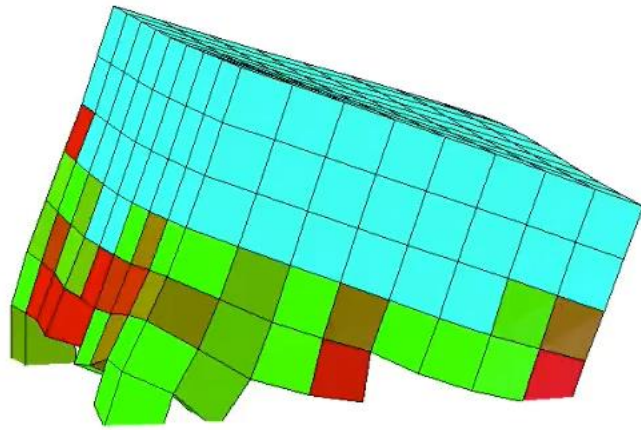
# Xenobots: Evolved *in silico*, assembled *in vivo*



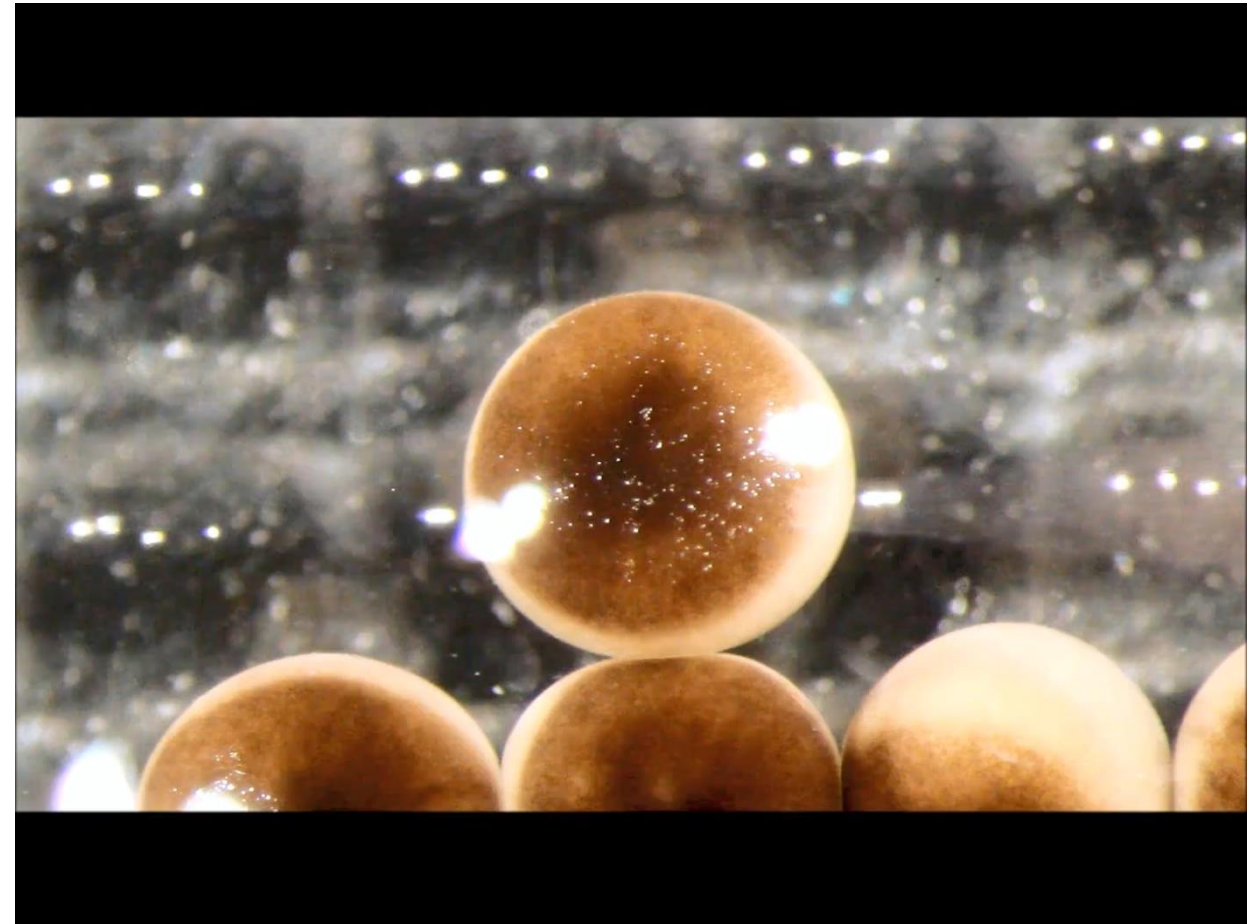
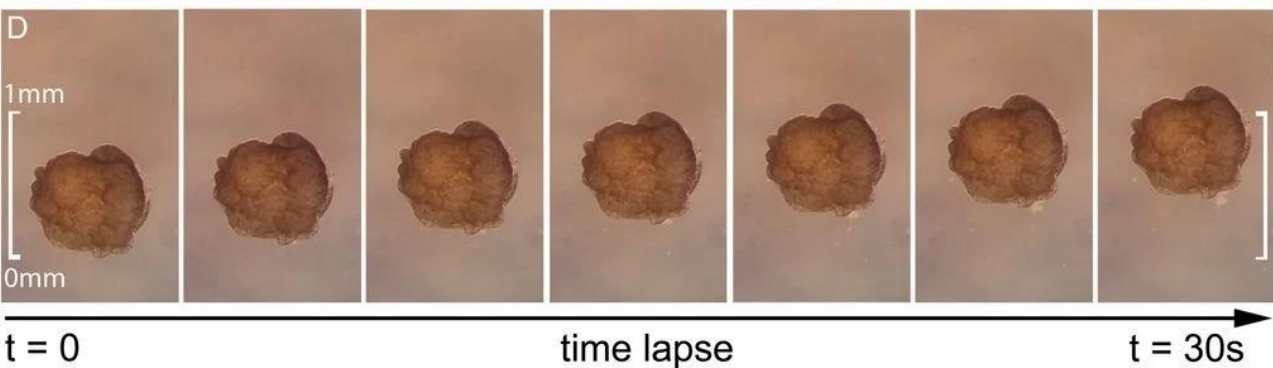
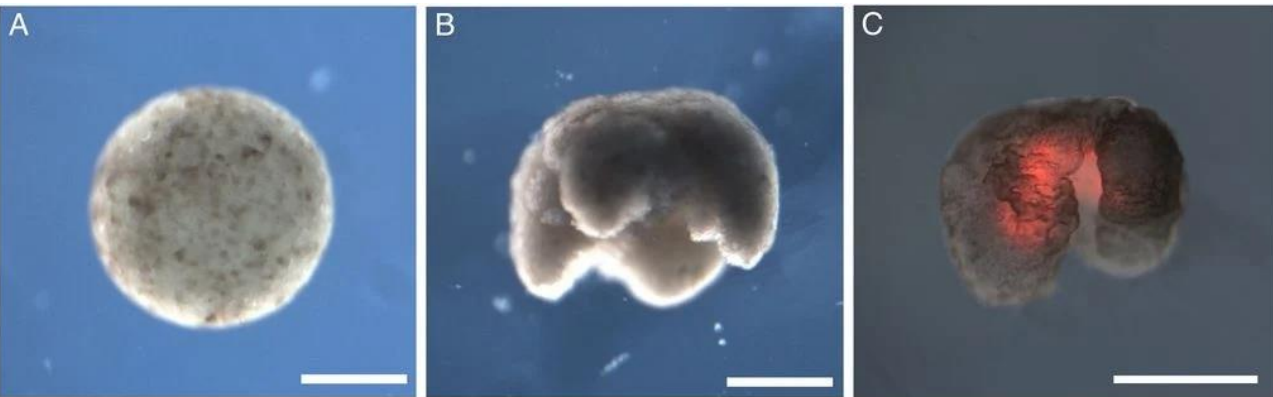
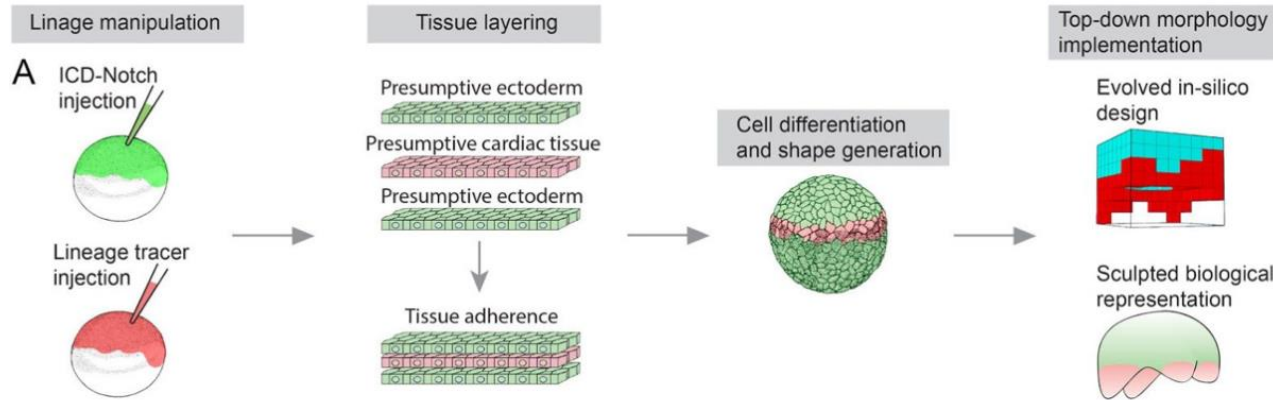
Kriegman, Sam, Douglas Blackiston, Michael Levin, and Josh Bongard (2020) "A Scalable Pipeline for Designing Reconfigurable Organisms." *Proceedings of the National Academy of Sciences* 117(4) : 1853–59. <https://doi.org/10.1073/pnas.1910837117>.

# A scalable pipeline for designing reconfigurable organisms.

Sam Kriegman, Douglas Blackiston, Michael Levin, Josh Bongard  
University of Vermont, Tufts University.



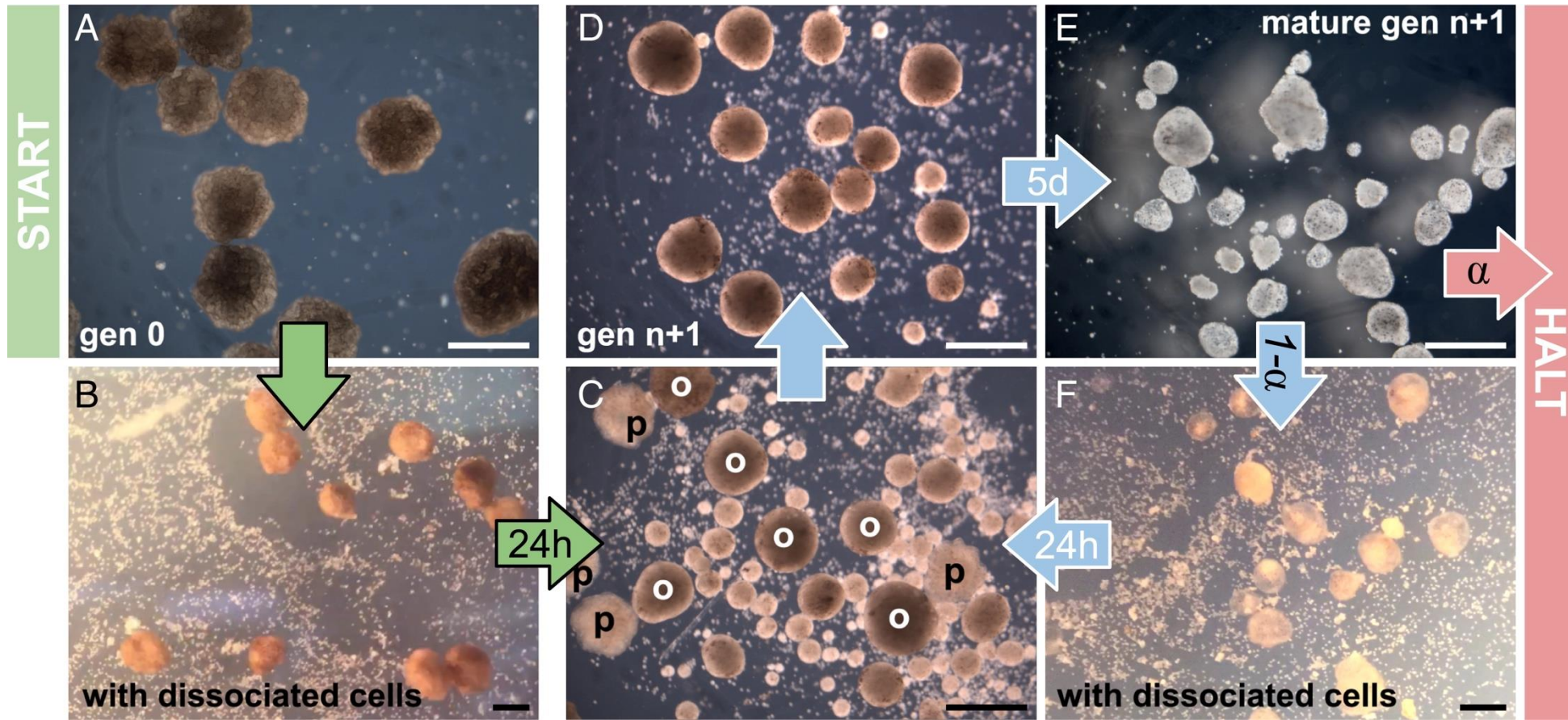
# Manual assembly of Xenobot



Caution: insertion of cardiac cells within Xenobot is not shown in the video

# Assembly of Xenobots by frog cells

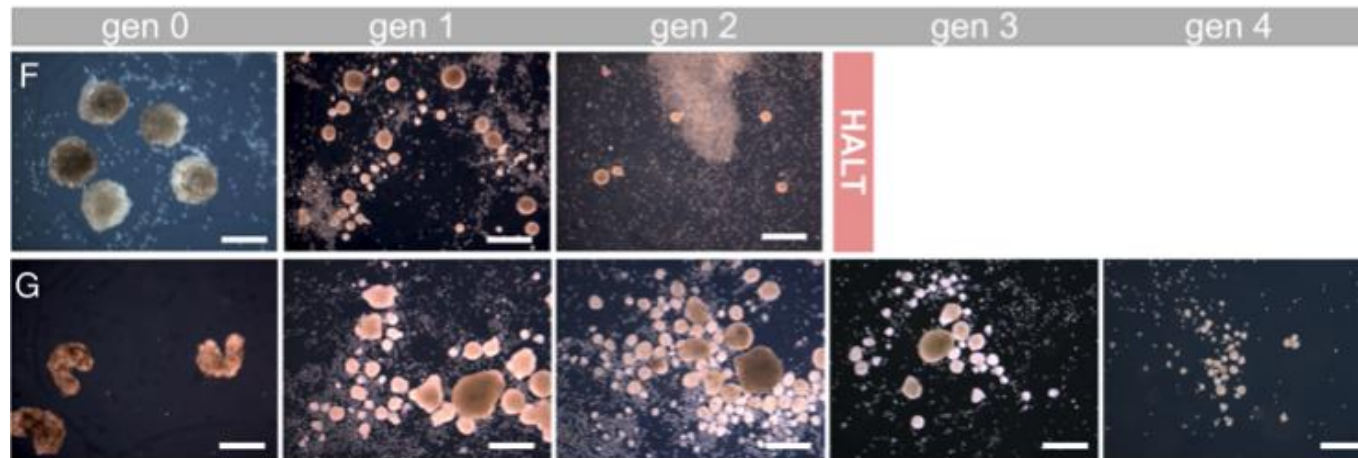
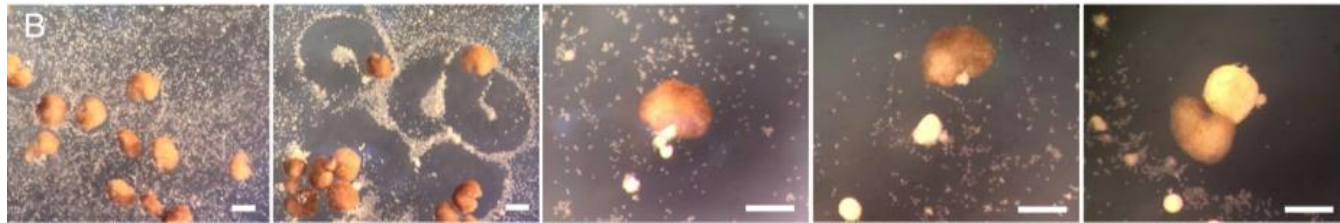
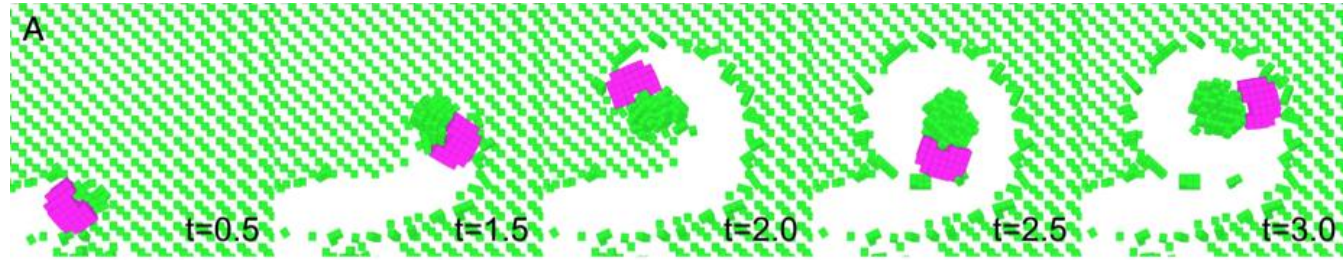
Spontaneous motion of frog cells assemble clusters of ectodermal stem cells that become Xenobots



...but Xenobots assembled by frog cells do not self-replicate

# Self-reproduction by self-assembly of Xenobots

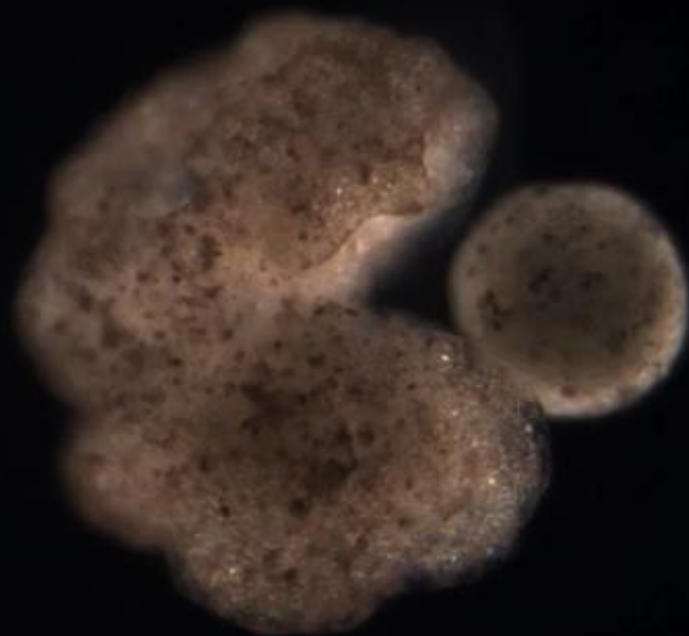
*In silico* evolution designs frog cell shapes that assemble self-replicating Xenobots



Kriegman, Sam, Douglas Blackiston, Michael Levin, and Josh Bongard (2021) Kinematic Self-Replication in Reconfigurable Organisms. *Proceedings of the National Academy of Sciences* 118(49) <https://doi.org/10.1073/pnas.2112672118>.

# Kinematic self replication in reconfigurable organisms.

Sam Kriegman<sup>1,2</sup> Douglas Blackiston<sup>1,2</sup> Michael Levin<sup>1,2</sup> & Josh Bongard<sup>3,\*</sup>



<sup>1</sup> Allen Discovery Center, Tufts University

<sup>2</sup> Wyss Institute for Biologically Inspired Engineering, Harvard University

<sup>3</sup> Department of Computer Science, University of Vermont

\* [jbongard@uvm.edu](mailto:jbongard@uvm.edu)

# *Check Points*

- What are the requirements for self-assembly?
- What is programmable self-assembly?
- What is evolution used for in the Xenobot project?