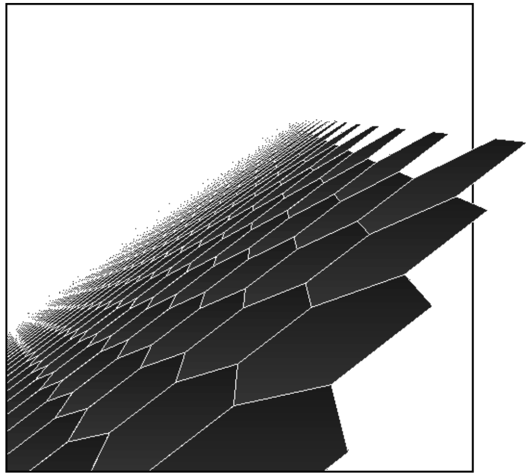
Towards self-reproducing robots

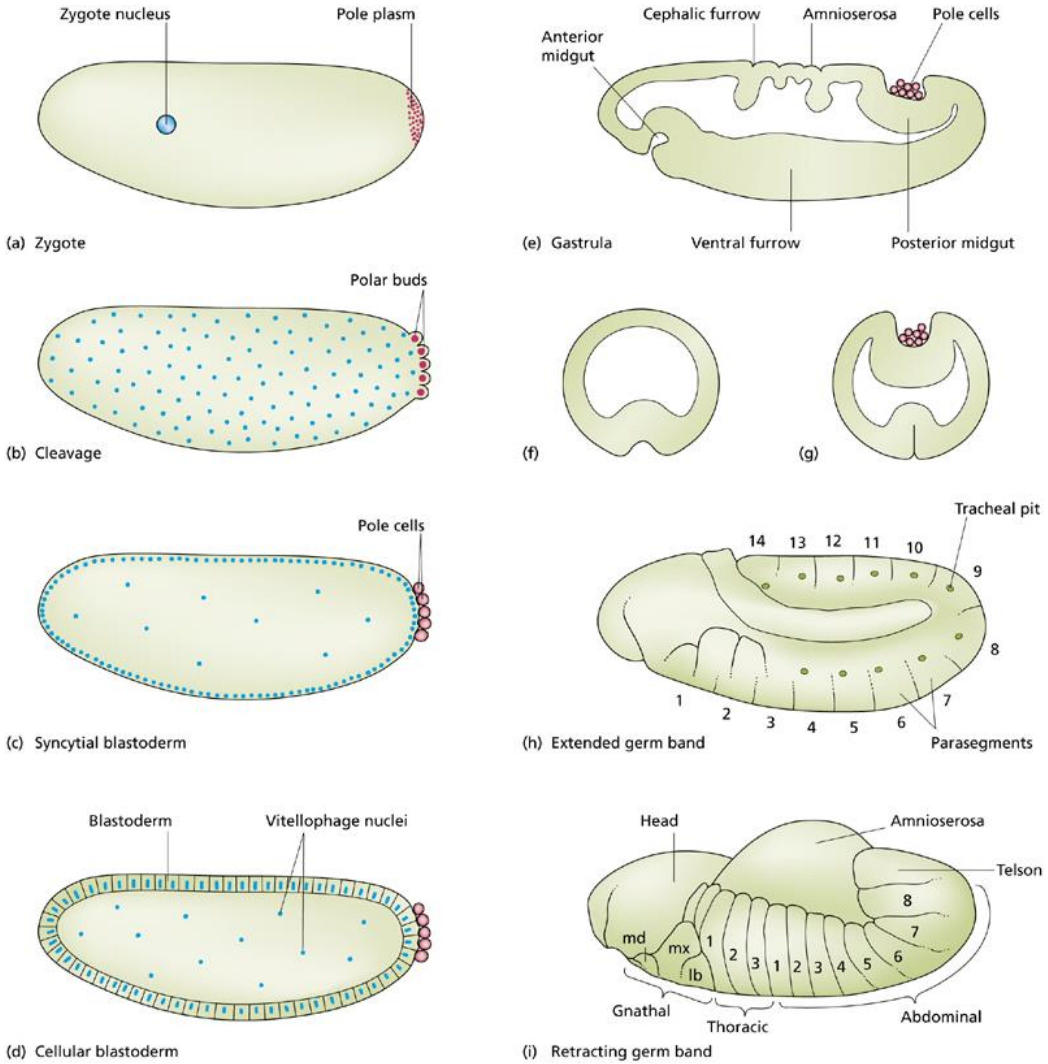


What you will learn in this class

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

Self-reproduction by growth

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



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

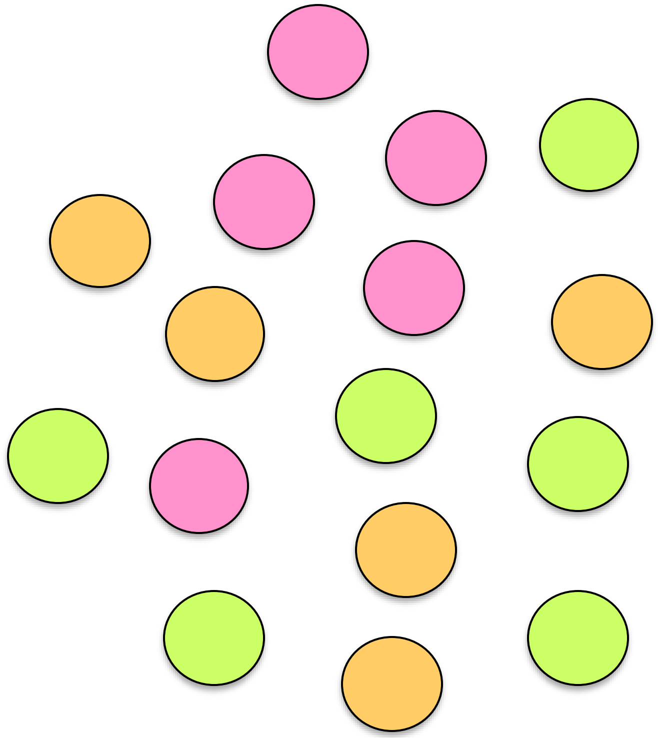
“Self-reproducing robots by self-assembly are possible if a reservoir of specialized cells is available in the environment”

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

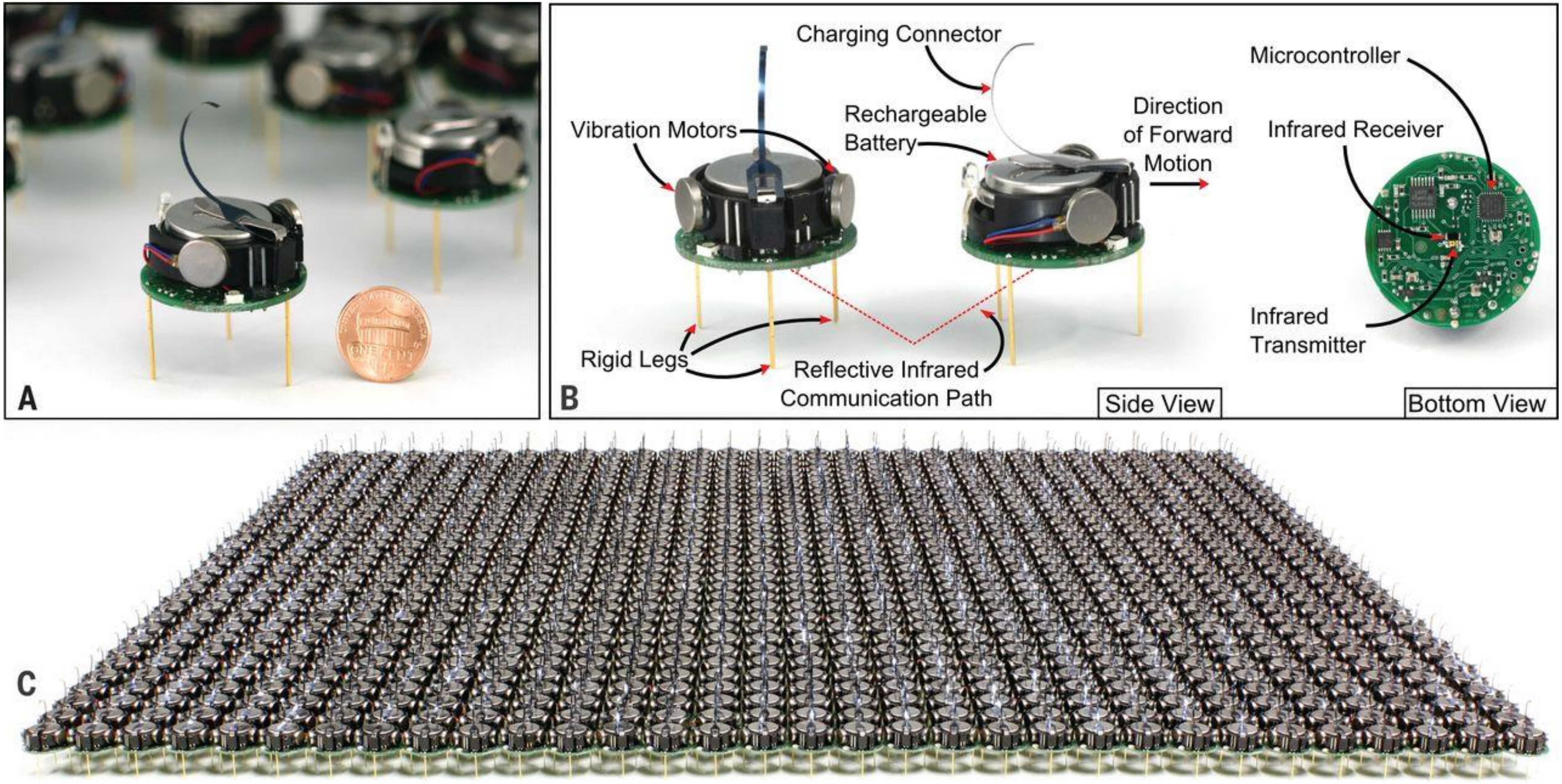
A population
of diverse cells



Intrinsic and/or extrinsic
energy potential

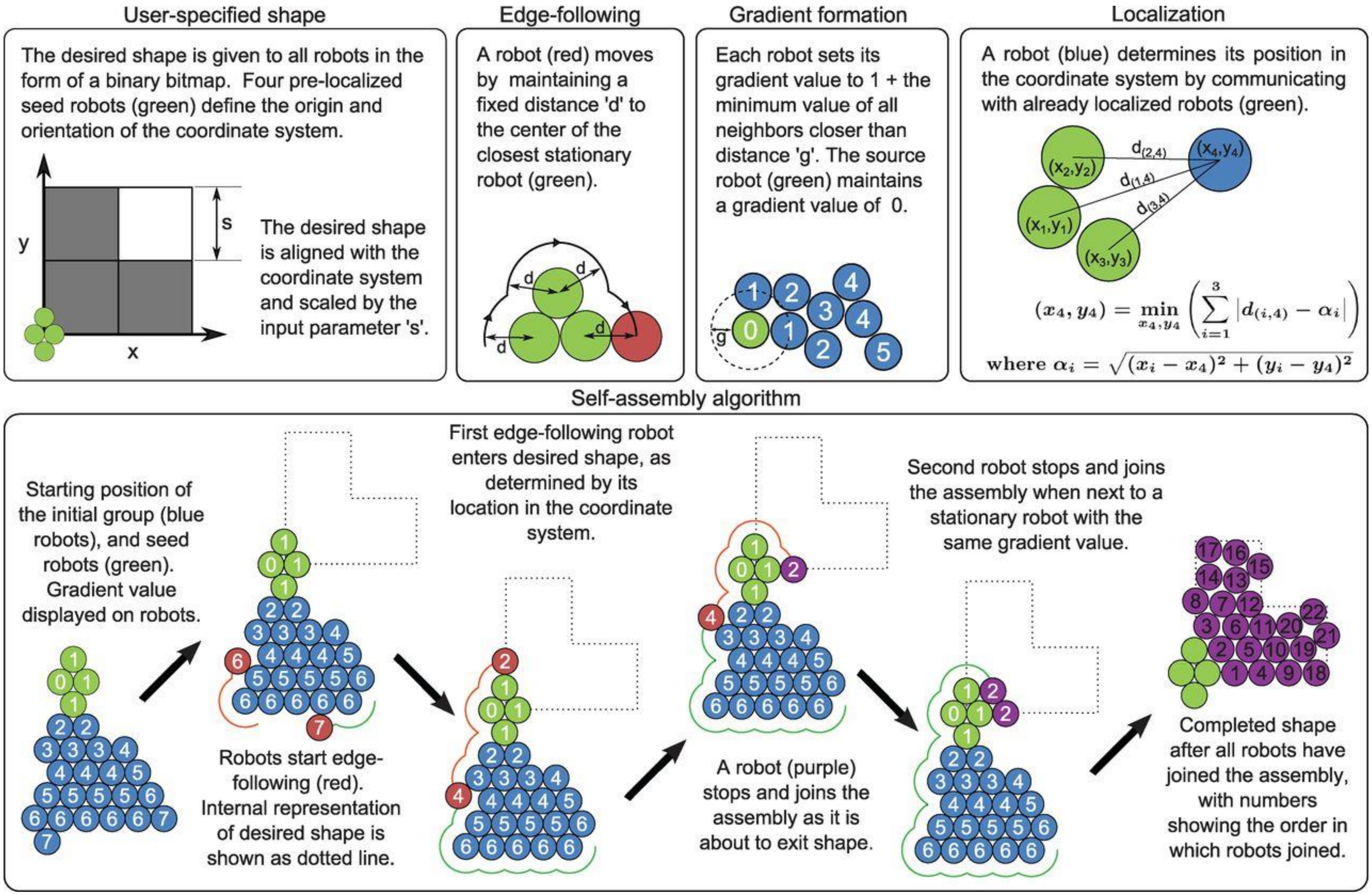
Penrose, L. S. & Penrose, R. *Nature* **179**, 1183 (1957).

Self-assembling Kilobots



Rubenstein et al. (2014) *Science*

Self-assembly Algorithm

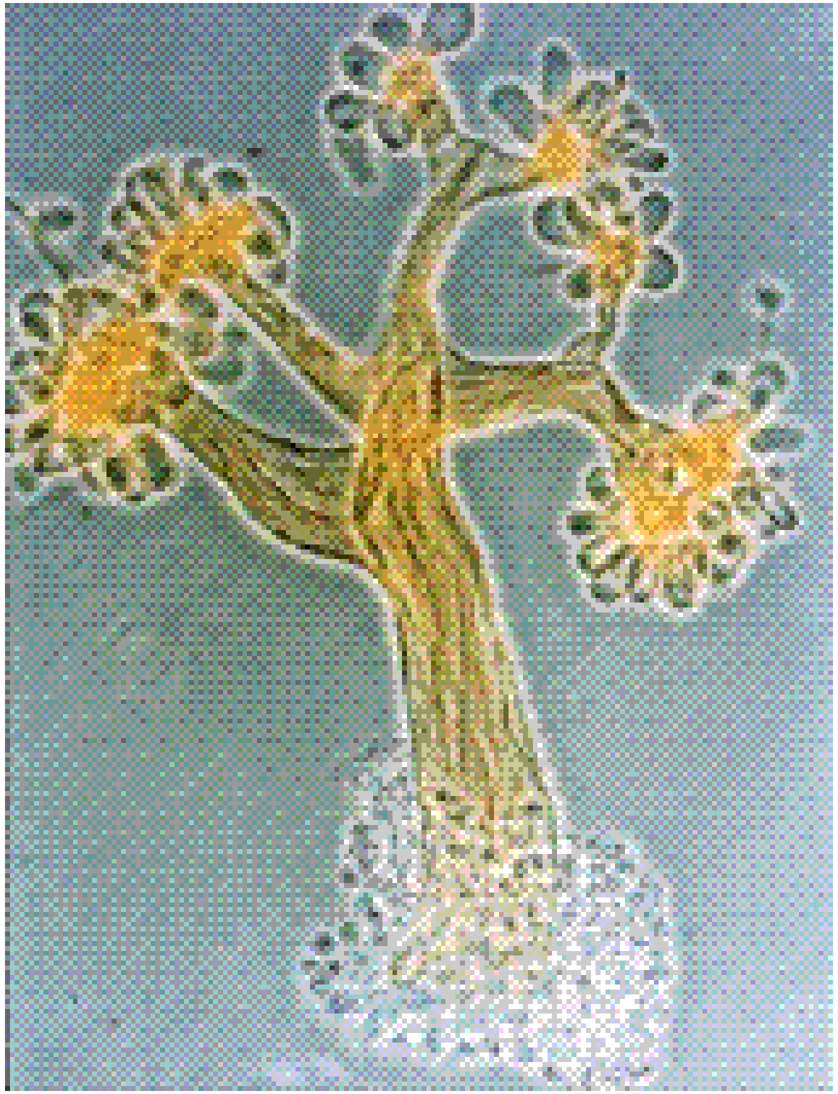


Self-Organizing Systems Research Group

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

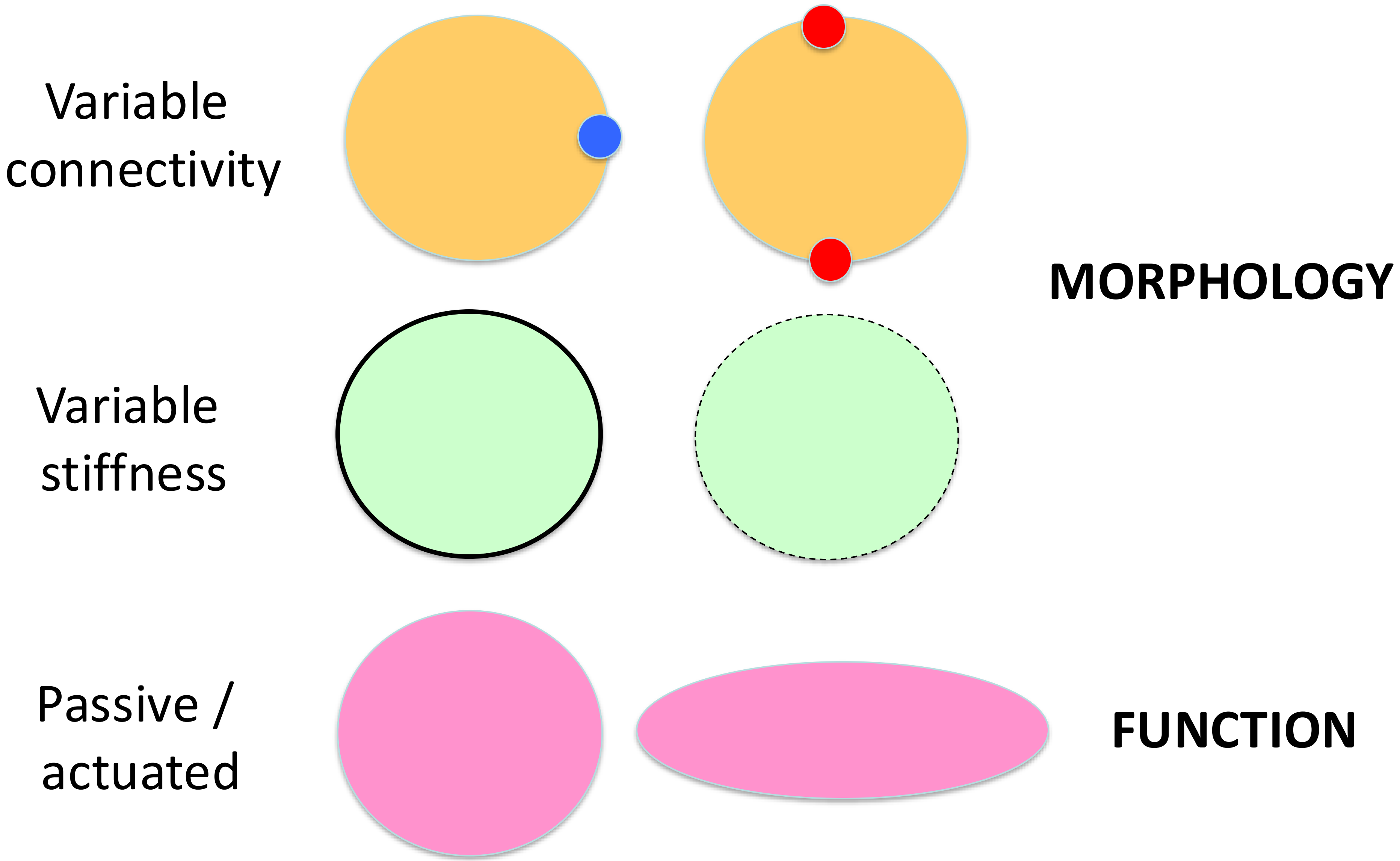
Cells in Multicellular Organisms
stiffness, specialization, connectivity

Cyanobacteria

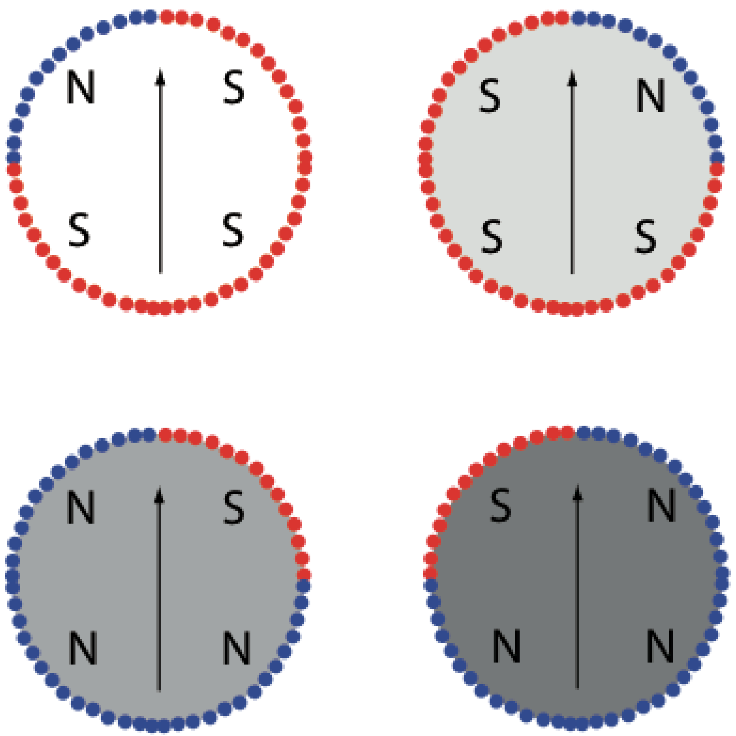


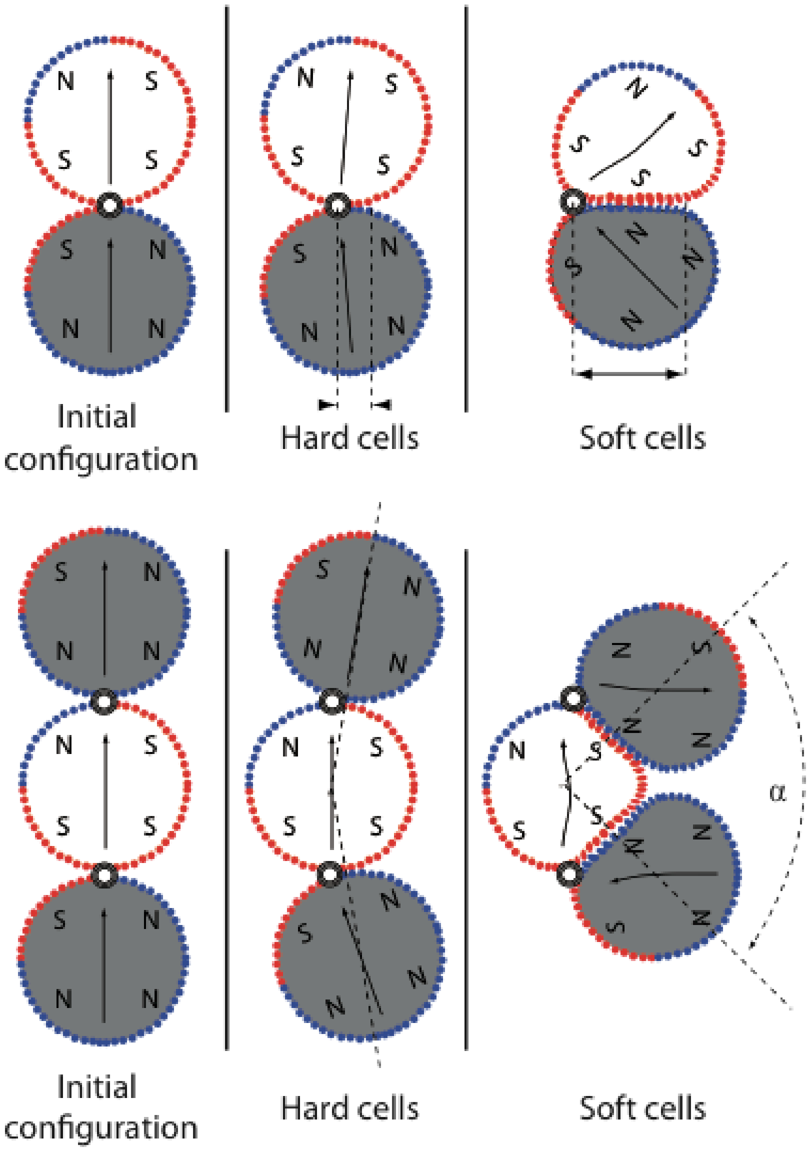
Myxobacteria

Cell diversity



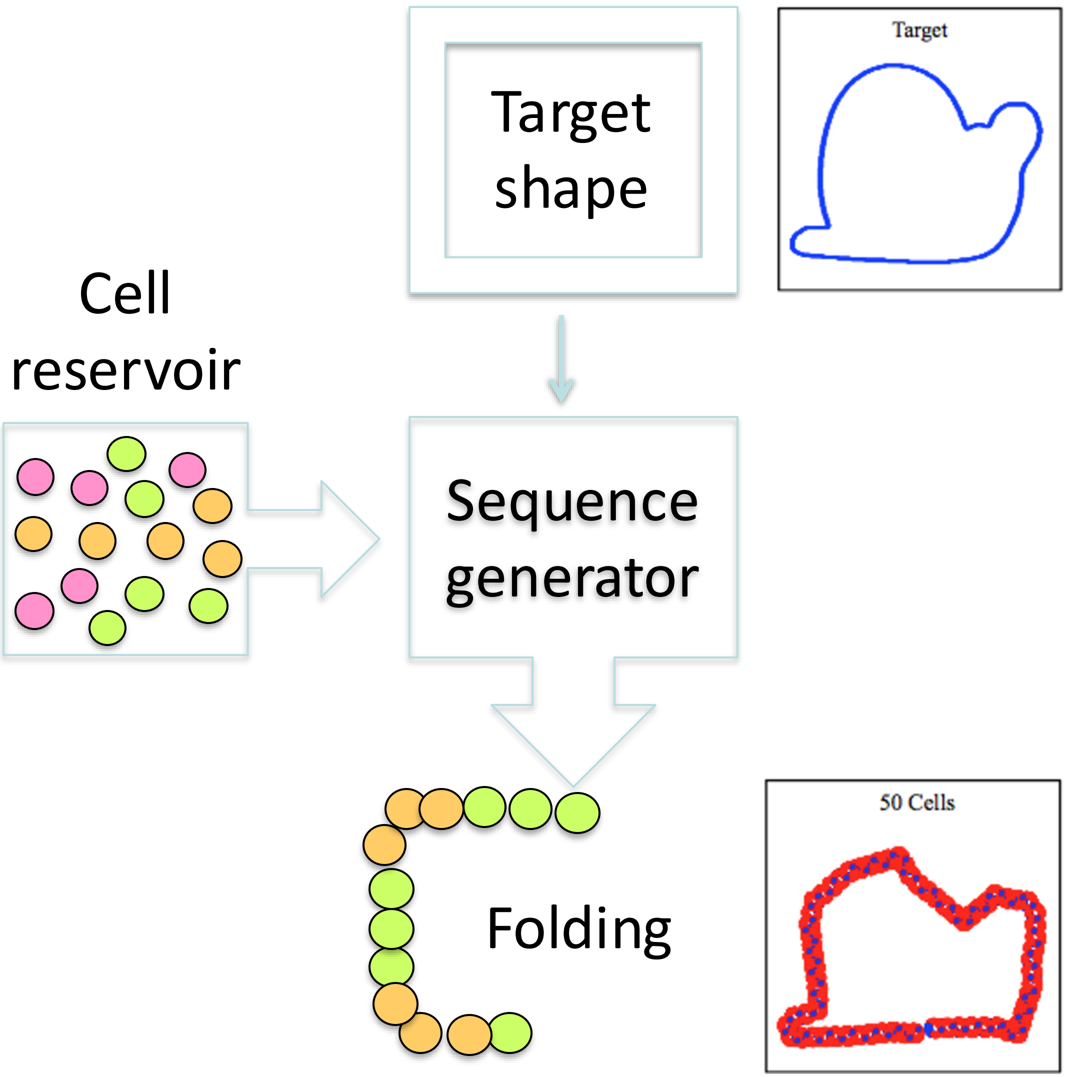
Softness affects folding angle





Germann et al (2014)
Soft Robotics

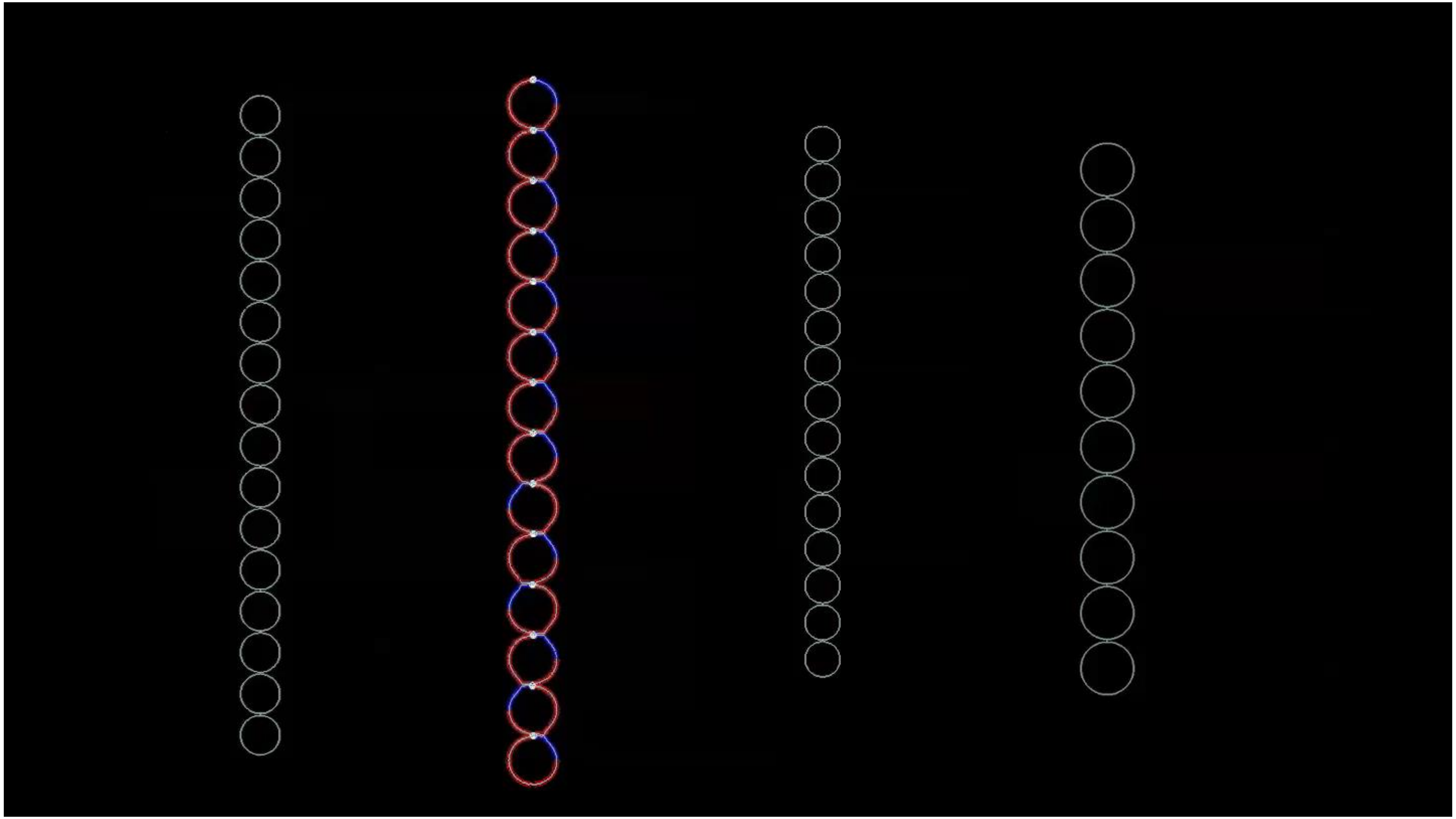
Programmable Self-Assembly



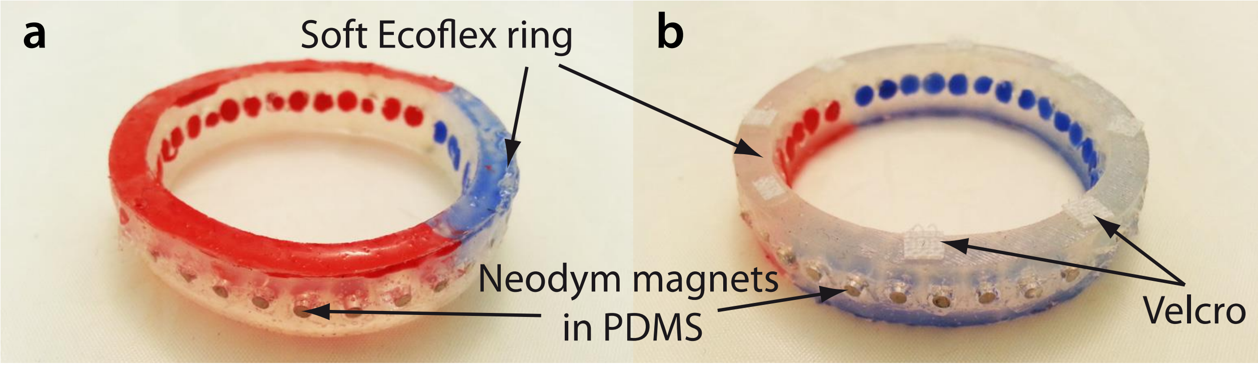
S. Griffith (2004), Growing Machines, MIT PhD thesis

Programmable self-assembly in silico

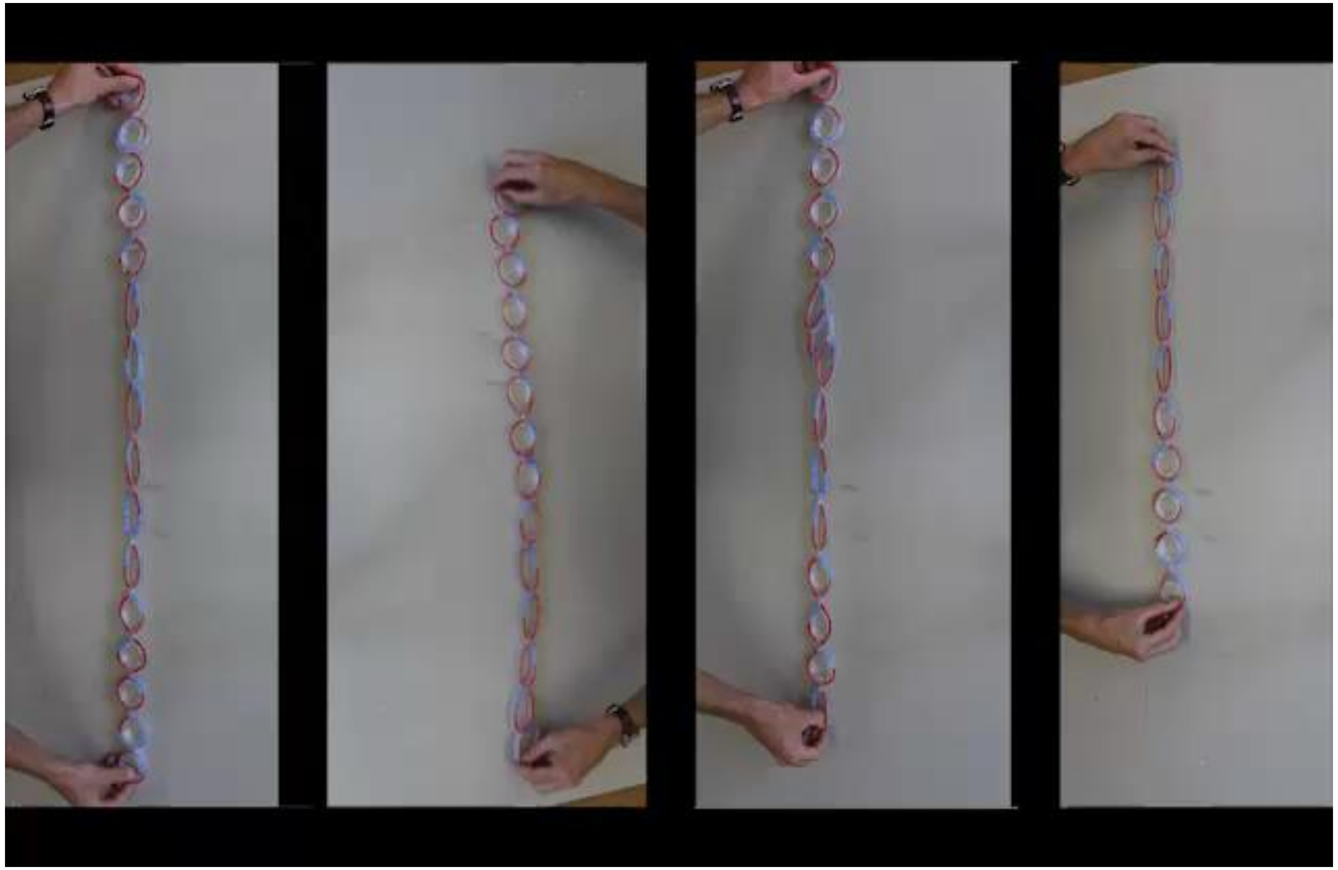
Germann et al (2014) *Soft Robotics*



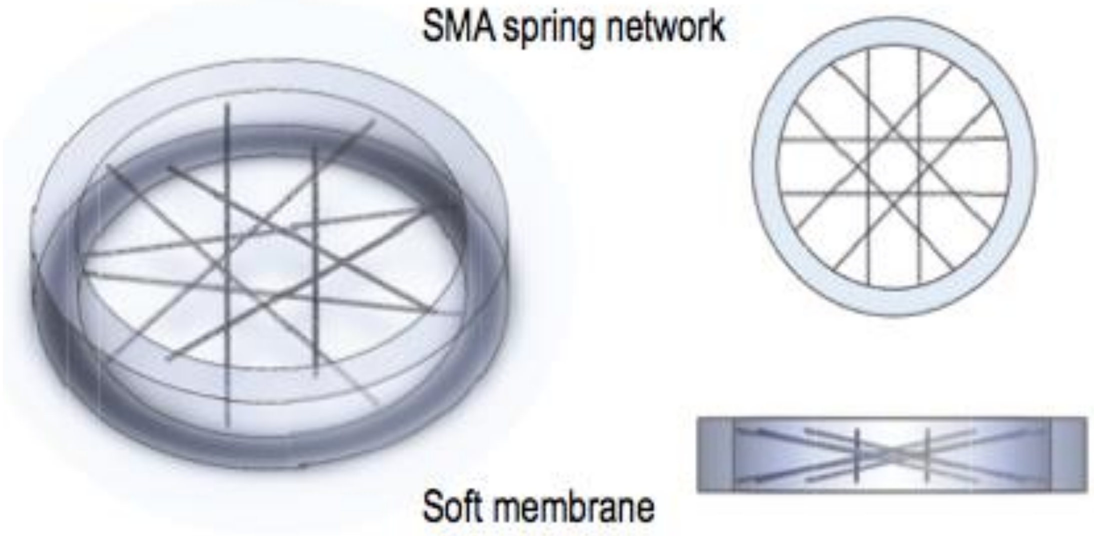
Programmable self-assembly in hardware

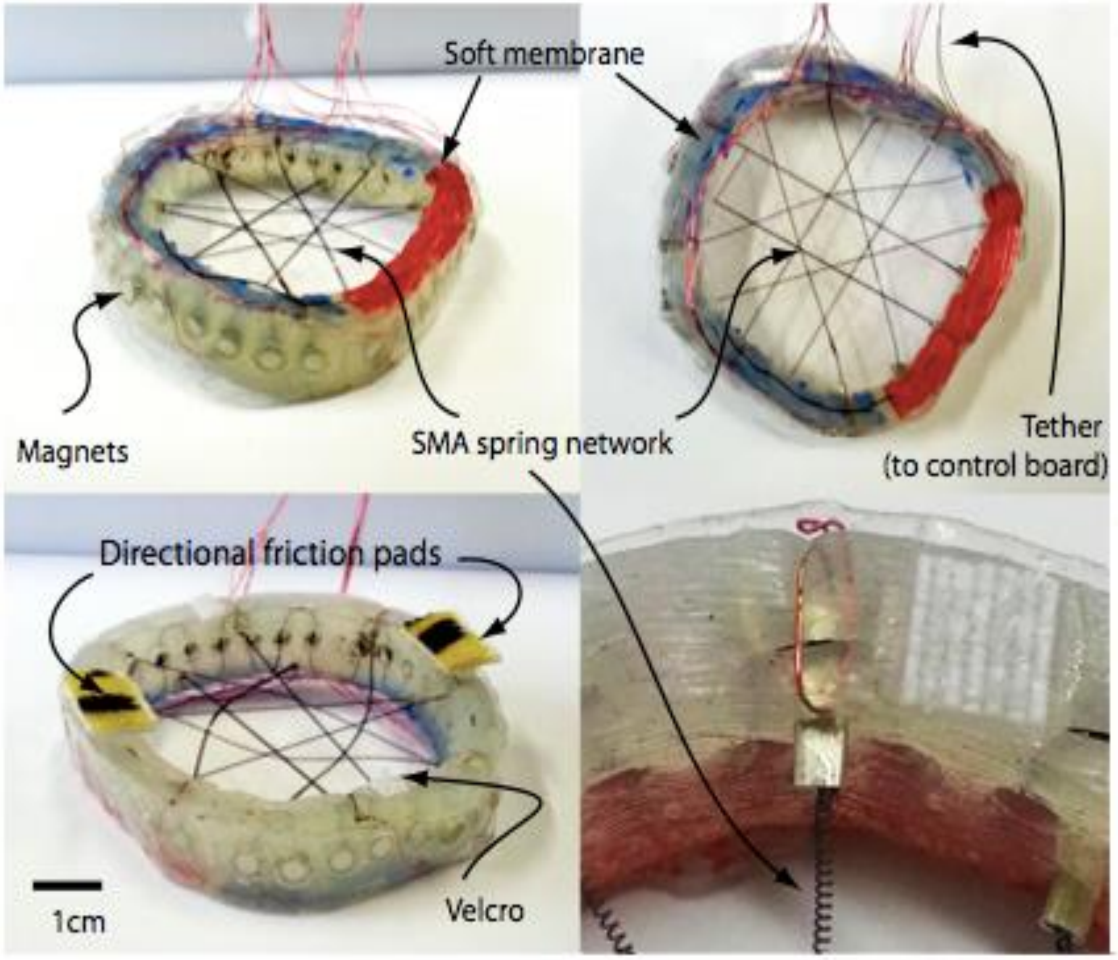


Germann et al (2014) *Soft Robotics*



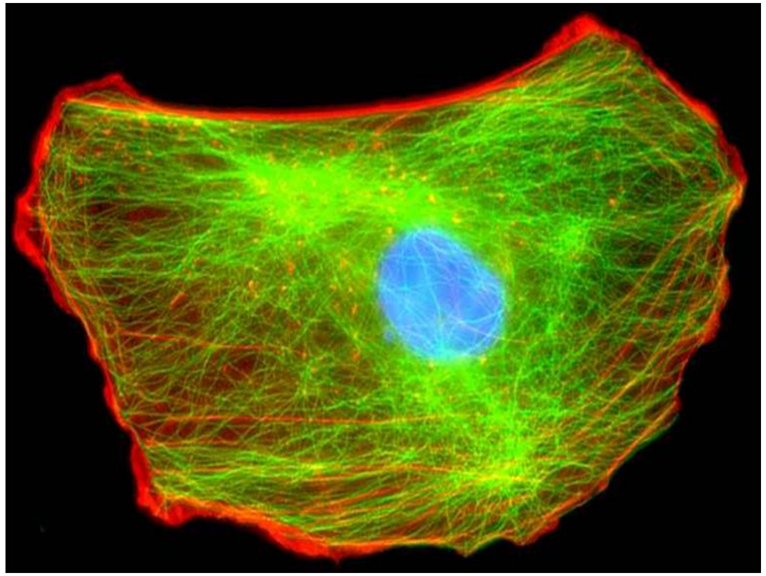
Adding muscle cells

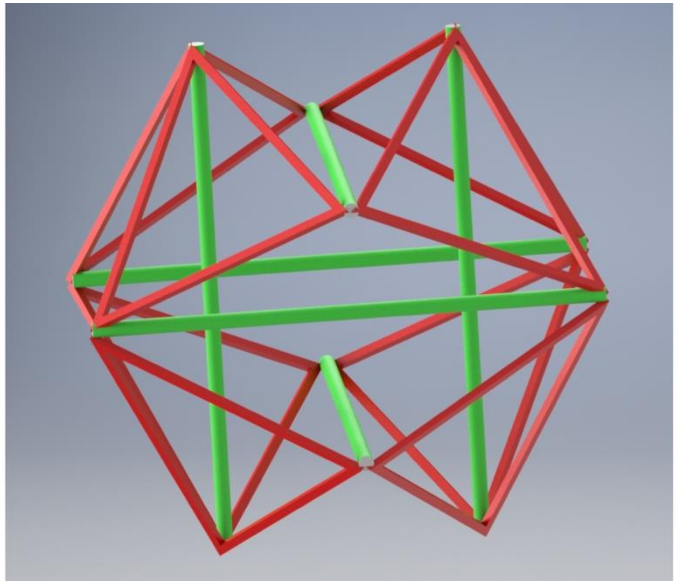


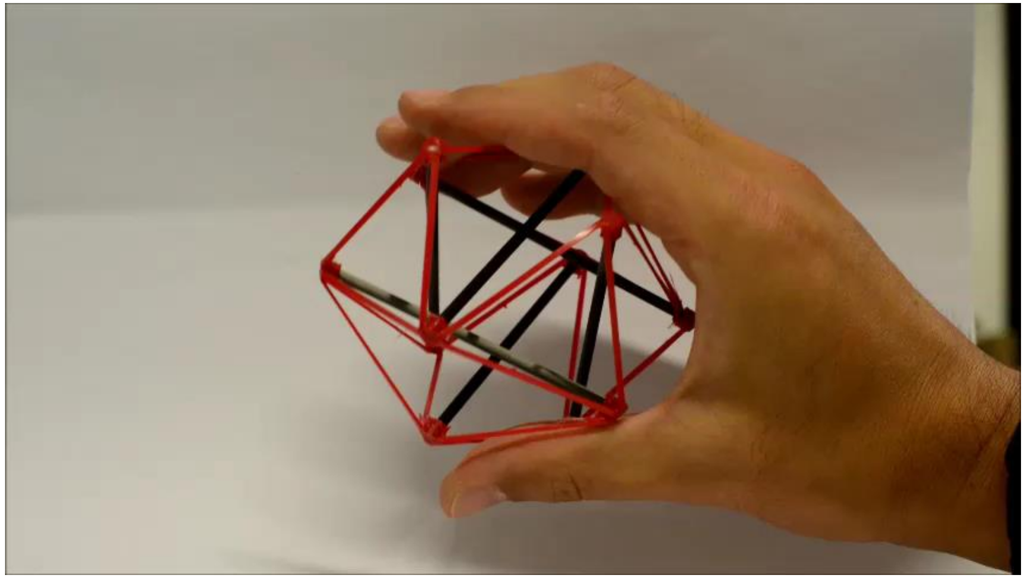


Soft Modular Worm

From 2D to 3D: Tensegrity robotic cells



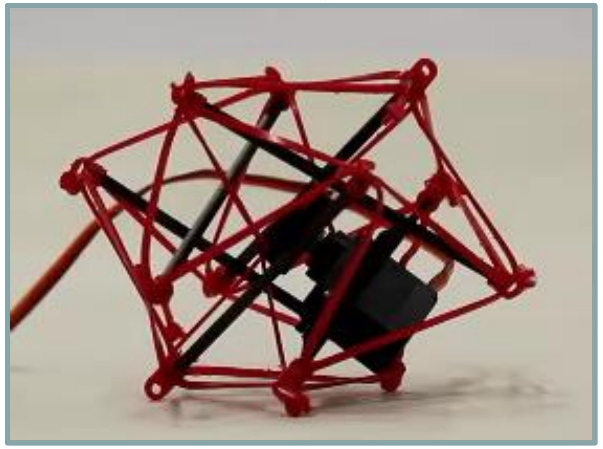




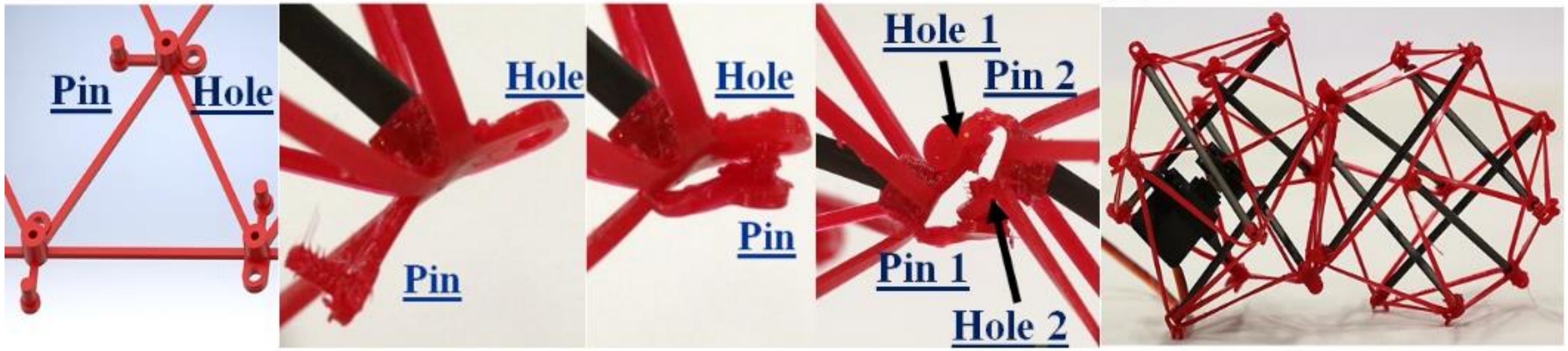
Actin filaments		Pre-stretched cables
Microtubules		Struts

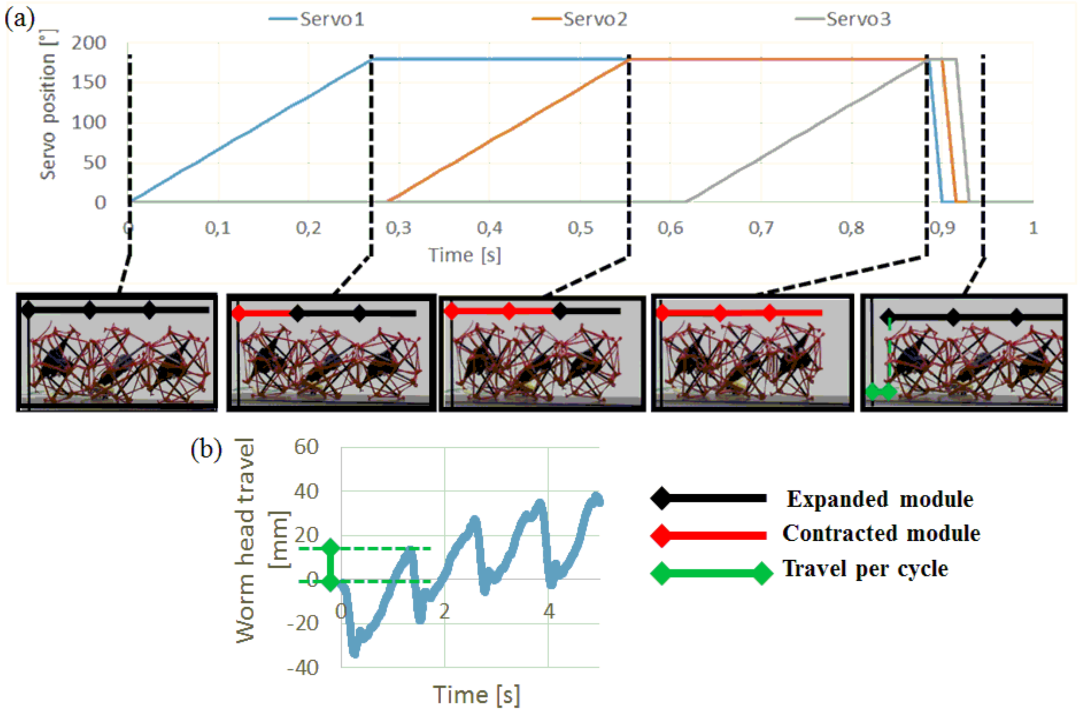
3D multicellular worm

A contracting module



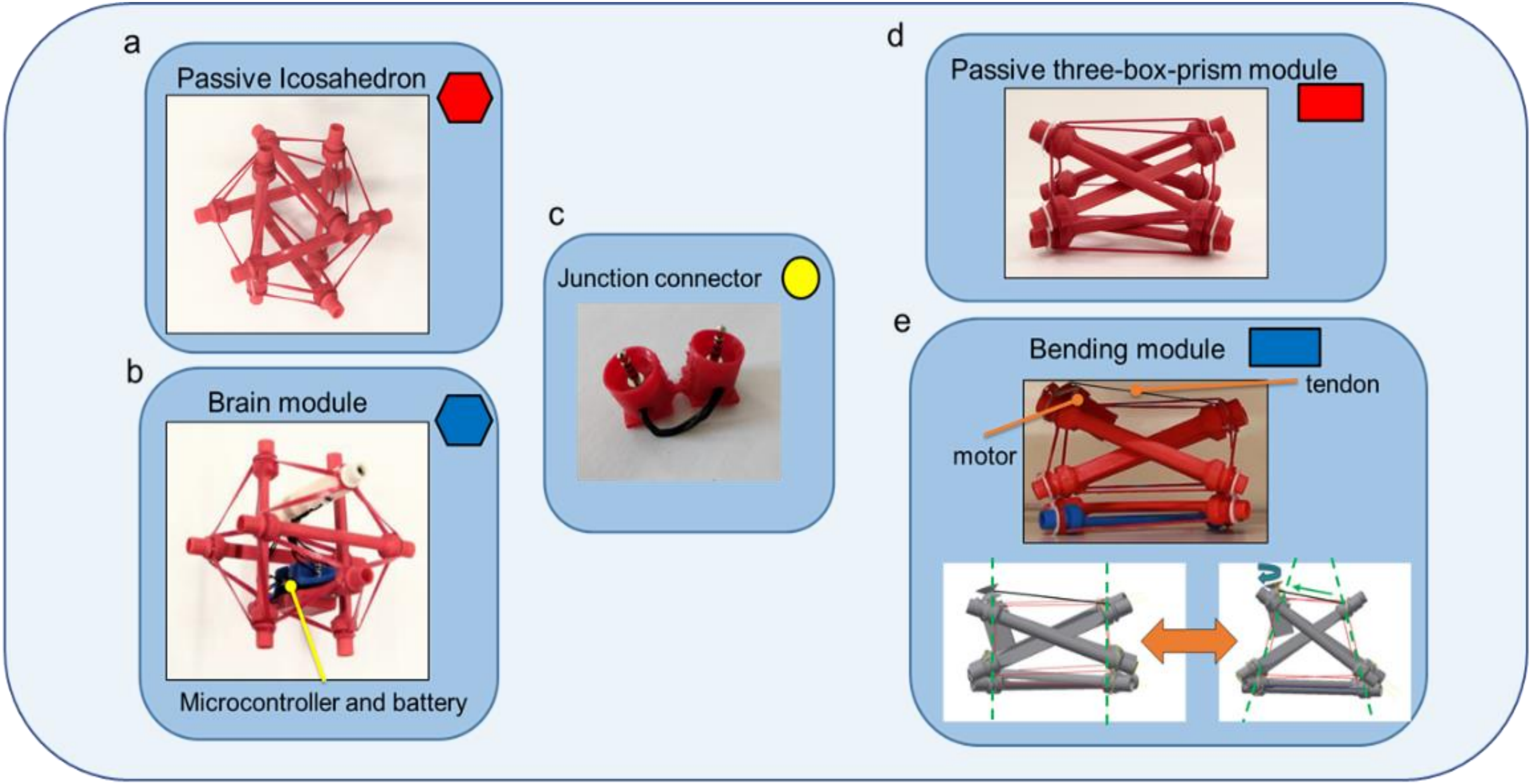
3D printed hole-pin latching



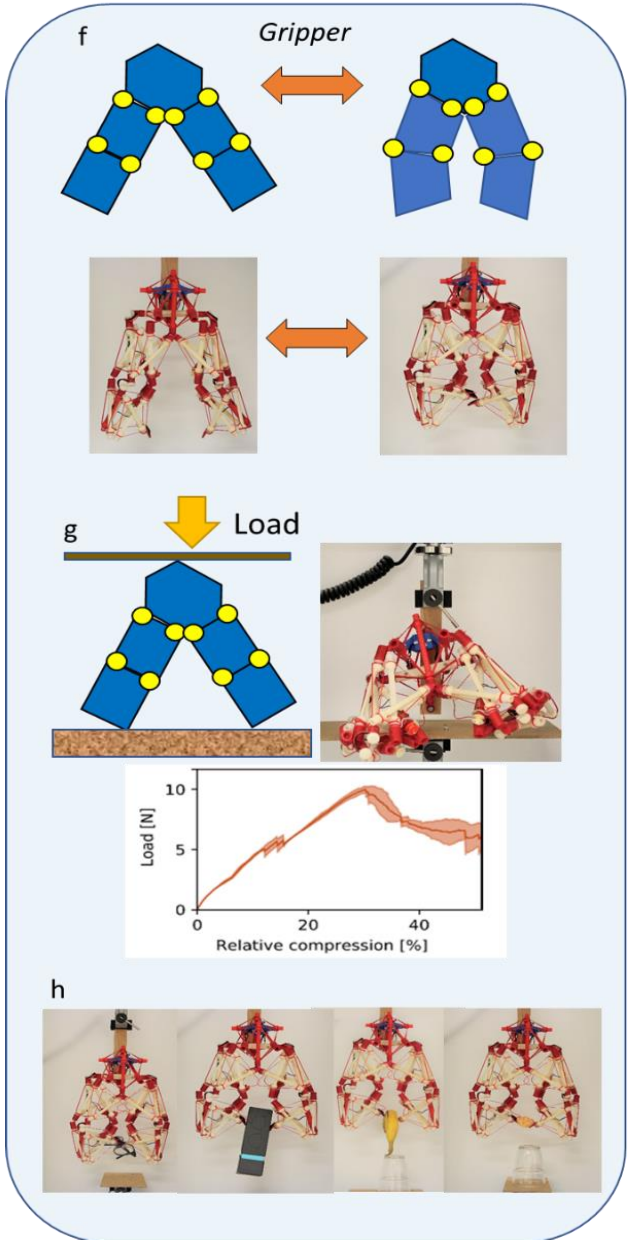


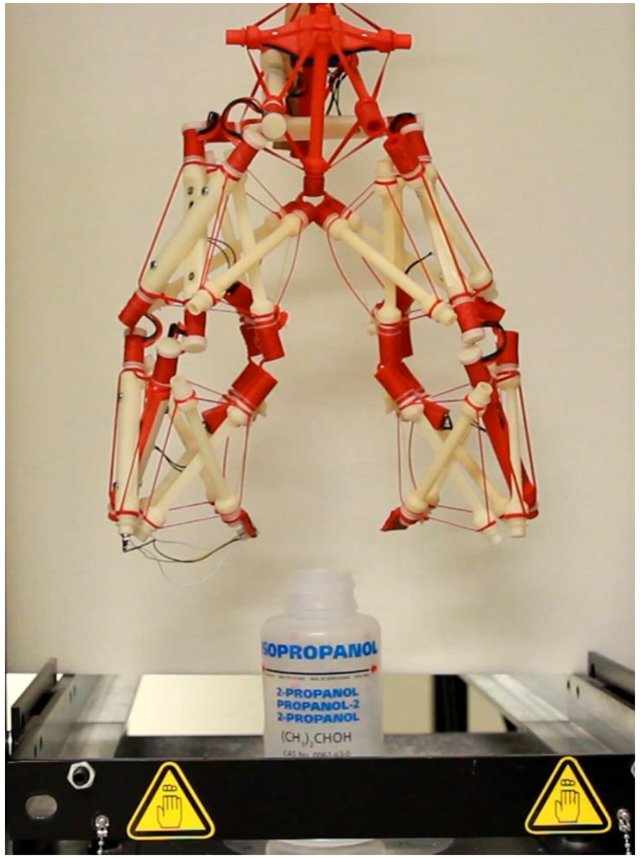
D. Zappetti, S. Mintchev, J. Shintake, e D. Floreano (2017) «Bio-inspired Tensegrity Soft Modular Robots», in *Biomimetic and Biohybrid Systems*, 497–508

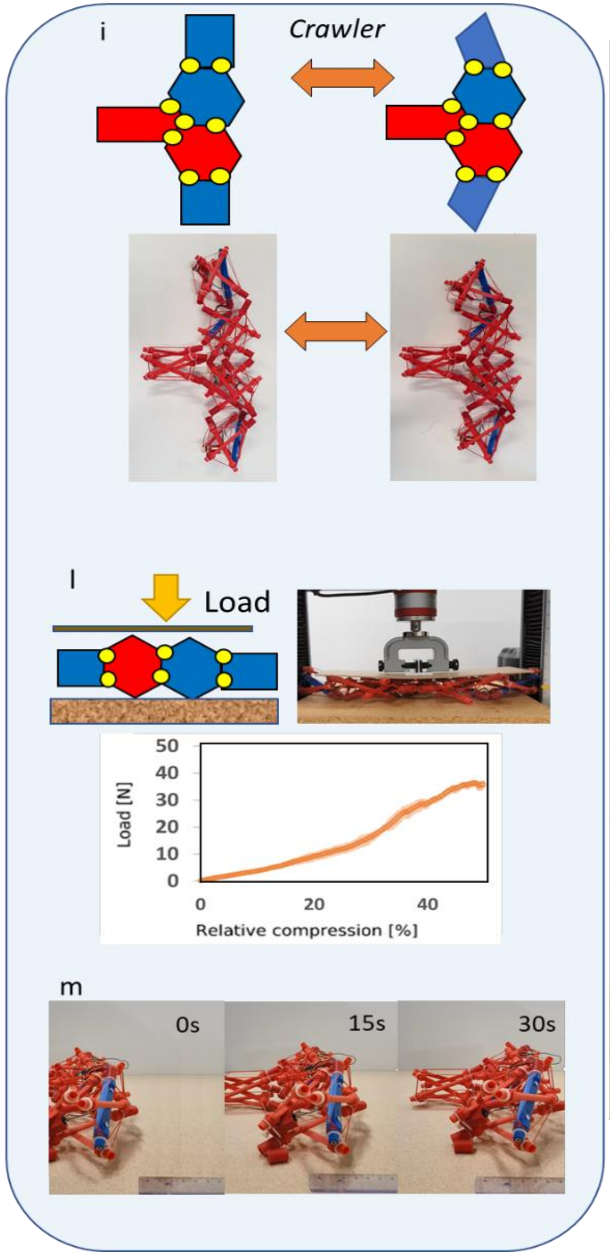
Different types of tensegrity cells

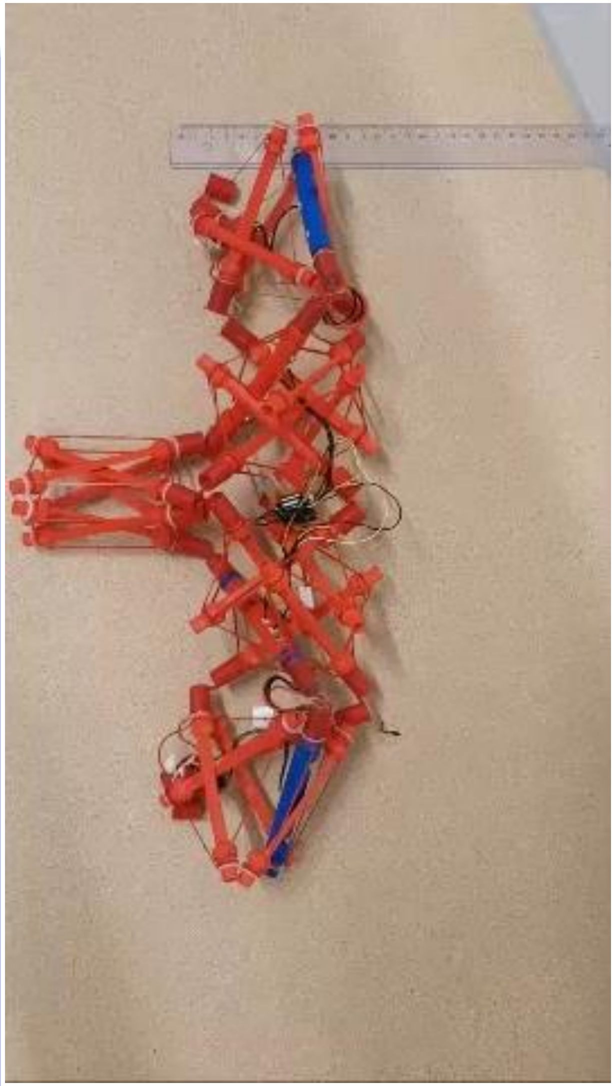


Multicellular tensegrity robots



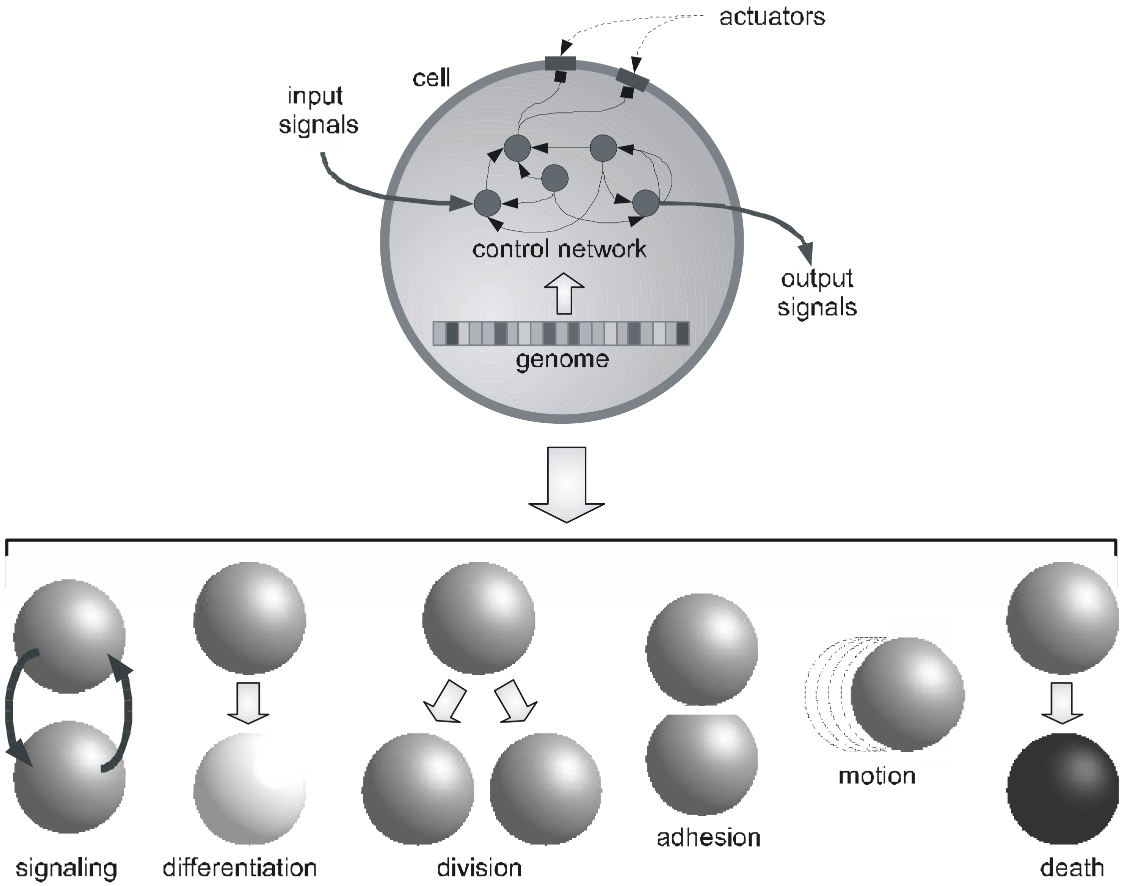


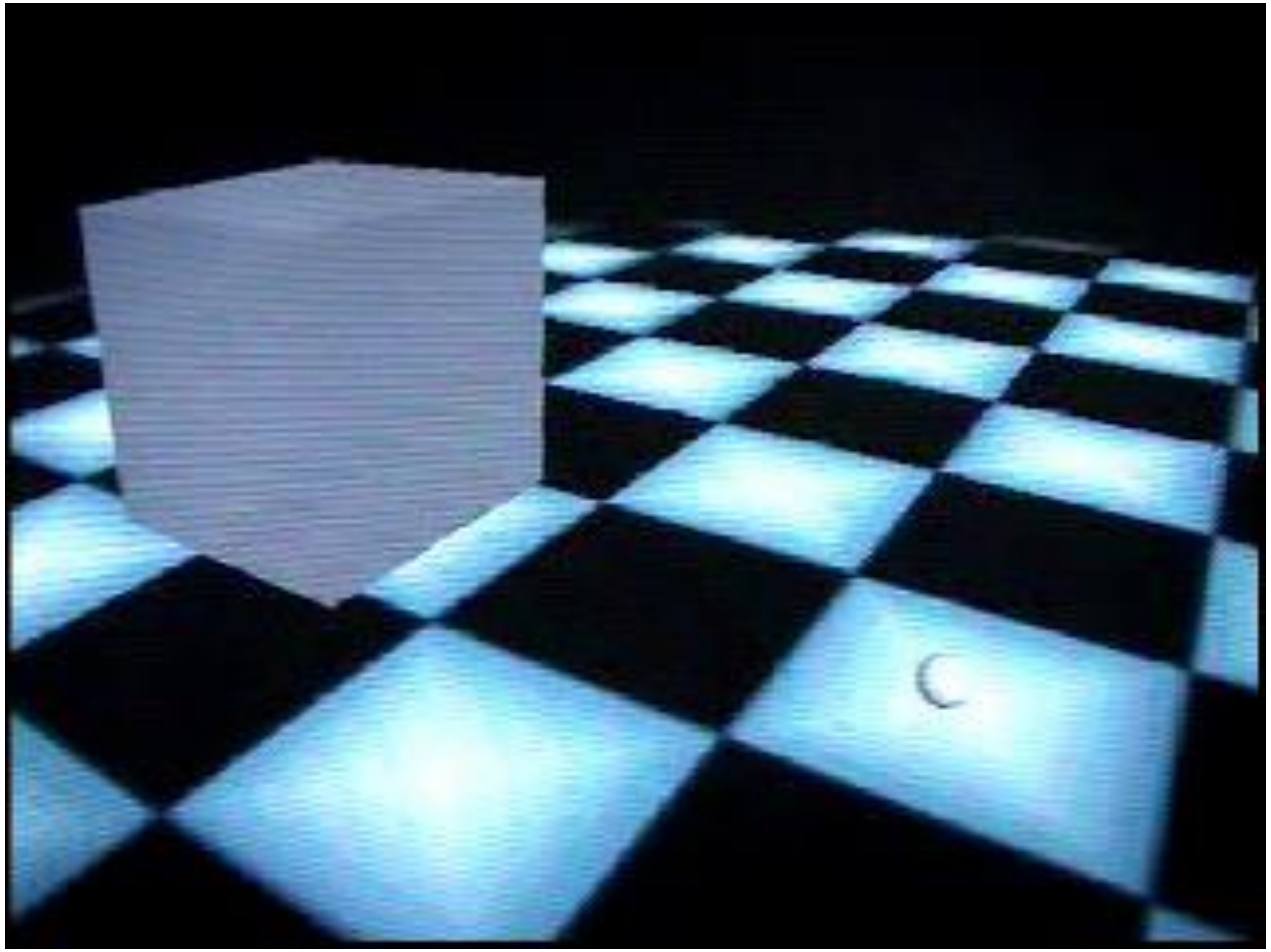




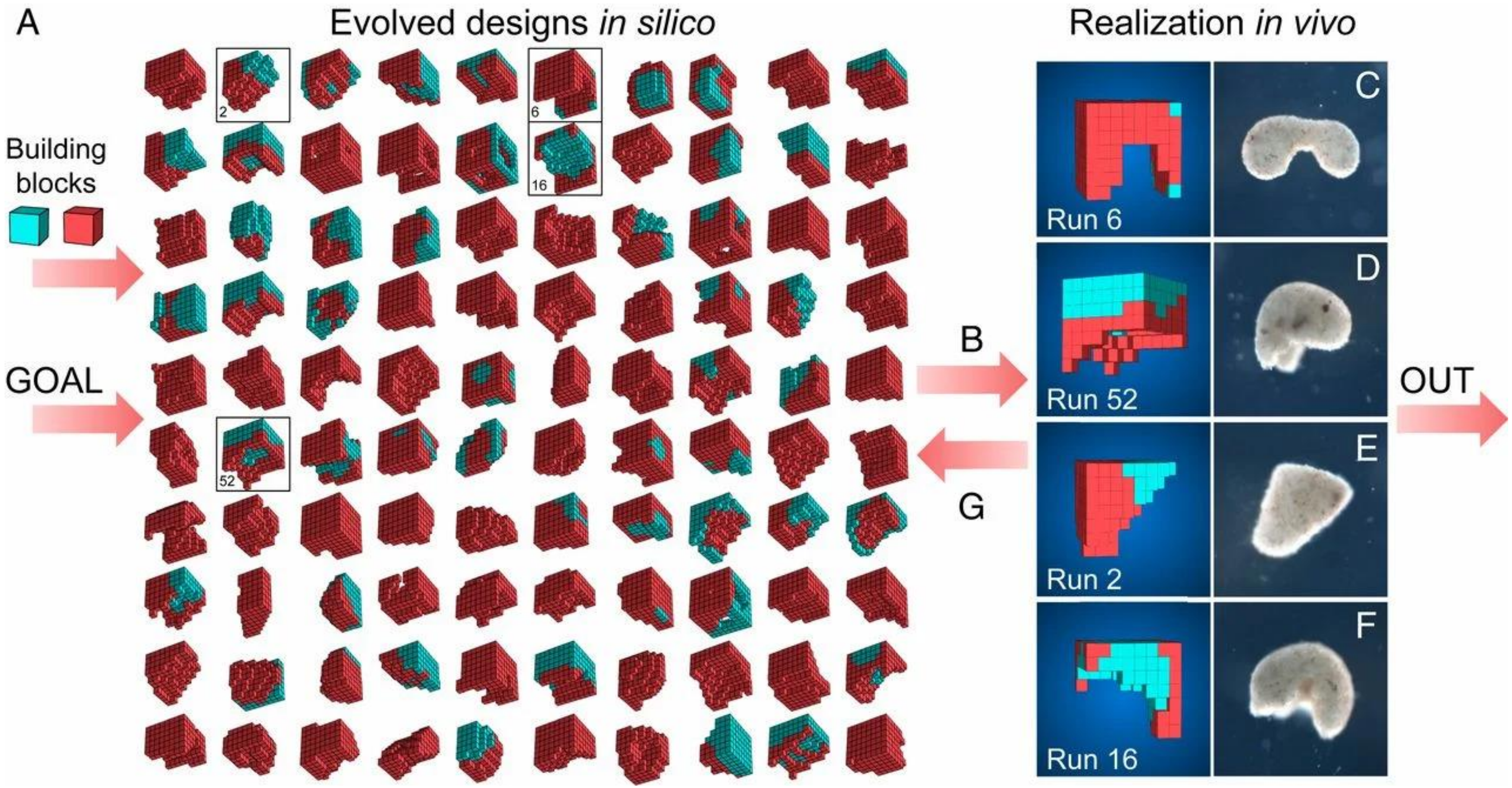
Artificial Ontogeny (Bongard and Pfeifer, 2001)

E*volutionary developmental process* to synthesize artificial multicellular "creatures"





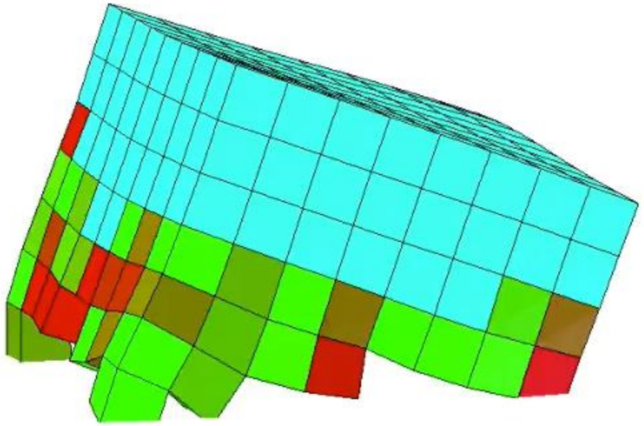
Xenobots: Evolved *in silico*, self-assembled *in vivo*



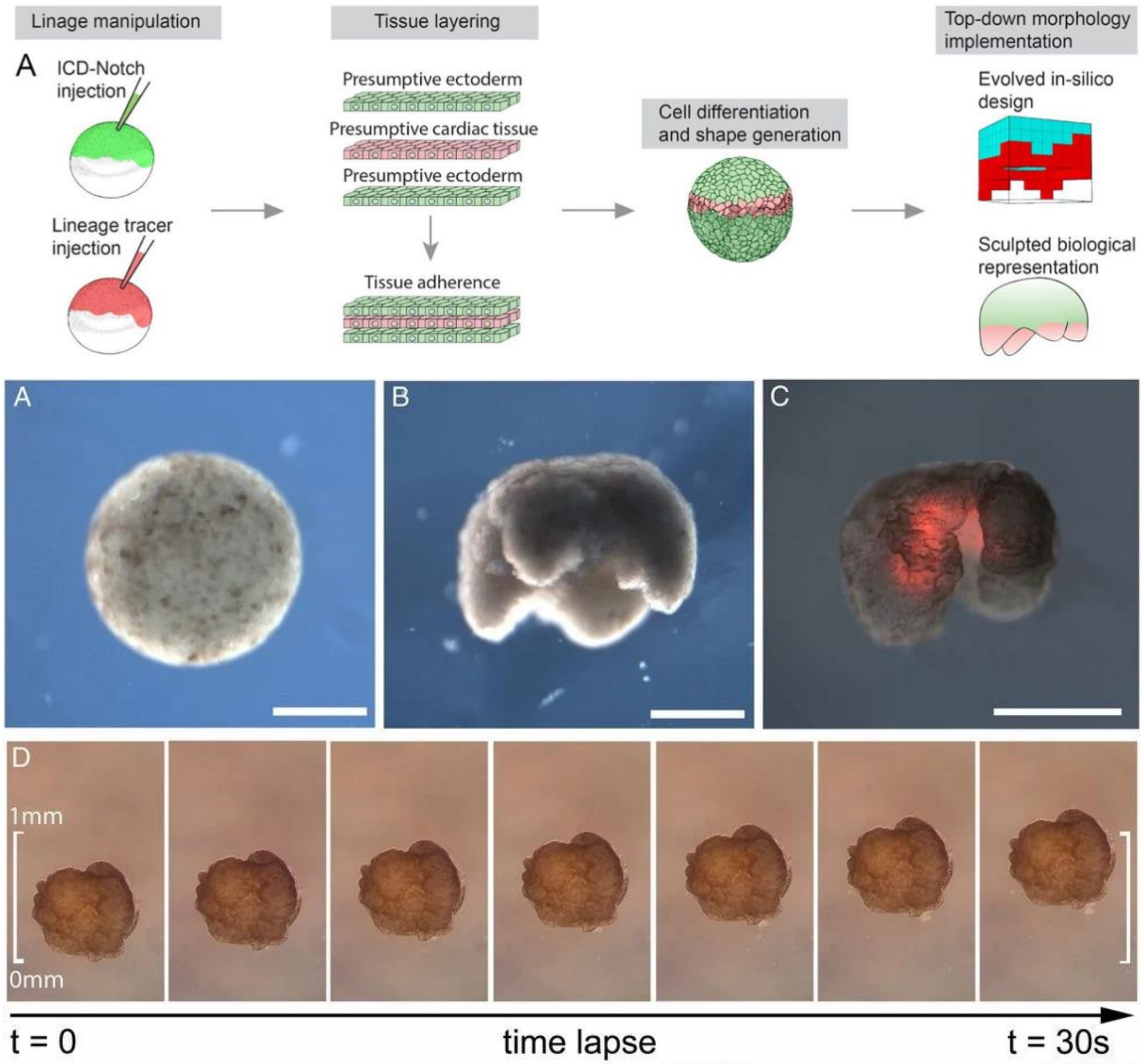
Kriegman, Sam, Douglas Blackiston, Michael Levin, and Josh Bongard (2020) A Scalable Pipeline for Designing Reconfigurable Organisms.” *Proceedings of the National Academy of Sciences* 117(4) : 1853–59. https://doi.org/10.1073/pnas.1910837117.

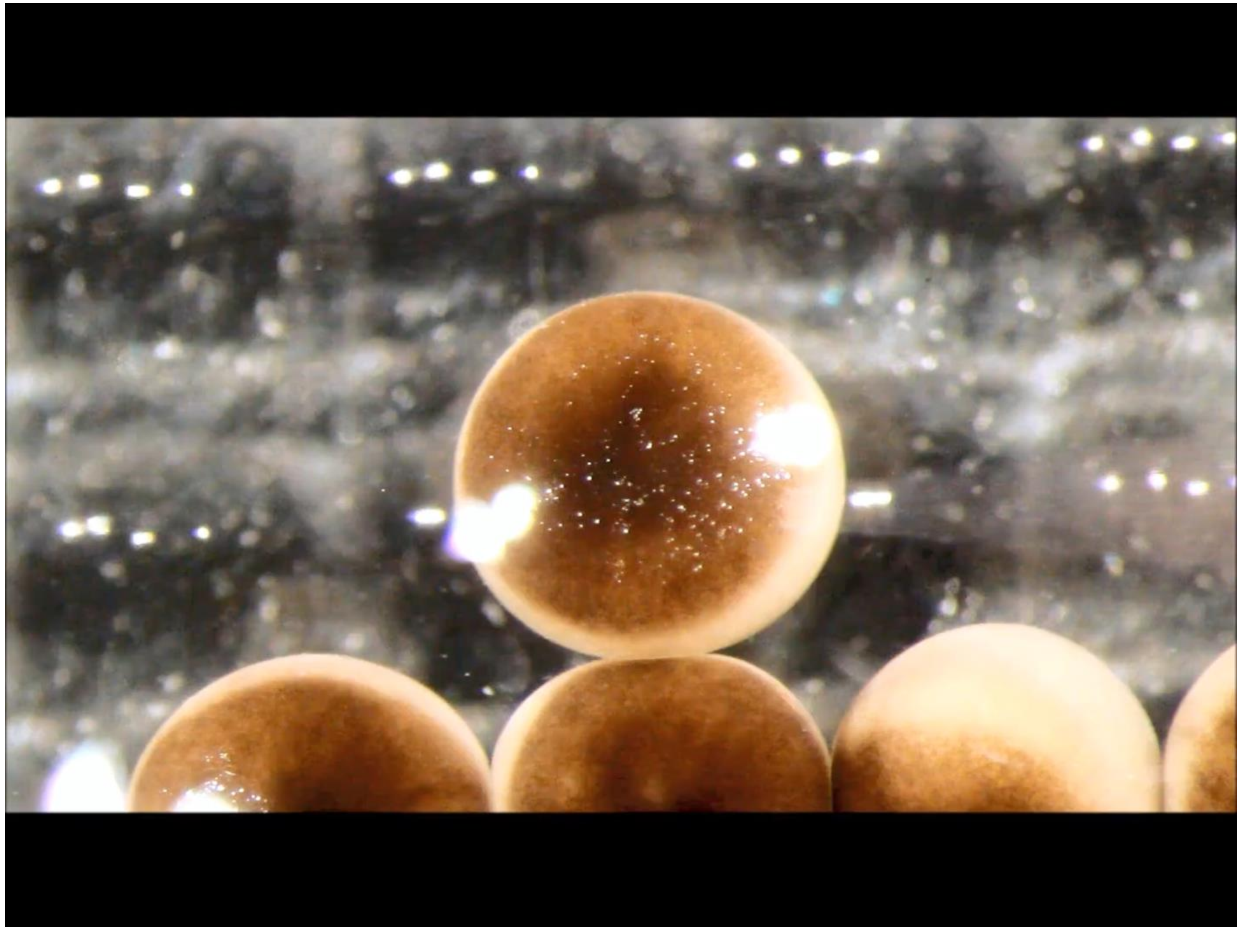
A scalable pipeline for designing reconfigurable organisms.

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



Manufacturing of self-assembling organism

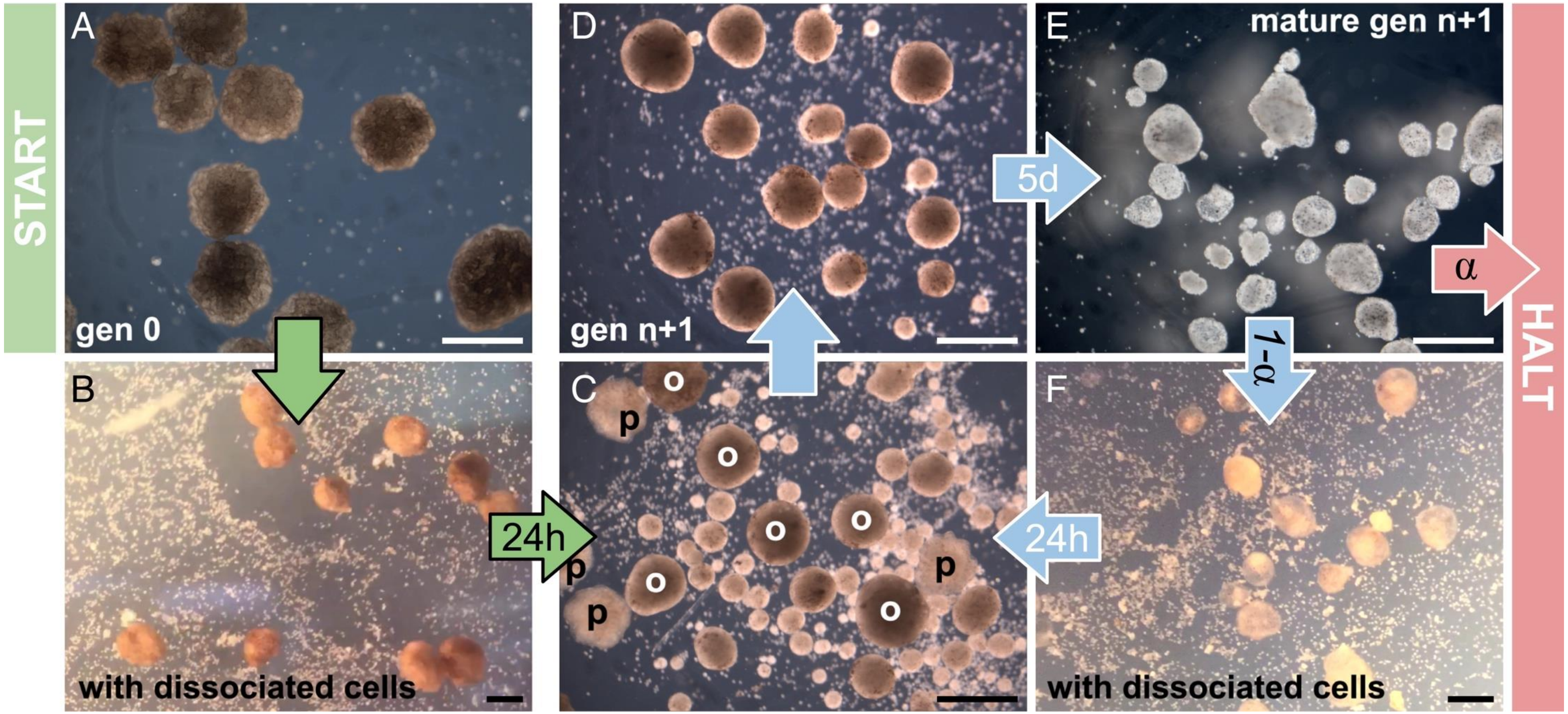




Caution: insertion of cardiac cells within Xenobot is not shown in the video

Assembly of Xenobots by frog cells

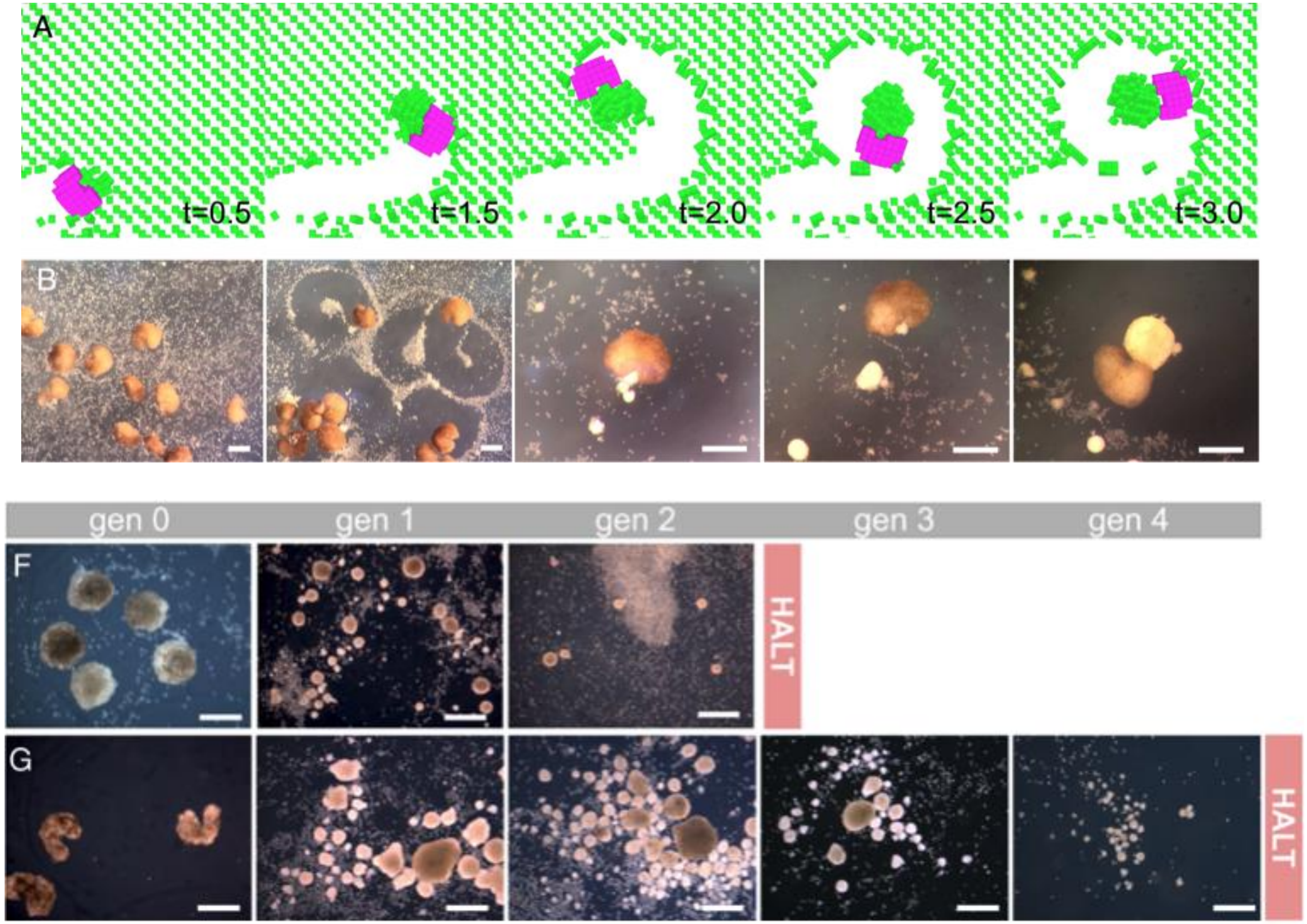
Spontaneous motion of frog cells assemble clusters of ectodermal stem cells that become Xenobots



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

Kinematic self-replication of Xenobots

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



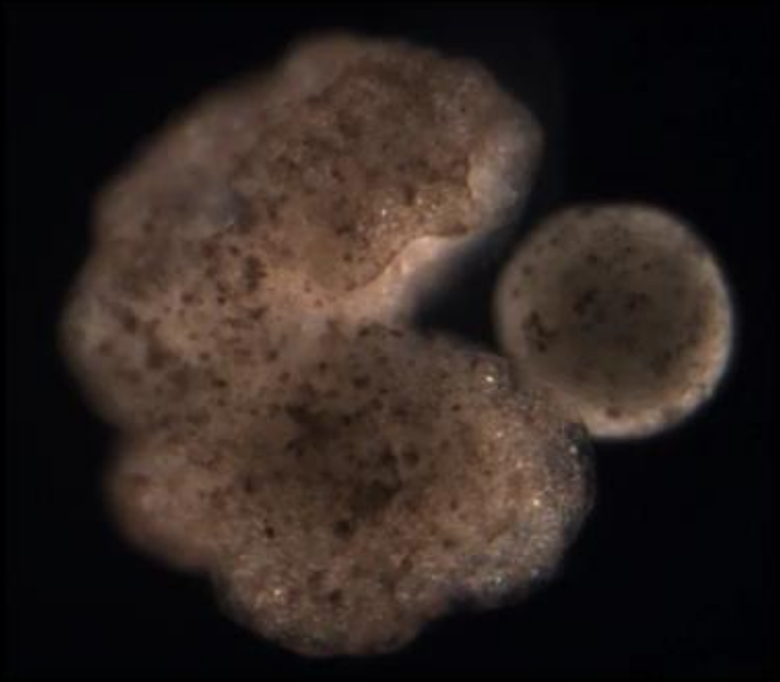
Spheroid Xenobots

Evolved 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[1,2] Douglas Blackiston[1,2] Michael Levin[1,2] & Josh Bongard[3,*]



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