

The Embodied Mind of a New Robot Scientist:

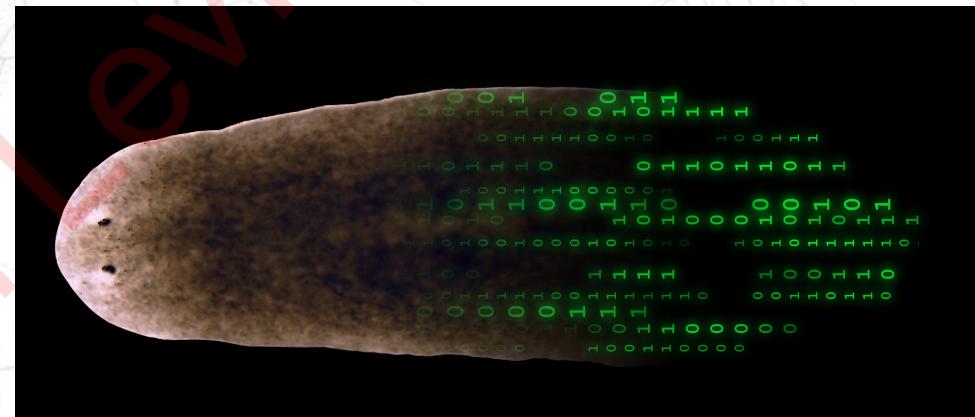
Symmetries Between AI and Bioengineering the Agential Material of Life
and their impact on technology and on our future

Michael Levin

Allen Discovery Center at Tufts

<http://www.drmichaellevin.org/>

<http://thoughtforms.life/>

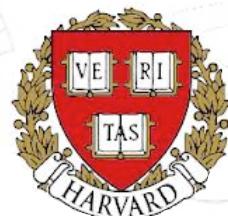


ALLEN
DISCOVERY CENTER
at Tufts University

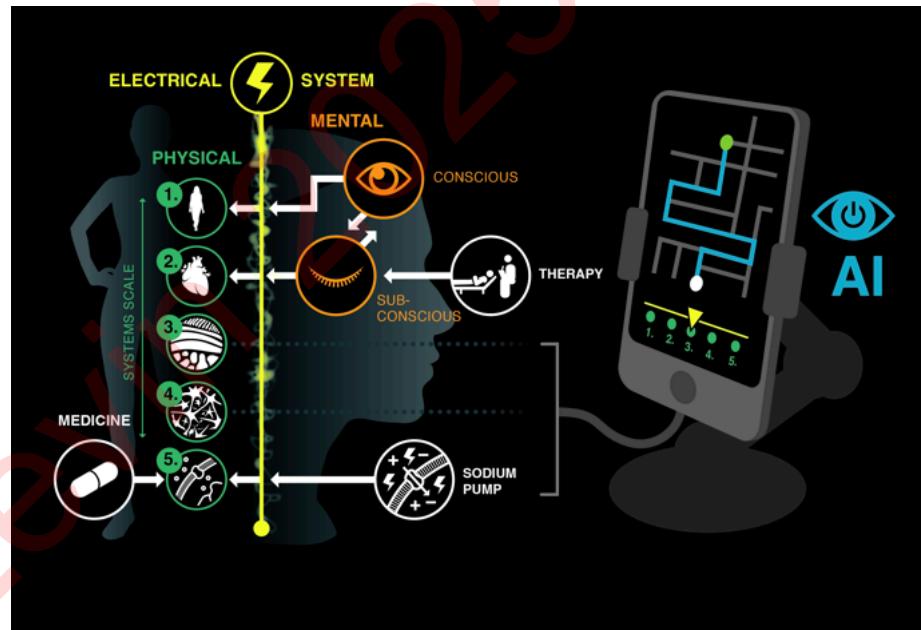
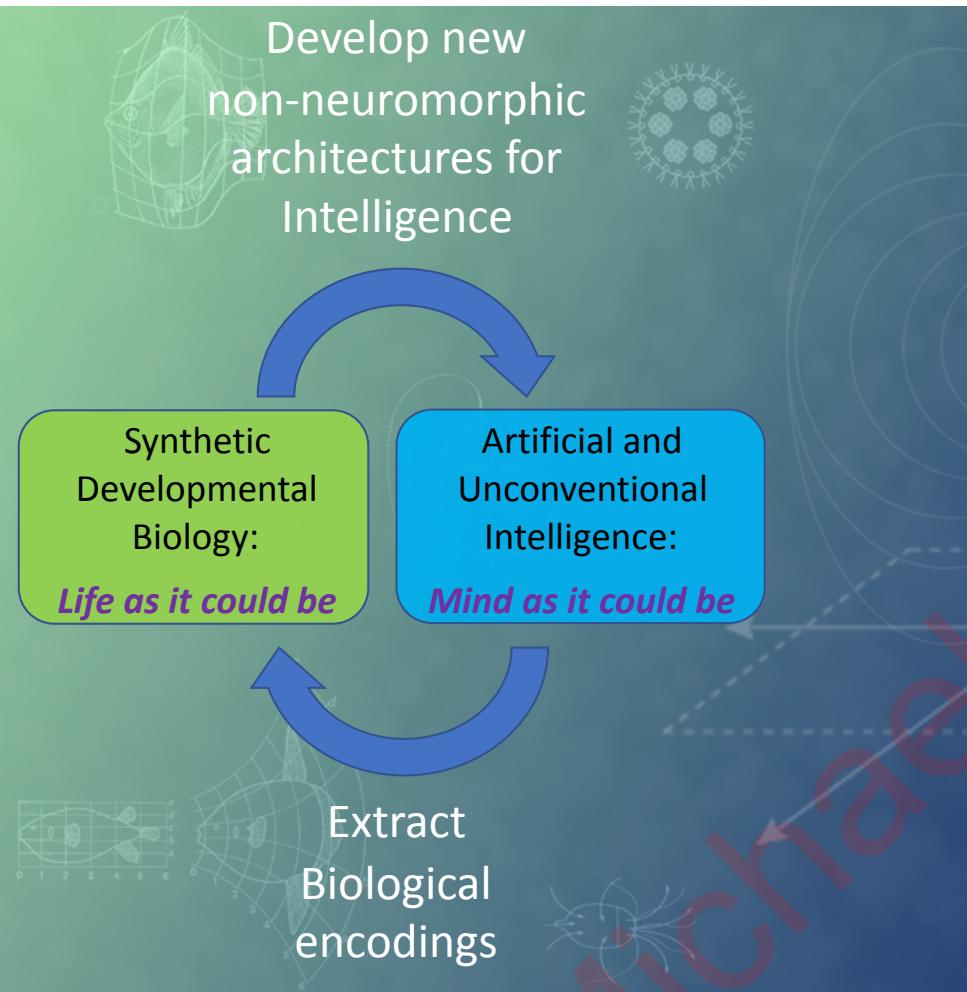
The Institute for
Computationally
Designed Organisms

Tufts University | University of Vermont

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Embodied Minds: engineering diverse intelligence

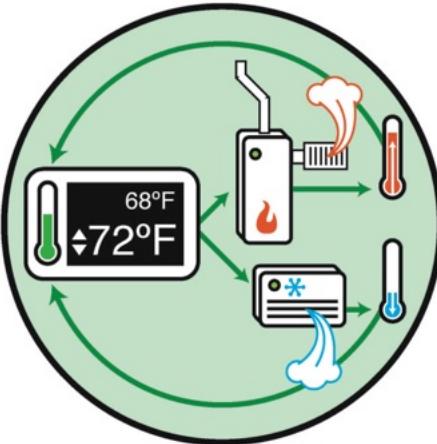


- goal: build tools to enable detection, communication, and ethical interaction with diverse intelligences
- model system: cell collectives navigating morphospace
- applications: regenerative medicine, synmorpho, AI/ALIFE

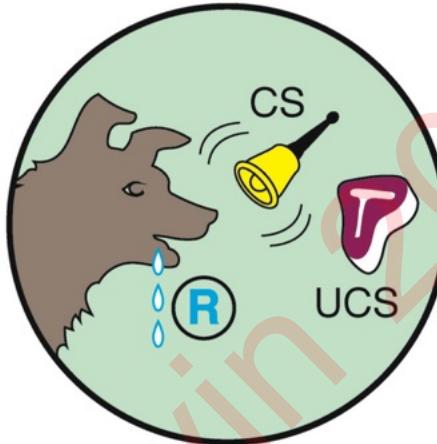
Impedance Match Between Tools and What You Can See



Hardware modification only



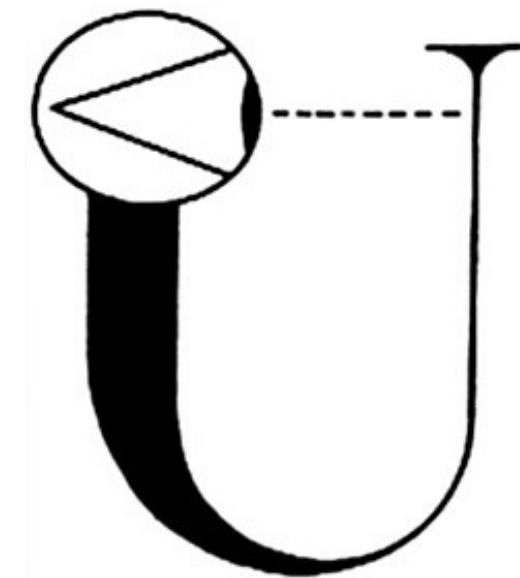
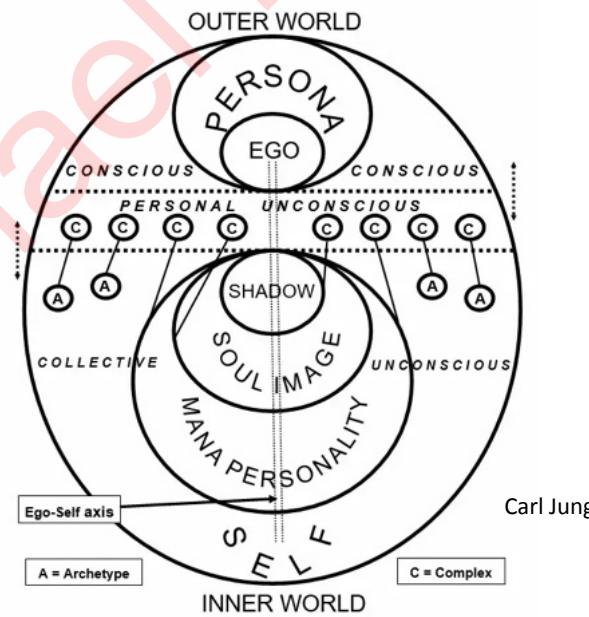
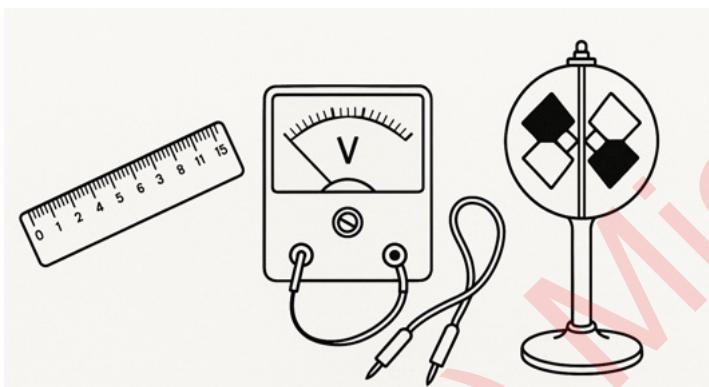
Modify the data encoding setpoint of goal-driven process



Training by rewards/ punishments



Communicate cogent reasons



wheeler 1979

If you want to study minds, use high-agency tools

Symmetry Between Scientist and World

Parr, Friston, and Zeidman

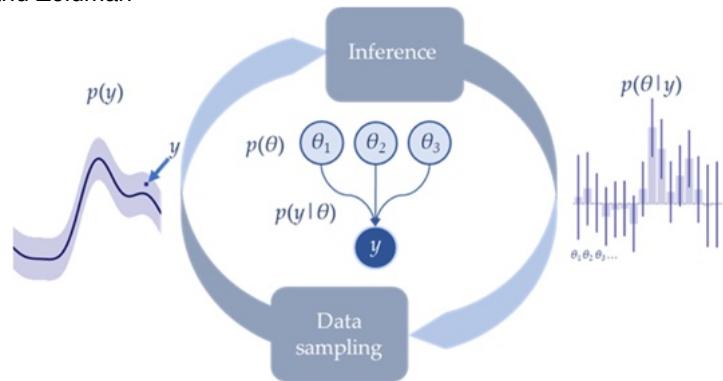
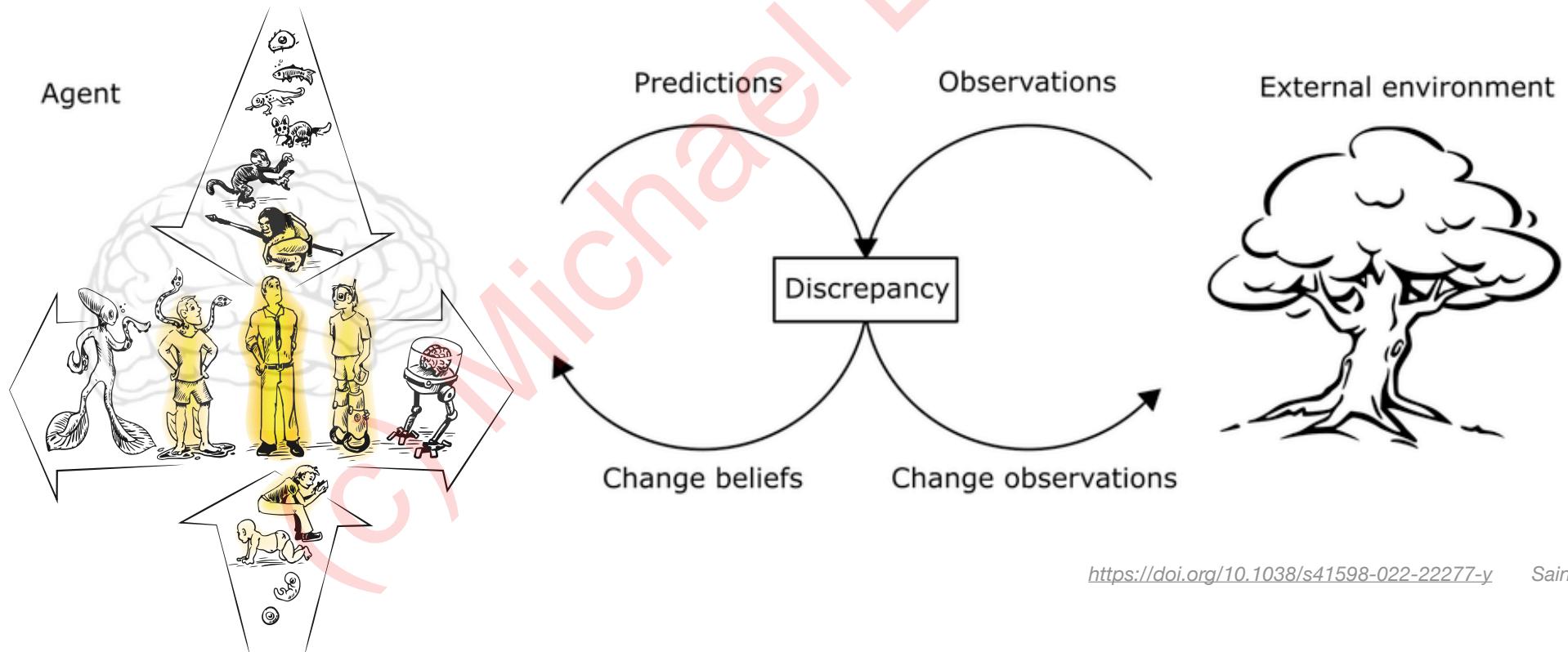
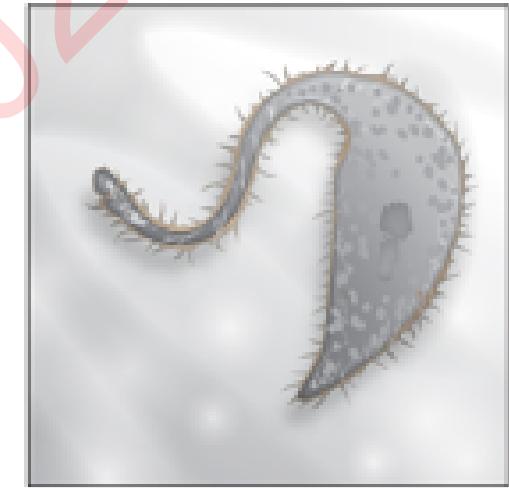
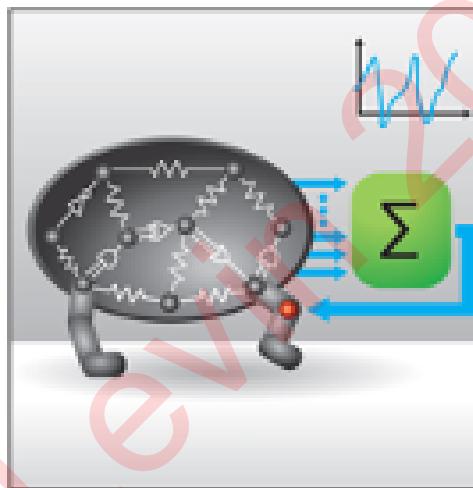
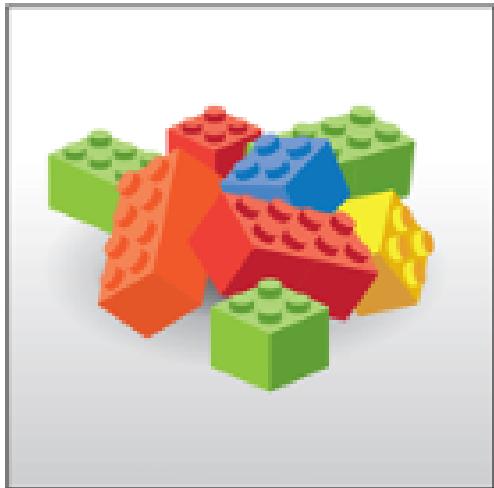


Figure 1. The active sampling cycle. This graphic illustrates the basic idea behind this paper. Analogous with action–perception cycles of the sort found in biological systems, it shows reciprocal interactions between the process of sampling data (in biology, through acting upon the world to solicit new sensations) and drawing inferences about these data (akin to perceptual inference).

science as active inference



Engineering with Diverse Substrates



Passive material

Active material

Computational material

Agential material

Degree of agential material (from engineering perspective):

how much do I *not* need to micromanage? autonomy, communication

how much of the task is engineering vs. *reverse engineering*?

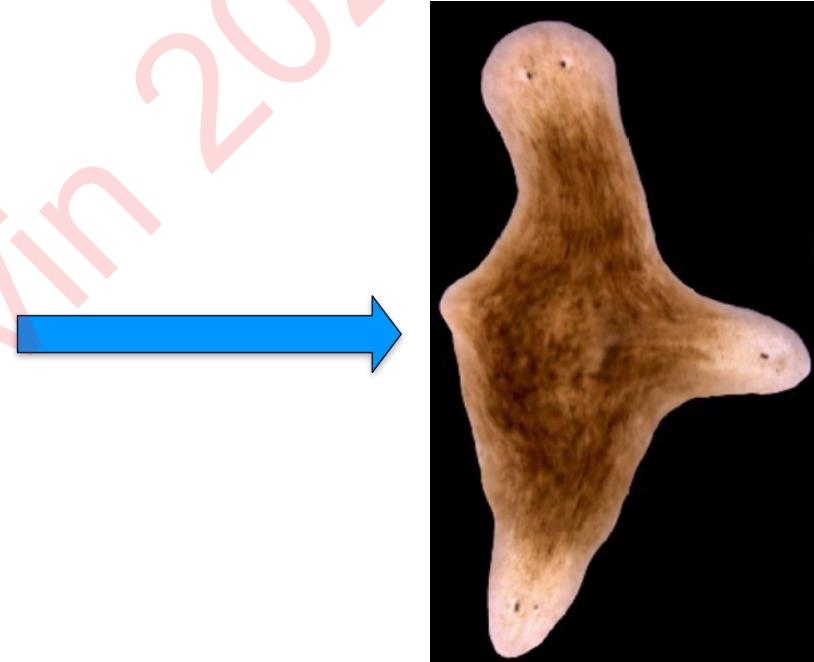
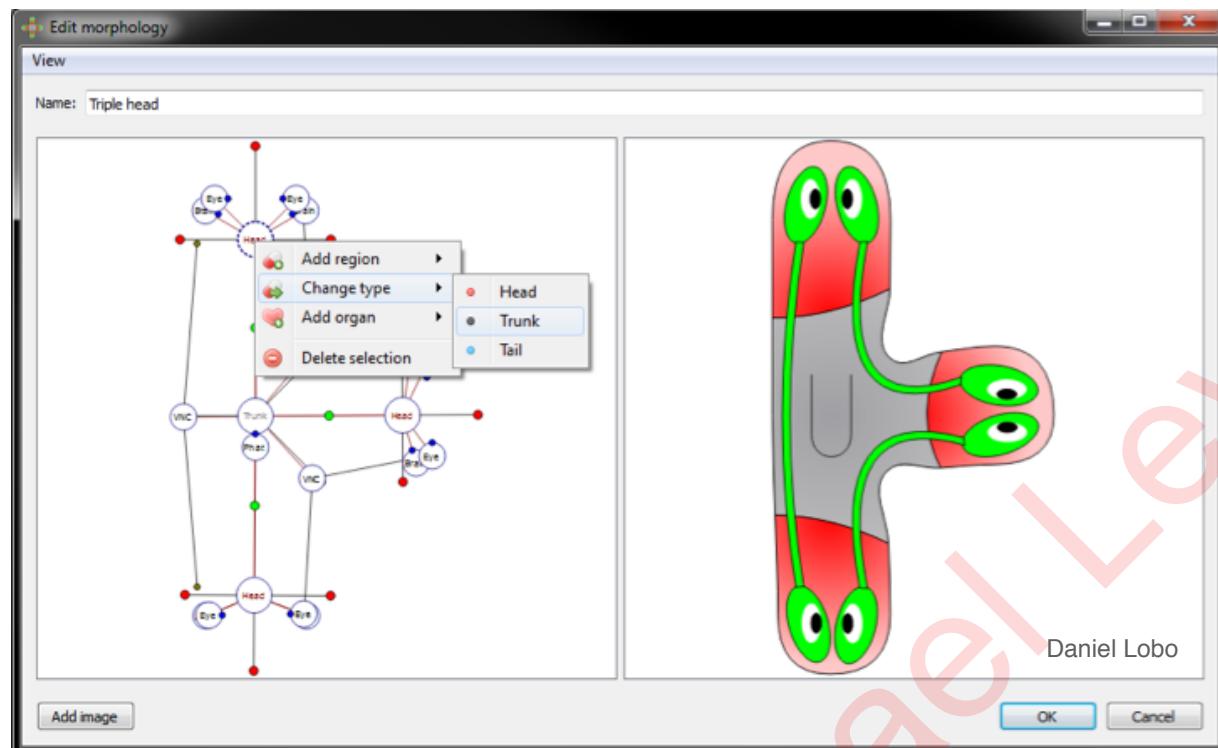
how much more do I get out that algorithm puts in? intrinsic motivation, agendas

what kind of tools (rewiring -> psychoanalysis) work best?

Engineering Agential Materials: Special Properties of Living Matter

(c) Michael Levin 2025

Biomedical Endgame: Anatomical Compiler



Why we need it:

- Birth defects
- Traumatic injury
- Cancer
- Aging

how to control what cells will build?

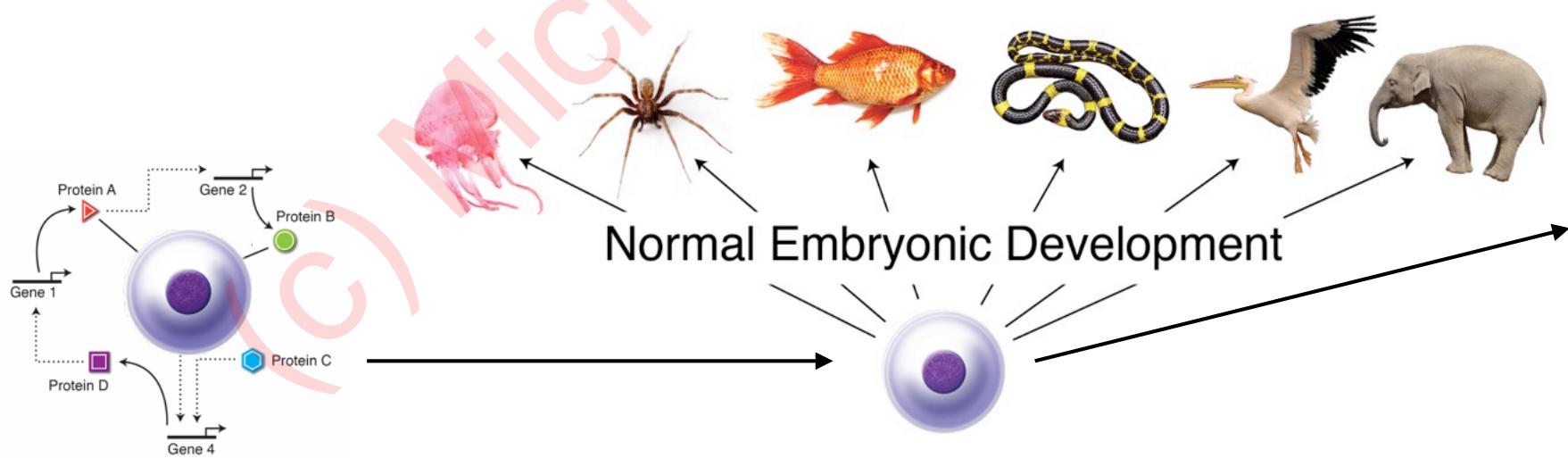
Anatomical compiler is *NOT* a 3D printer - it is a communications device (translator) because of agential material of life

Agential Material of Life



Lacrymaria = 1 cell
no brain
no nervous system

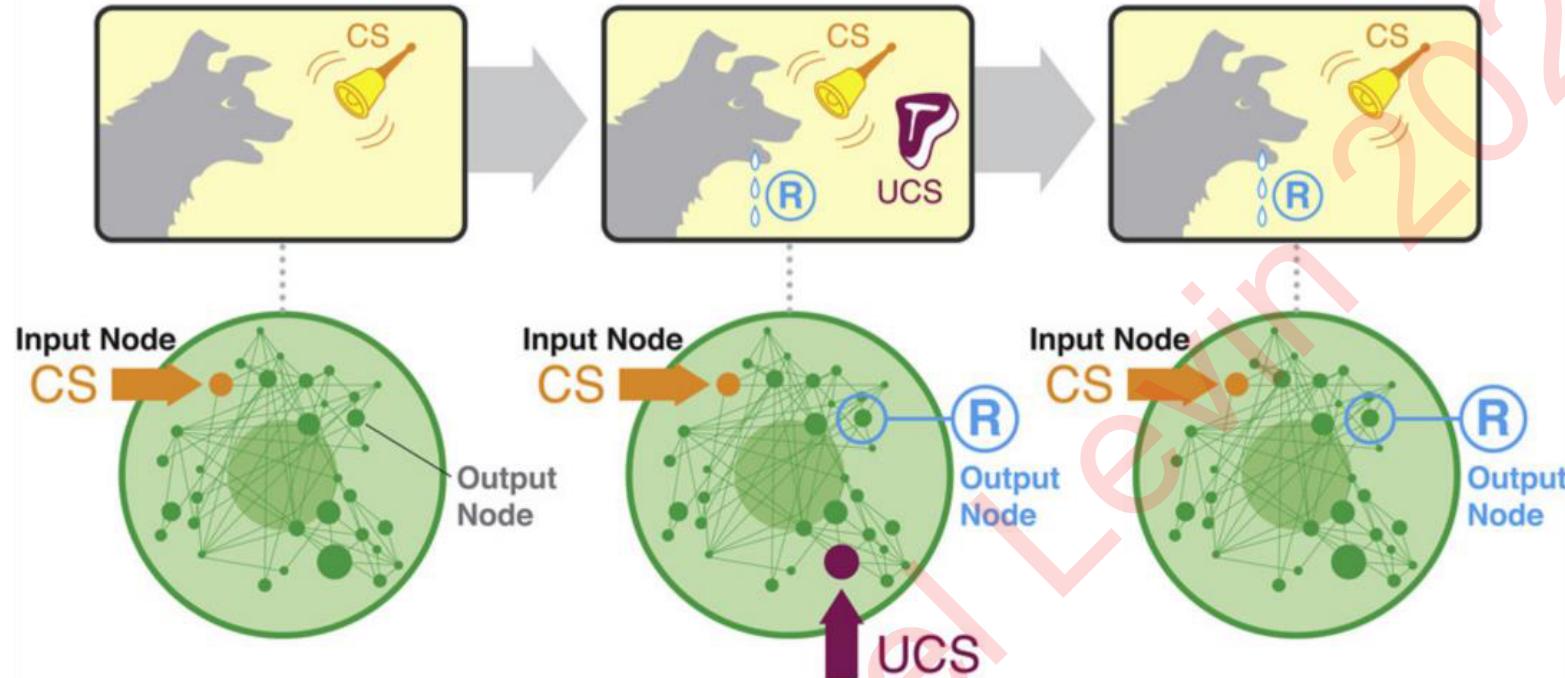
high competency
at cell-level
agendas



Rene Descartes

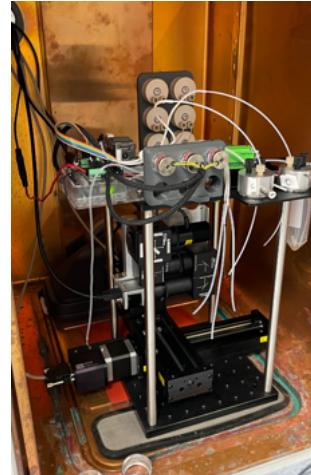


Collective Intelligence Below the Cell Level

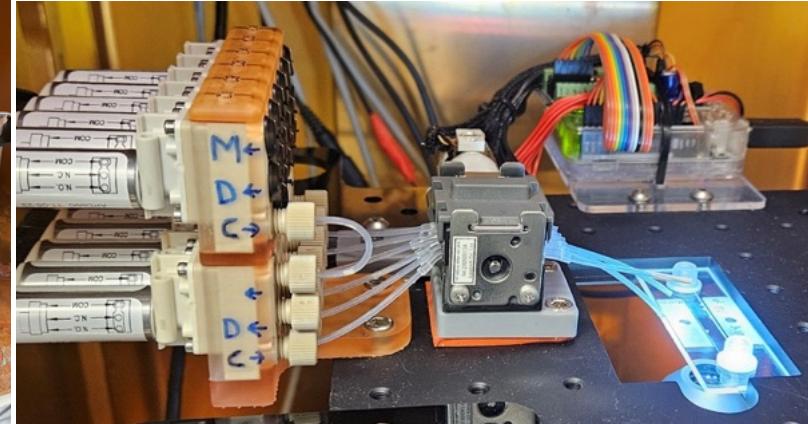


Biomedicine:

- drug conditioning



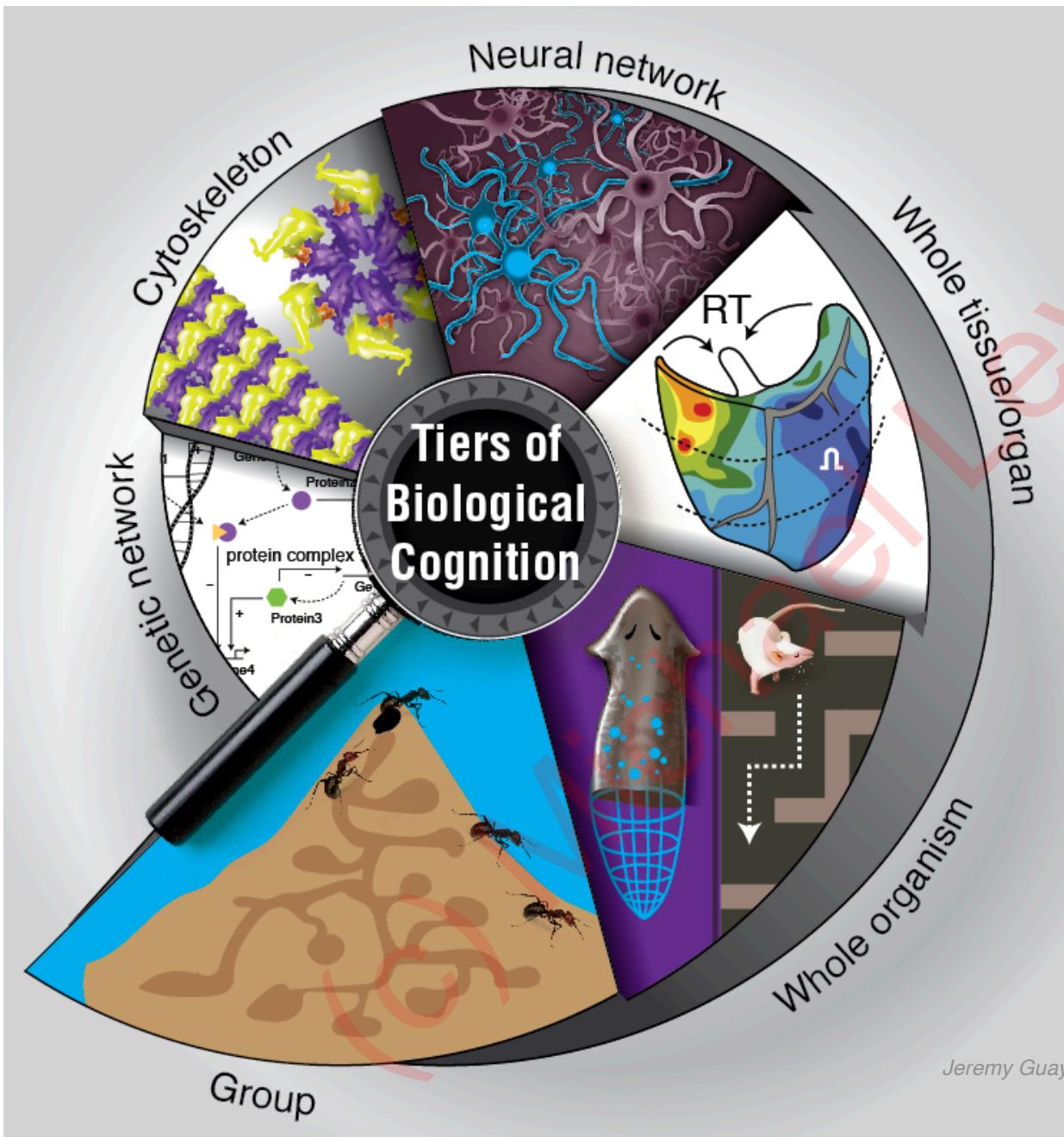
Patrick Erickson



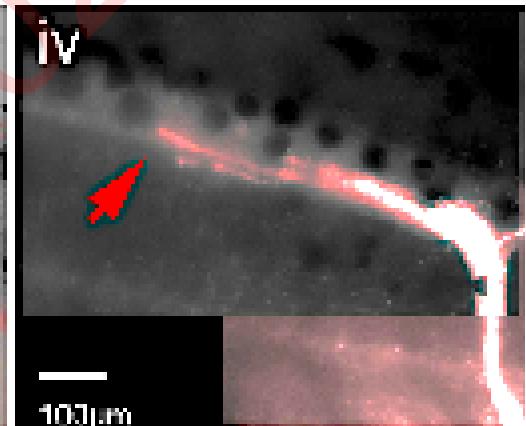
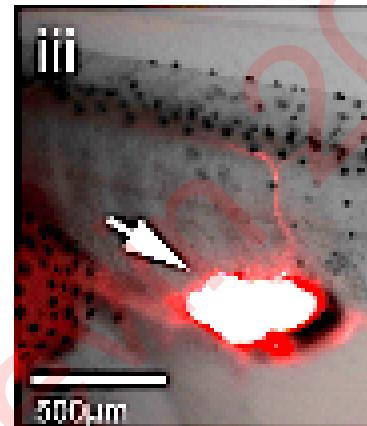
Nested Cognition, not Merely Structure

Multi-scale Competency Architecture

each level of organization solves problems in its own space (morphospace, transcriptional space, physiological space, 3D behavioral space, etc.) using some of the same tricks, at various levels of sophistication



On-the Fly Adjustment to Novel Architectures



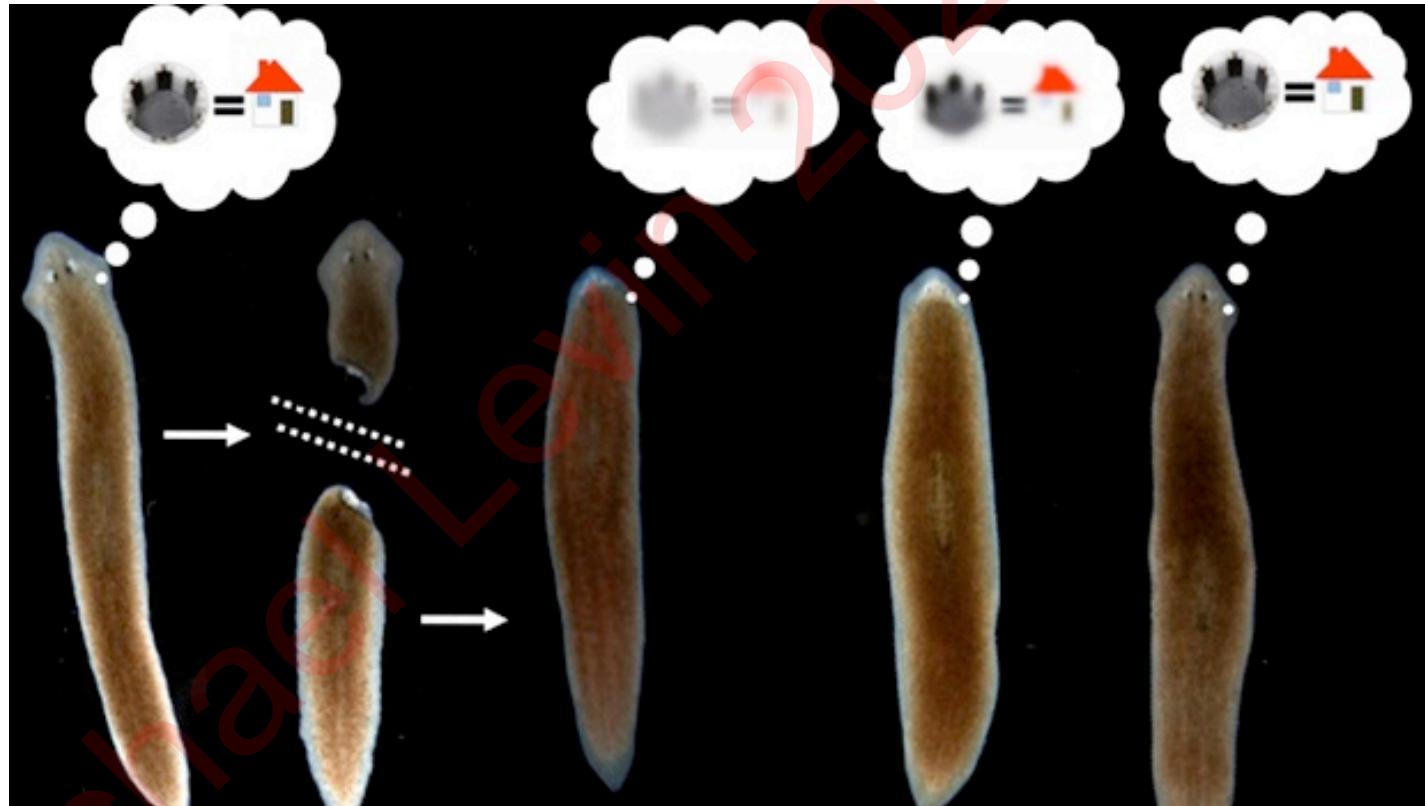
Ectopic eyes on tail provide vision!



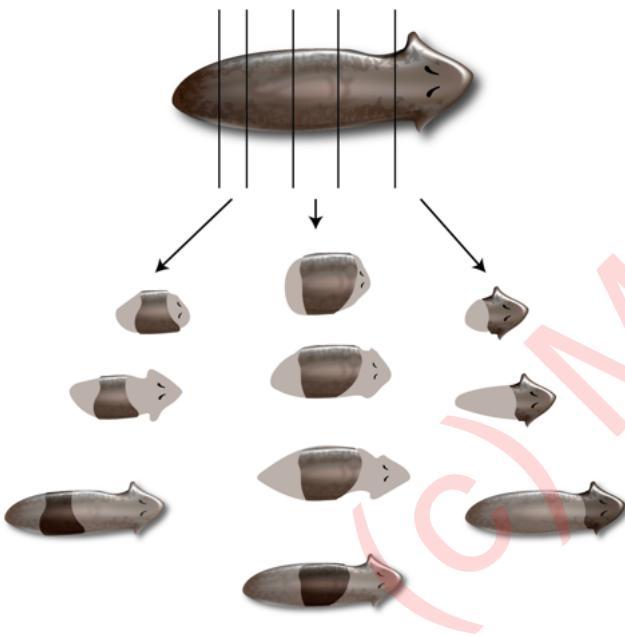
Douglas Blackiston

Brain dynamically
accommodates new
sensory-motor architectures

Memories Move Through Somatic Medium



Tal Shomrat



© 2016. Published by The Company of Biologists Ltd | *Biology Open* (2016) 5, 1177-1188 doi:10.1242/bio.020149

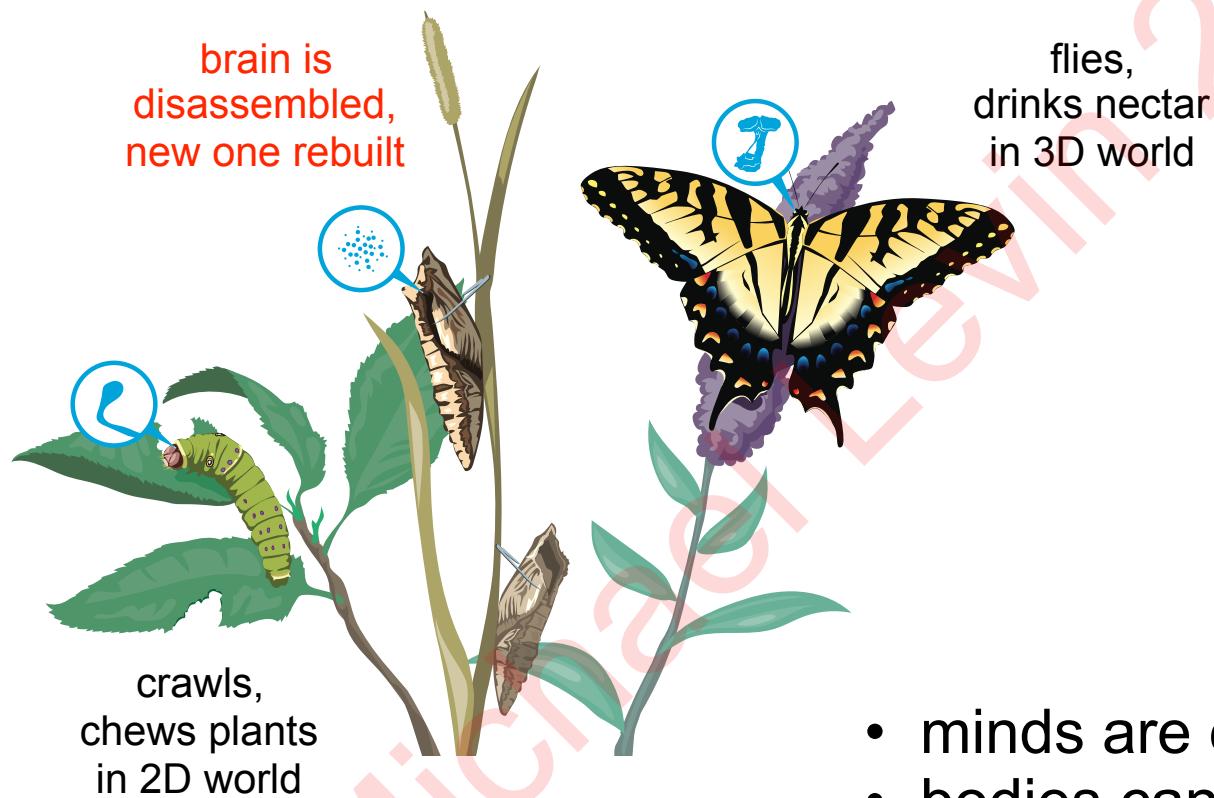


HYPOTHESIS

Vertically- and horizontally-transmitted memories – the fading boundaries between regeneration and inheritance in planaria

Moran Neuhofer^{1,*}, Michael Levin^{2,*} and Oded Rechavi^{1,2,3,*}

Memories Persist Through Drastic Refactoring of Substrate & Re-map onto New Embodiment

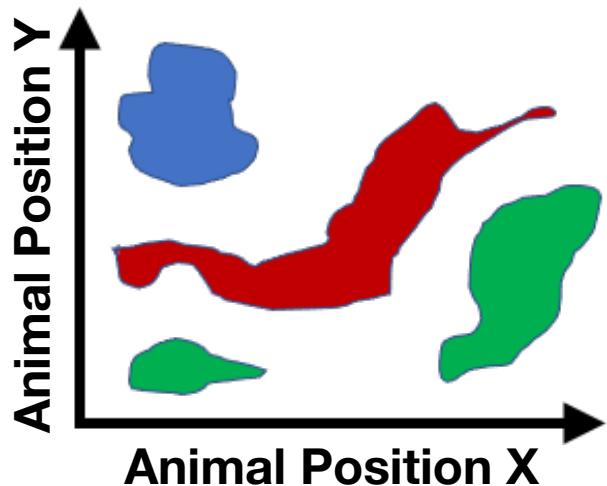


Douglas Blackiston

- minds are embodied
- bodies can change drastically
- memories are **generalized and remapped onto new architecture**
- what is it like to be a caterpillar changing into a butterfly?

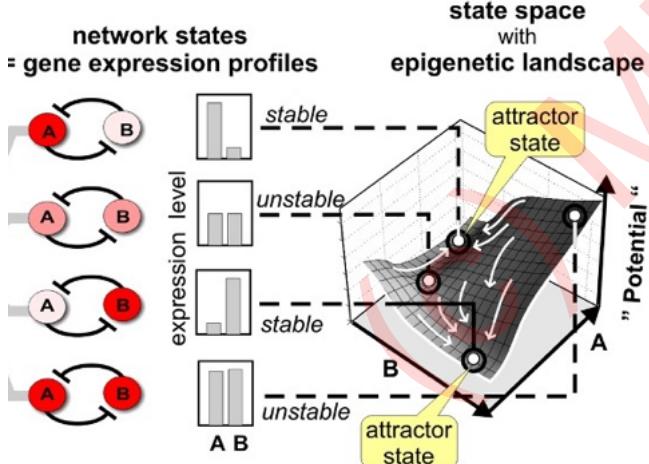
Problem-solving in Diverse Spaces

3D Space (behavior)

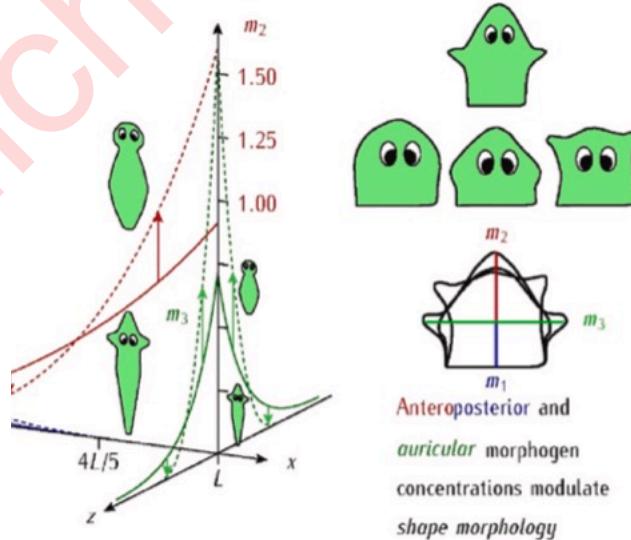


Transcriptional Space

Huang, S.; Ernberg, I.; Kauffman, S., *Semin Cell Dev Biol* 2009, 20, (7), 869-76.

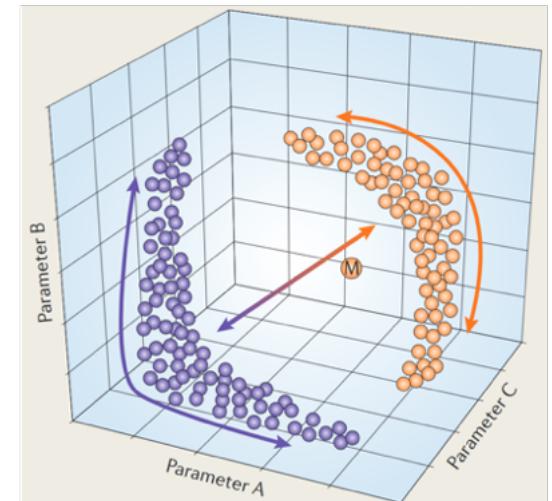


Morphospace

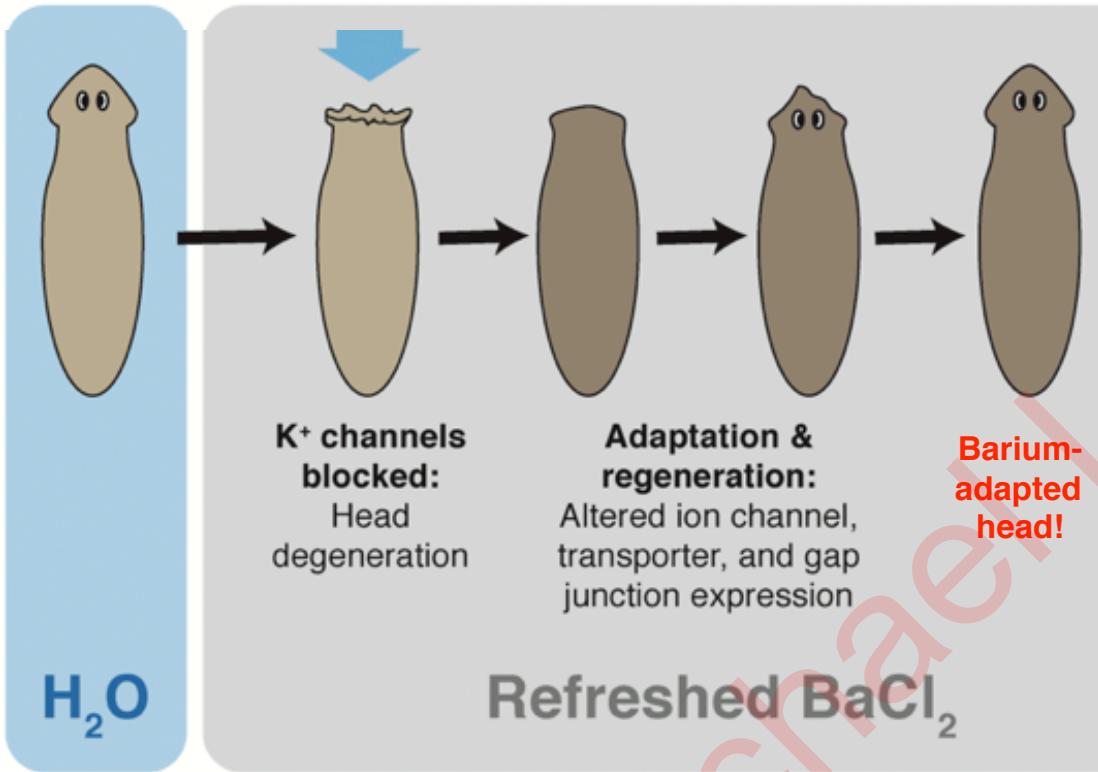


Physiological Space

Marder, E., & Goaillard, J. M. (2006). Variability, compensation and homeostasis in neuron and network function. *Nat Rev Neurosci*, 7(7), 563-574.



Moravec's Paradox: problem-solving in transcriptional space -> physiological space

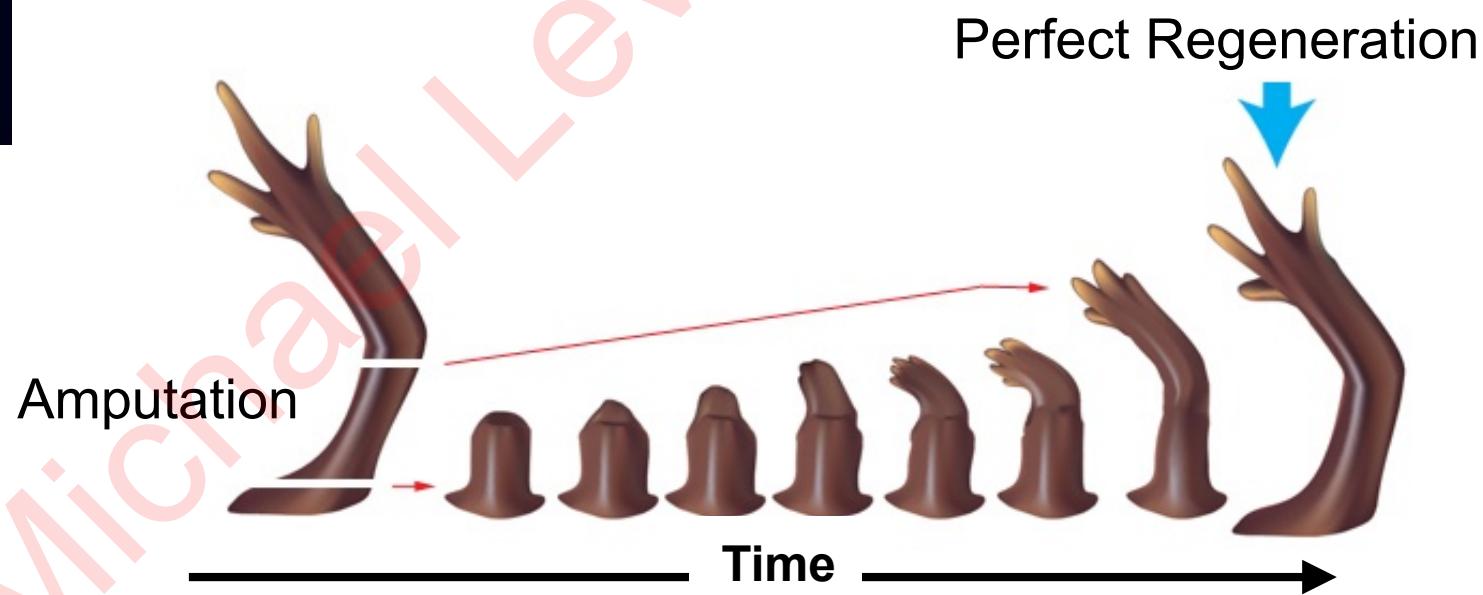


Small number of genes regulated out of entire genome! ~20K effectors



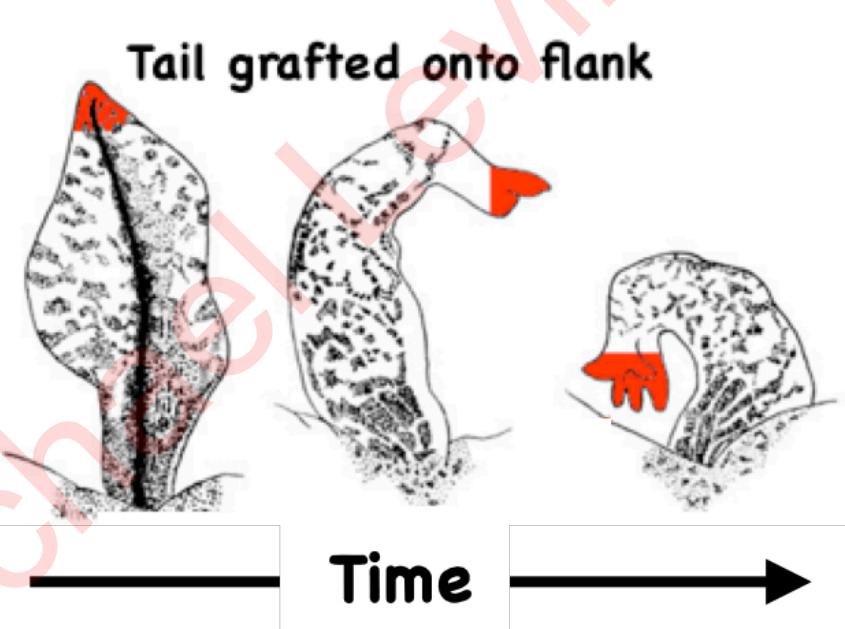
- planarian heads degenerate after exposure to barium
- planaria eventually adapt and regenerate heads that tolerate barium
- a relatively few transcripts were altered to produce barium tolerance
- how did the system choose exactly the right genes to modulate, to deal with this evolutionarily-novel challenge?

Self-Repair - Anatomical Homeostasis



it stops when the correct large-scale setpoint (target morphology) has been reached

It's not Just about Damage: Holistic Order

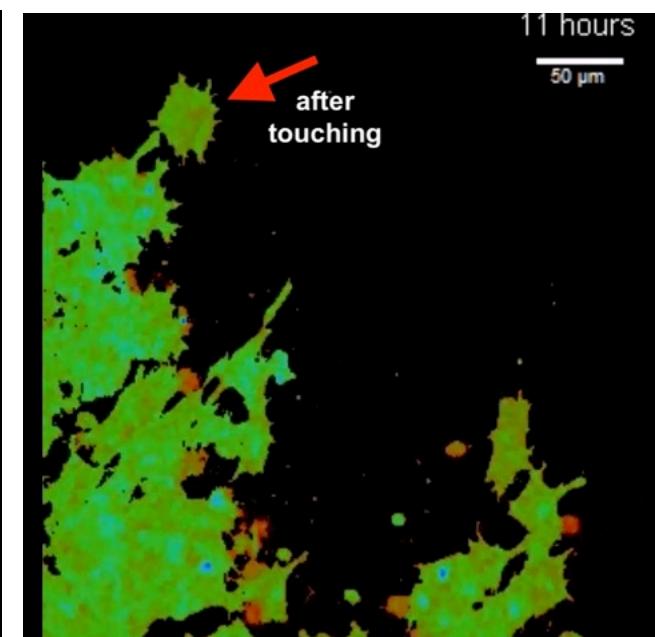
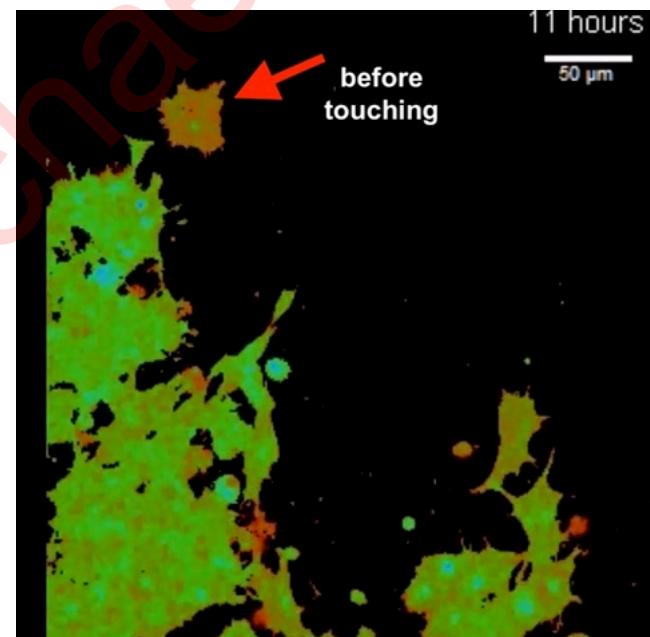
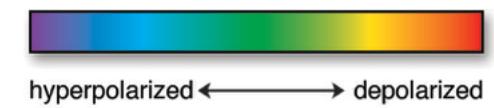
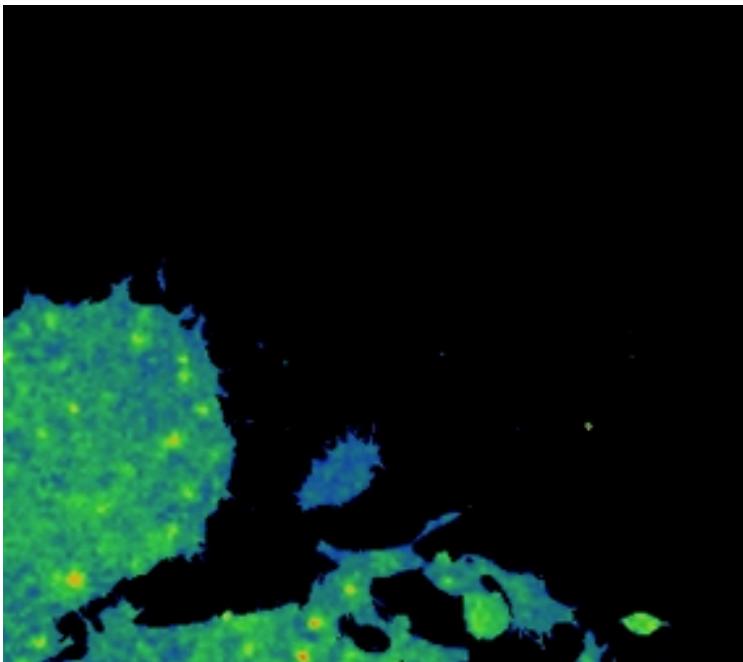


Farinella-Ferruzza, *Experientia*, 1956 (15)

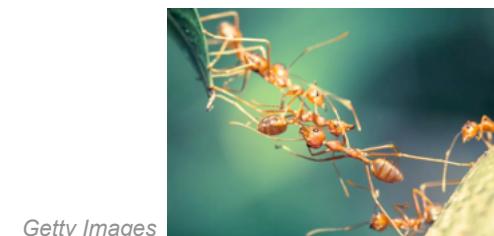
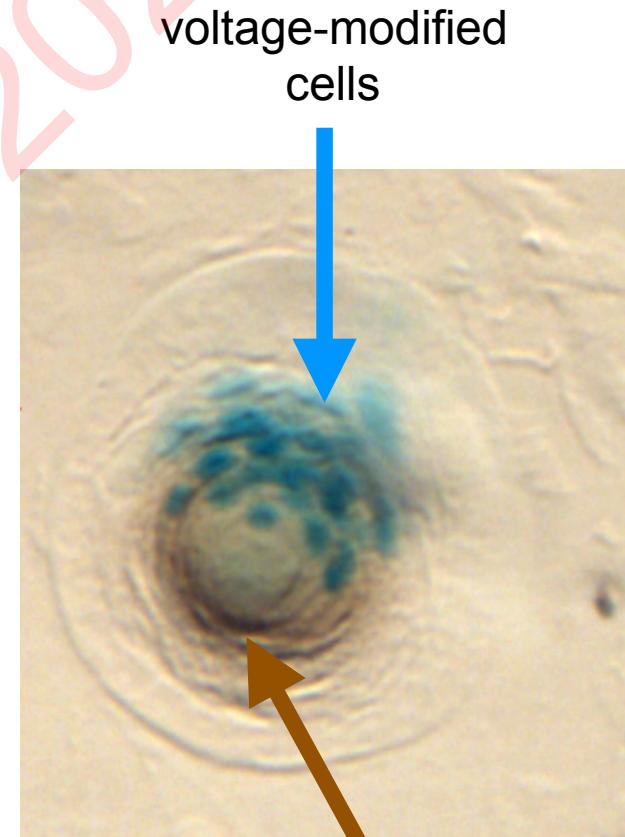
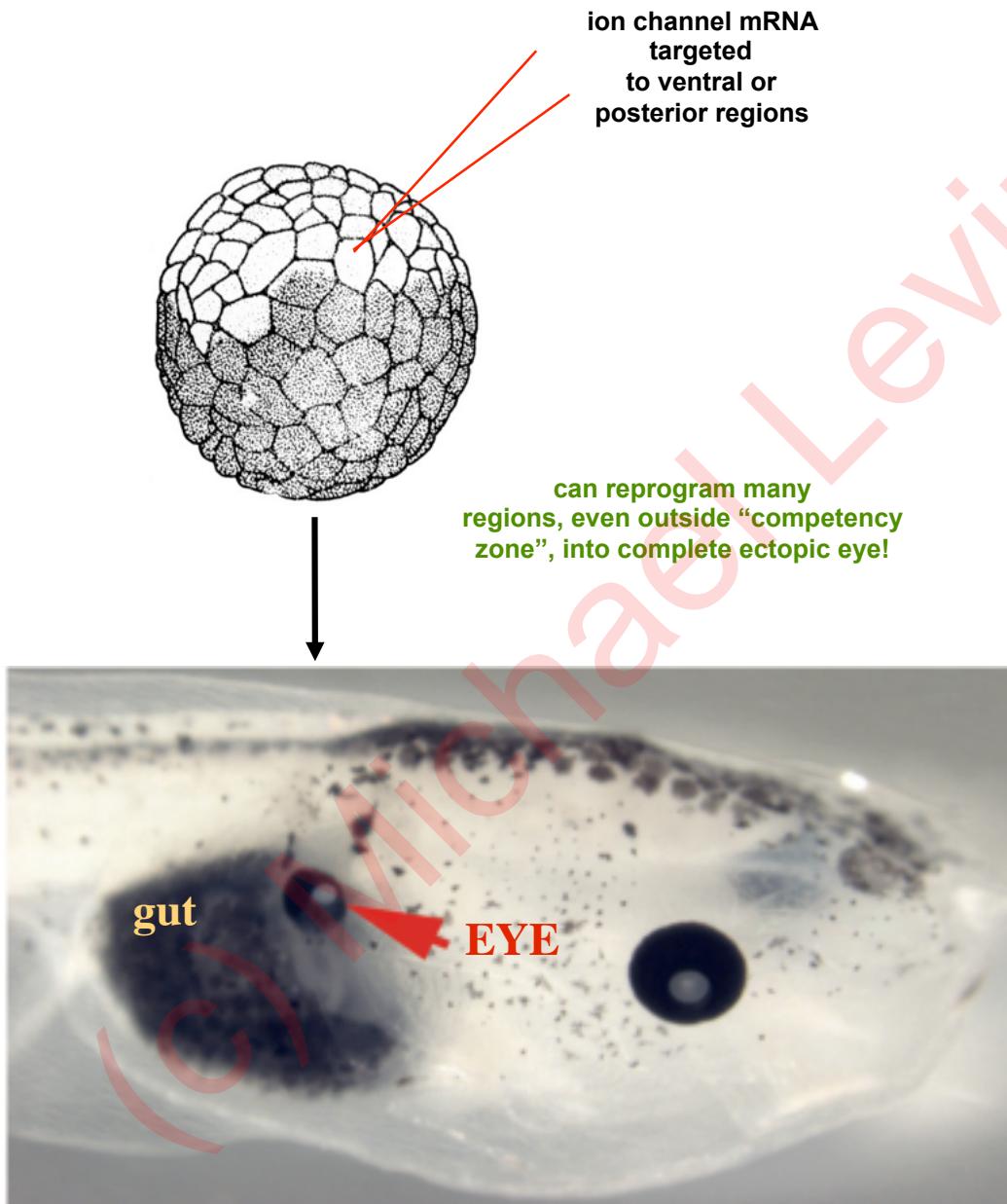
top-down control to align pairs to higher-order set point:

local order obeys global plan

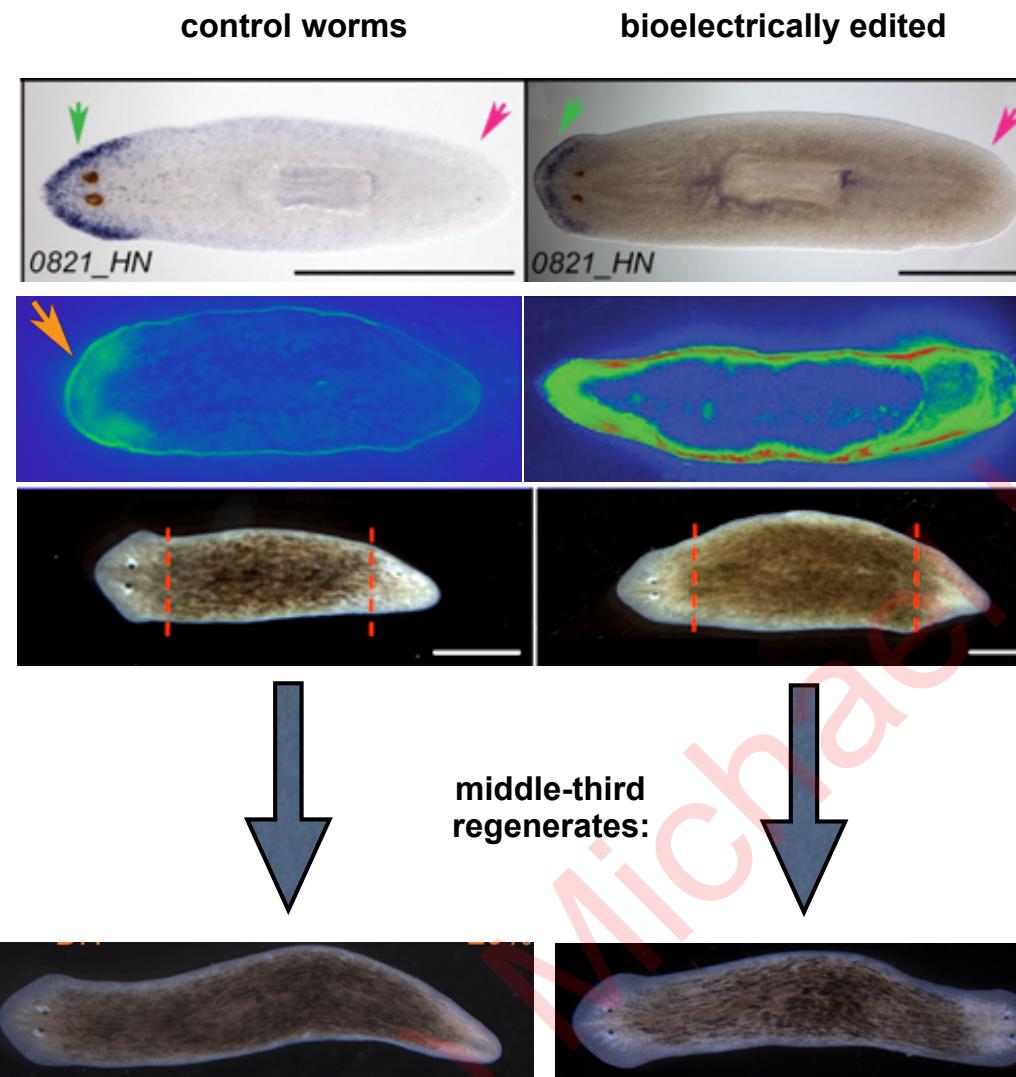
Bioelectrical Take-over at Cell Level: A very convincing message



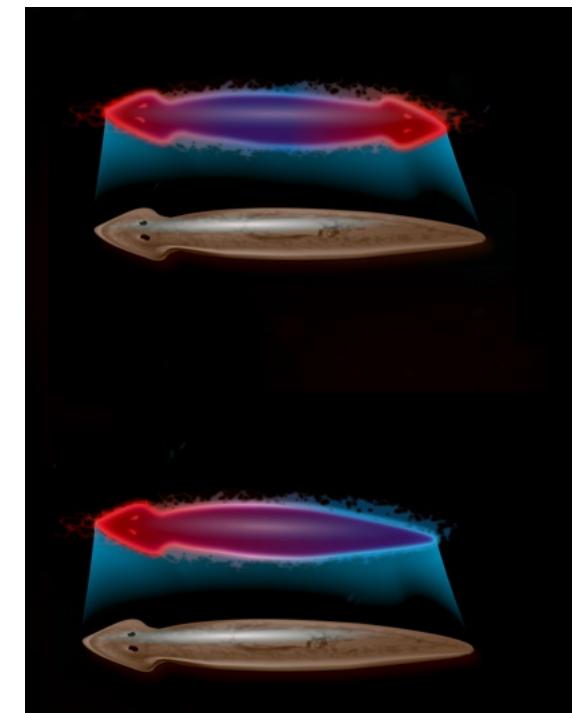
Bioelectric Interface to Agential Material: Self-scaling morphogenetic subroutines



Re-writing Anatomical Pattern Memory

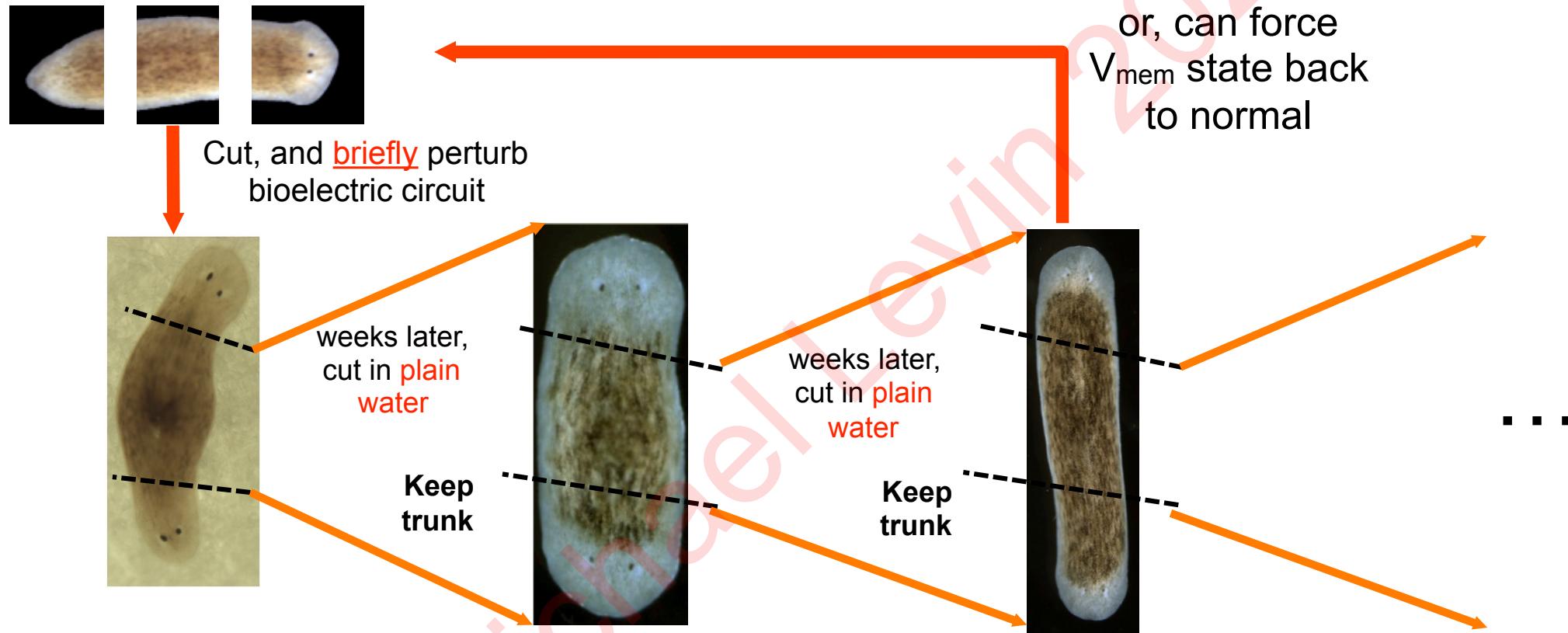


The Same Body can Store different Electrical Pattern Memories



The bioelectric pattern doesn't indicate what the anatomy is now, it encodes the latent pattern memory that will guide anatomy **if** it is cut at a future time = **counterfactual**

Reprogrammable Material at System Level



Basic properties of memory

- Long-term stability
- Lability (rewritable)
- Latency (conditional recall)
- Discrete possible outcomes (1H v. 2H)

Nestor Oviedo
Junji Morokuma



(c) Michael Levin 2025

Novel Forms of Life and Mind

Messages from Hacker Reveal Flexibility:

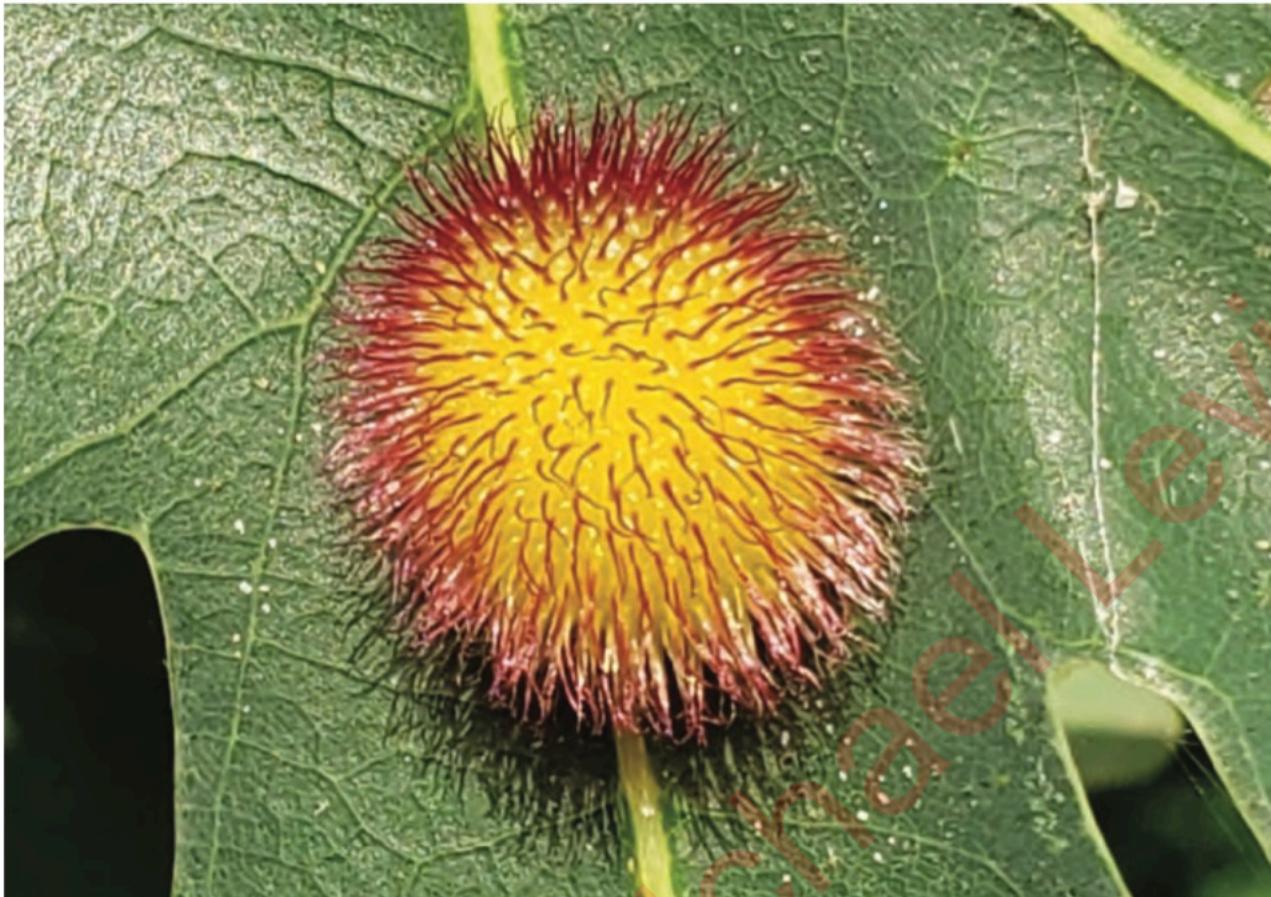
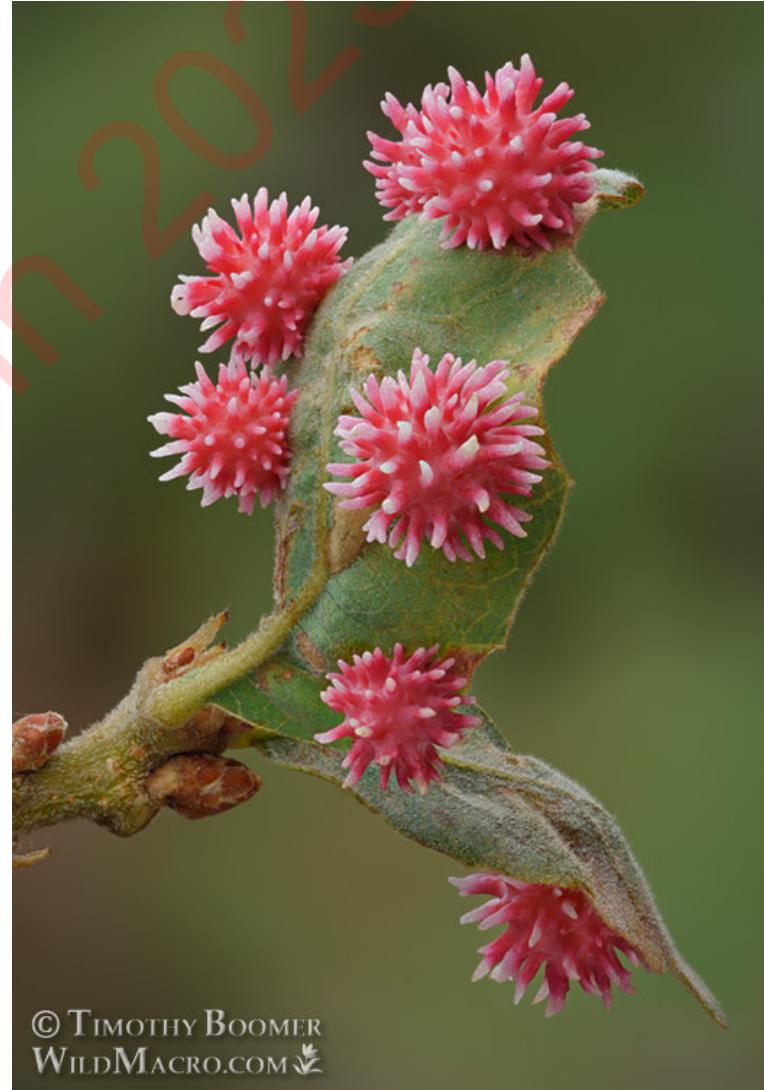


Photo Credit: Andrew Deans

Hedgehog Gall

Acraspis erinacei

August - November



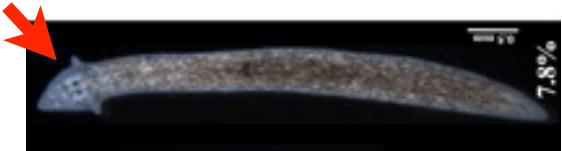
© TIMOTHY BOOMER
WILD MACRO.COM

Parasite hacks host to induce new anatomy (bio-prompting)

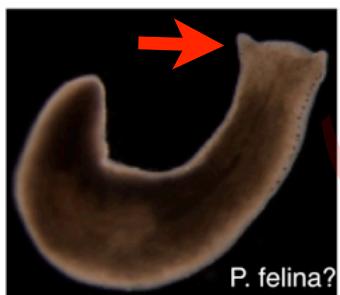
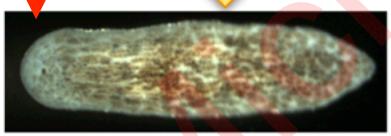
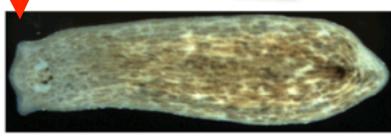
Exploring Morphospace with Planarian Bodies

Species-specific shapes = attractors in morphospace

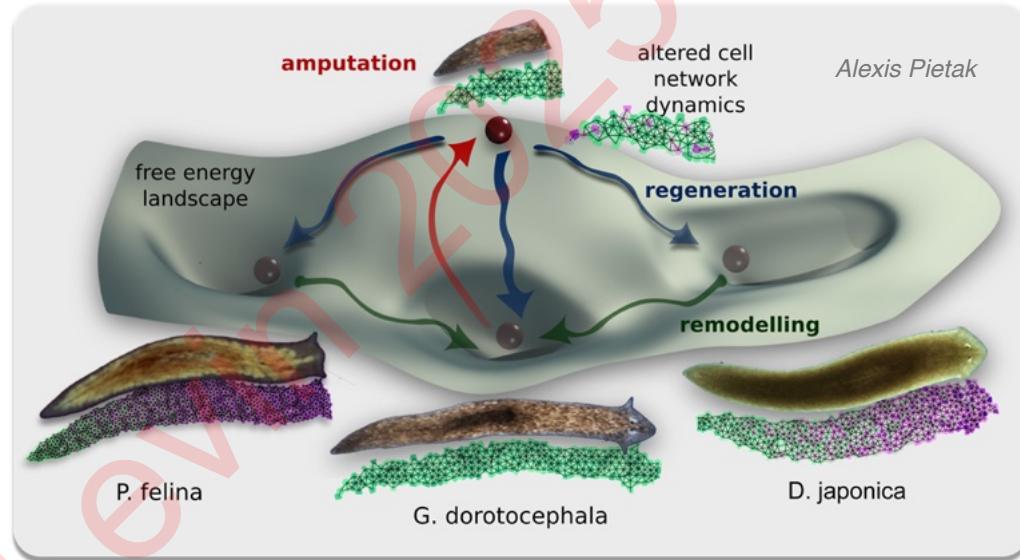
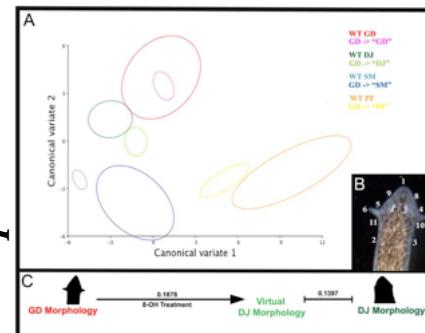
D. dorotocephala



cut off head, perturb network topology

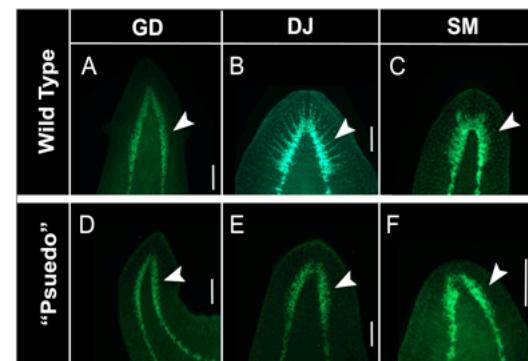
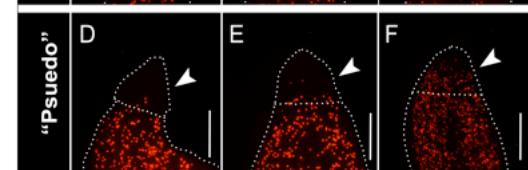
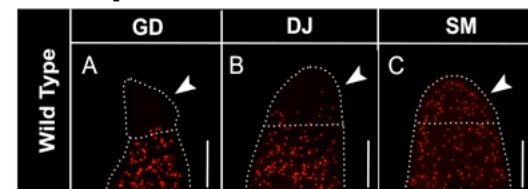


quantitative
morphometrics

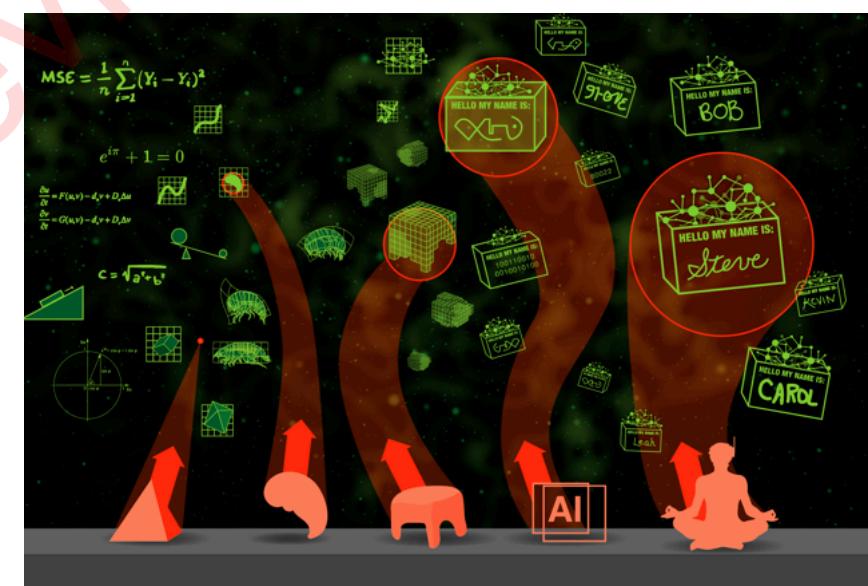
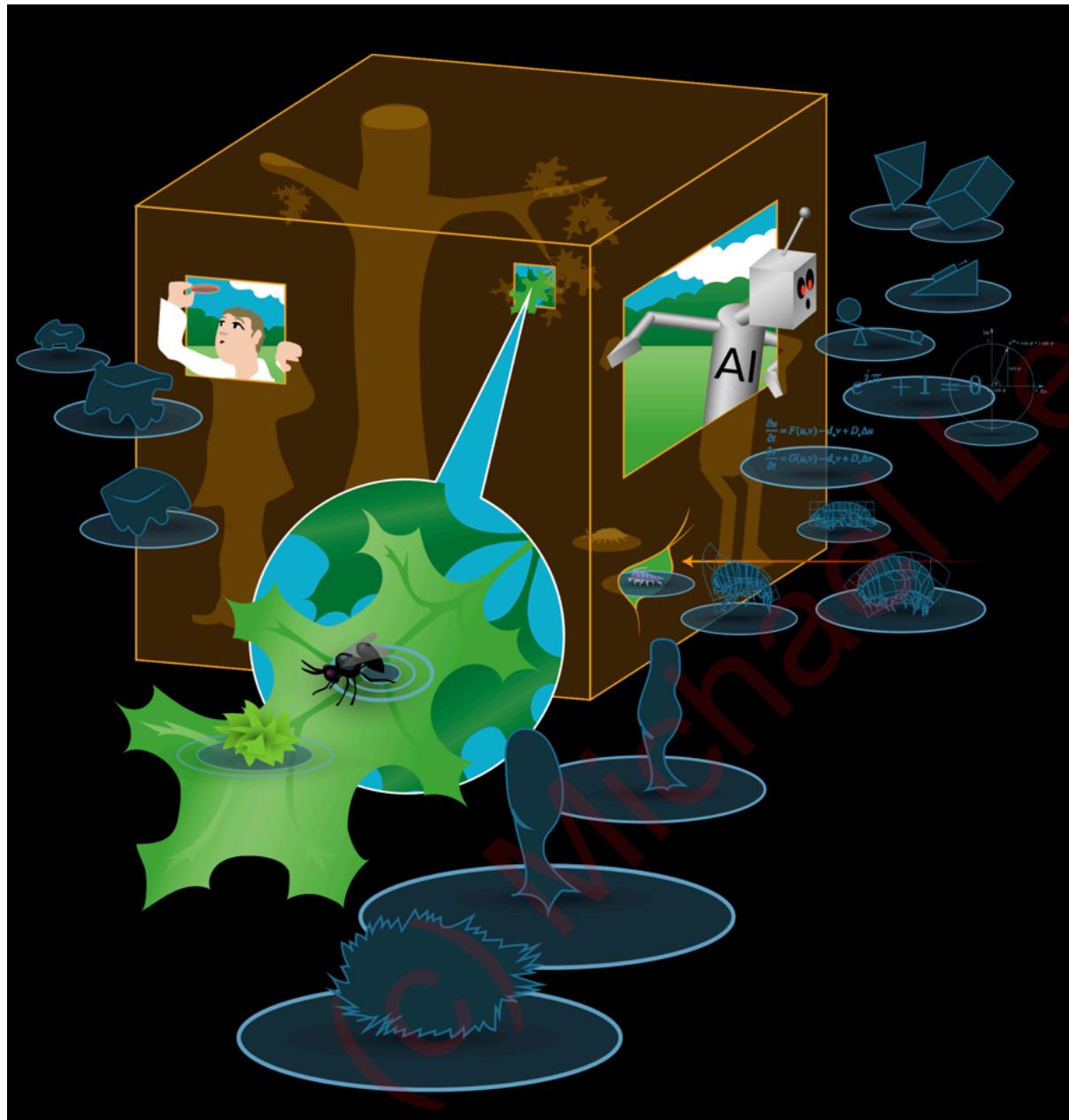


Maya Emmons-Bell

brain shape and stem cell patterns match also!

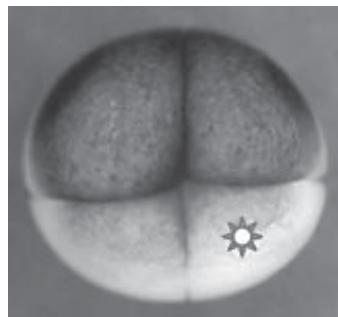


Exploring the Latent Space with New Embodiments: beyond evolutionarily-selected Setpoints



<https://thoughtforms.life/symposium-on-the-platonic-space/>

Rebooting Multicellularity

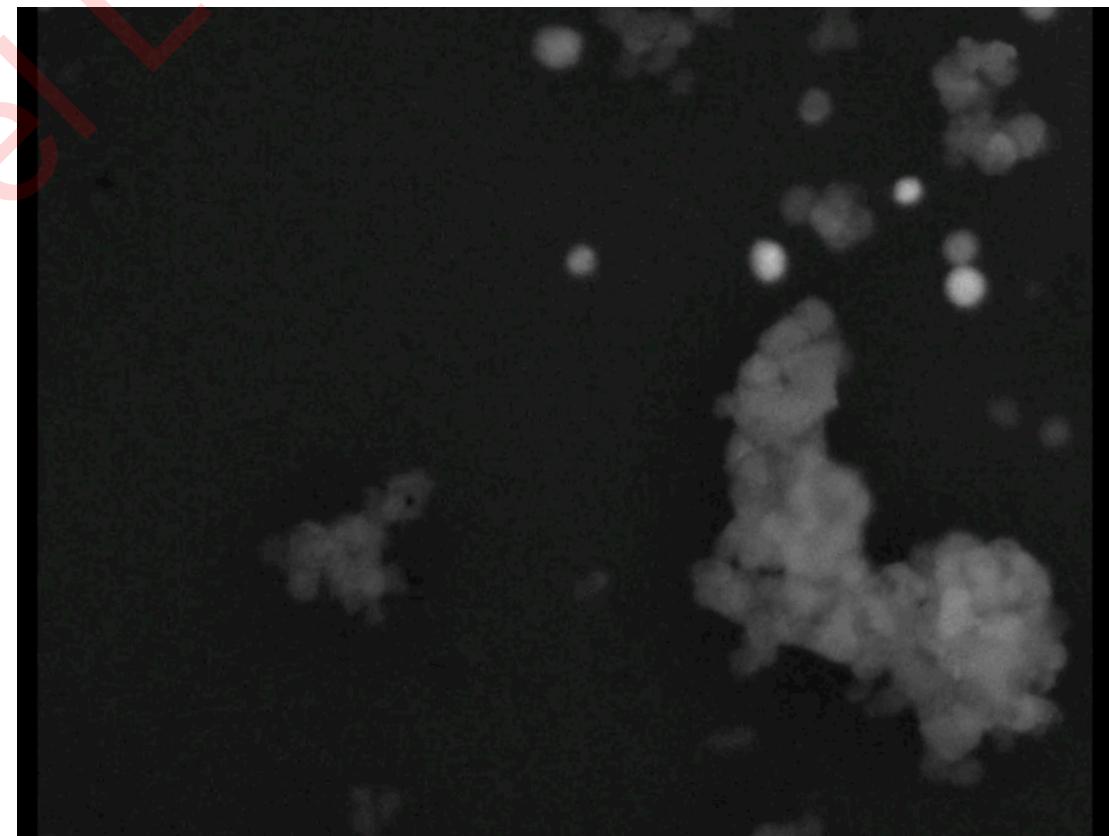


Early frog embryo

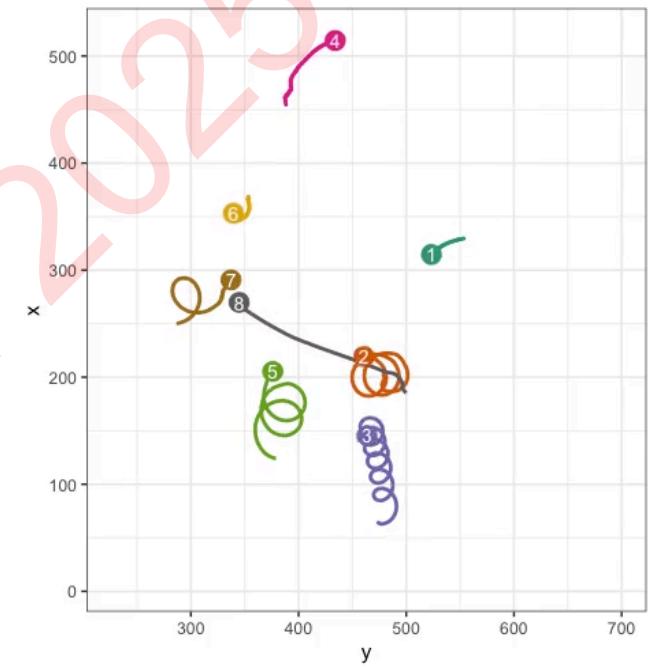
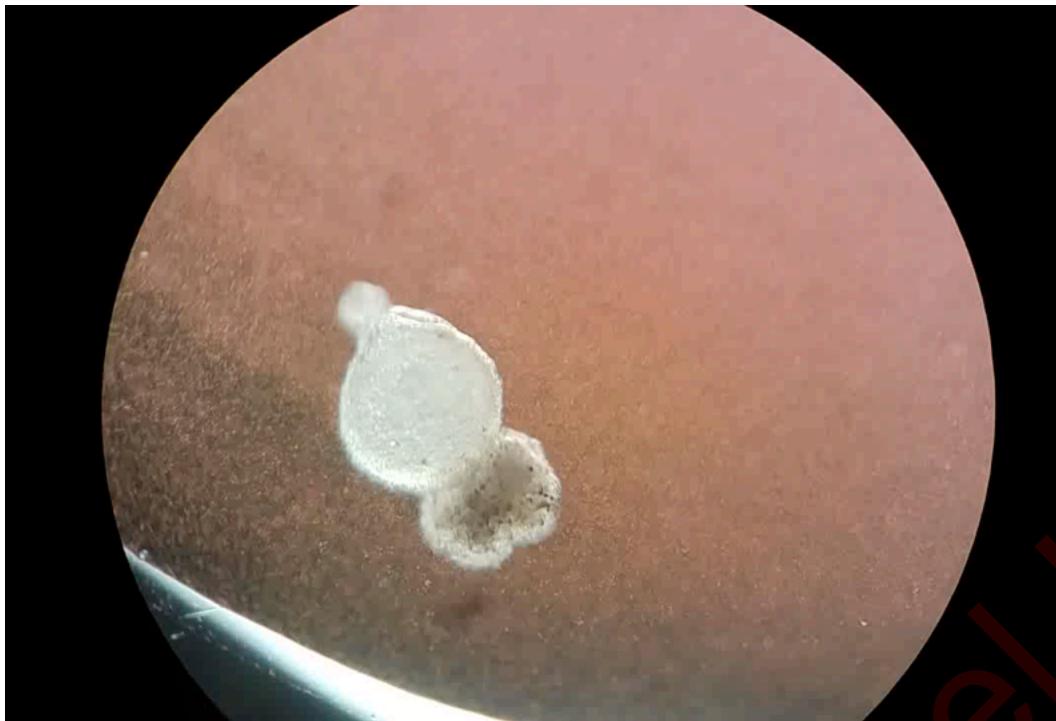


assay for form and function

Douglas Blackiston



Xenobot Ciliary Motility



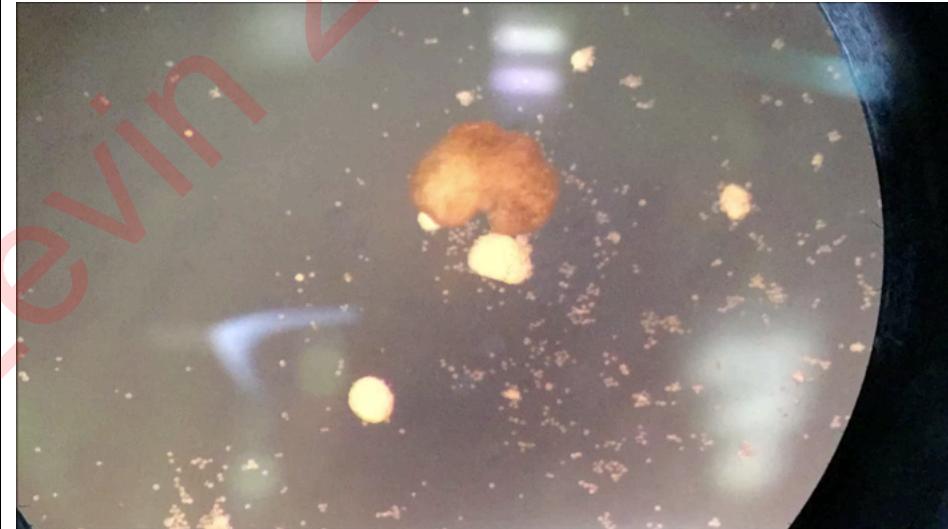
Douglas Blackiston

Xenobot in a maze (still water, no flow):



- 1) it traverses maze,
- 2) rounds the corners without bumping into walls, and
- 3) it makes a spontaneous decision to turn around without hitting anything.

Kinematic Replication in Xenobots:



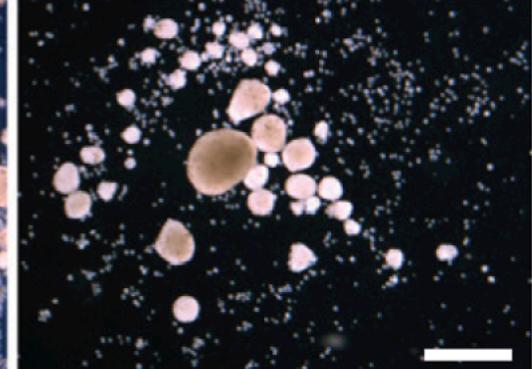
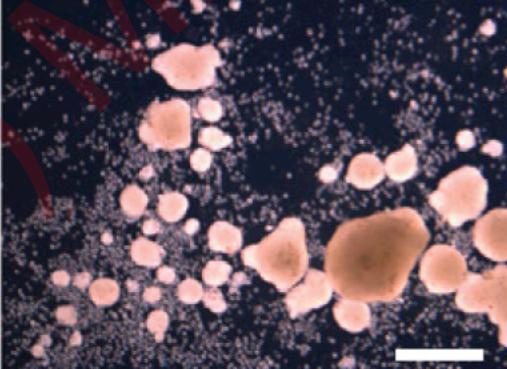
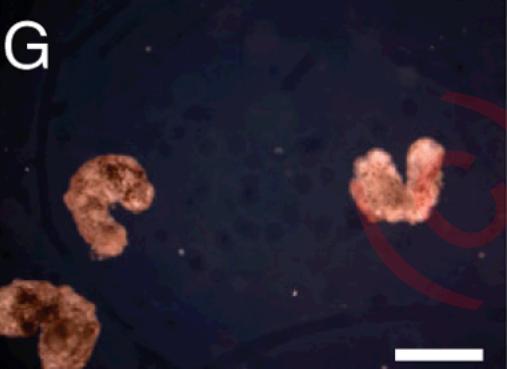
Douglas Blackiston

gen 0

gen 1

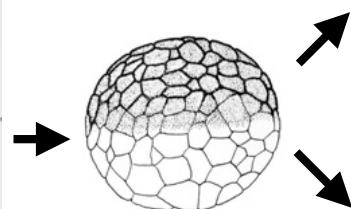
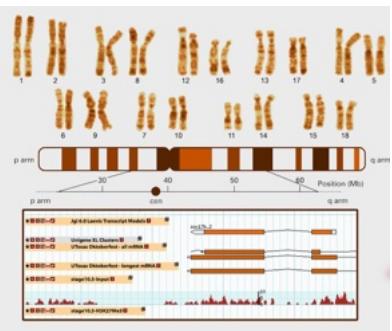
gen 2

gen 3

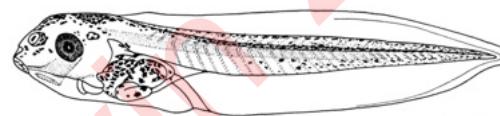
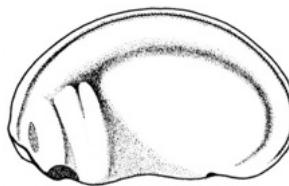


Xenobots have a Standard Frog Genome Novel Morphology, Transcriptome, Behaviors

Xenopus laevis
genome

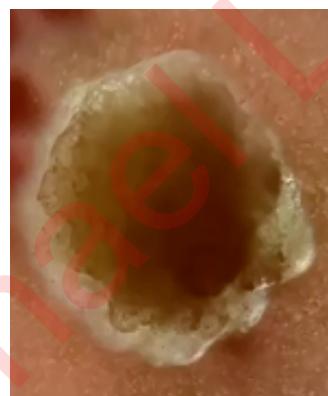


Path A: embryos



Douglas Blackiston

Path B: Xenobots



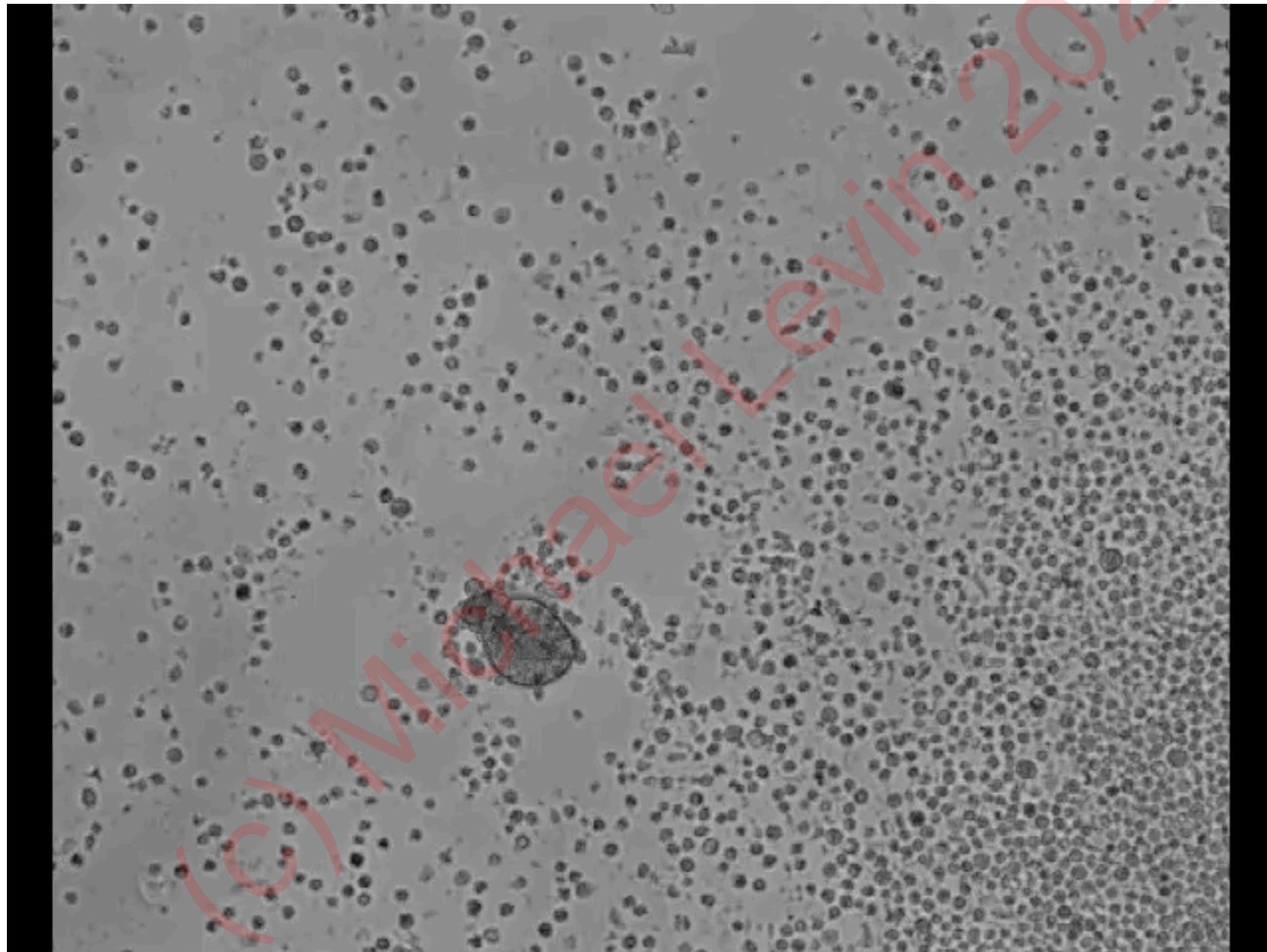
Developmental Time



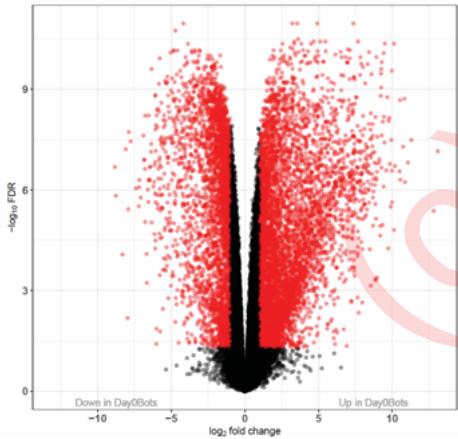
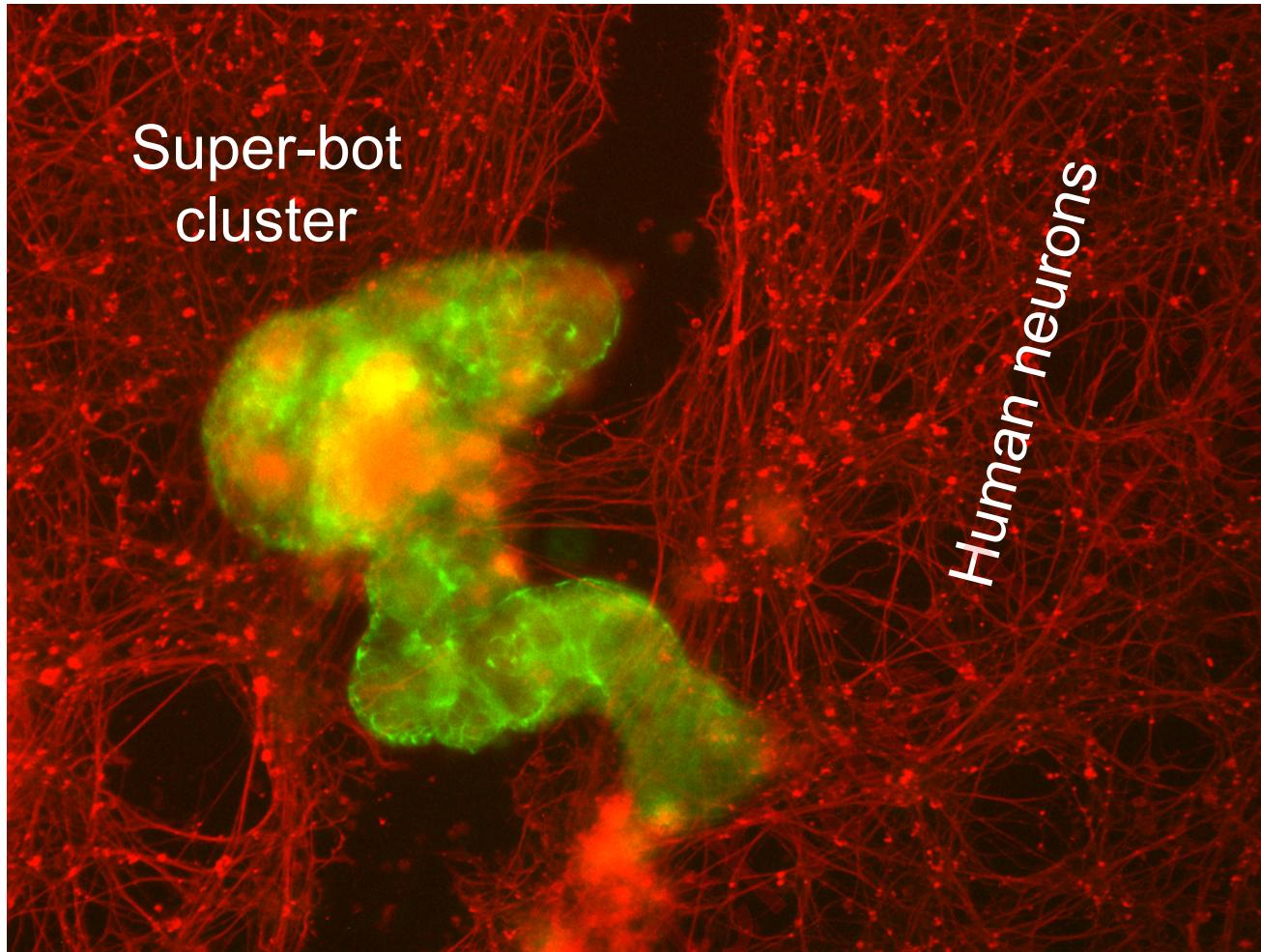
Behavior

no straightforward story of selection for these properties

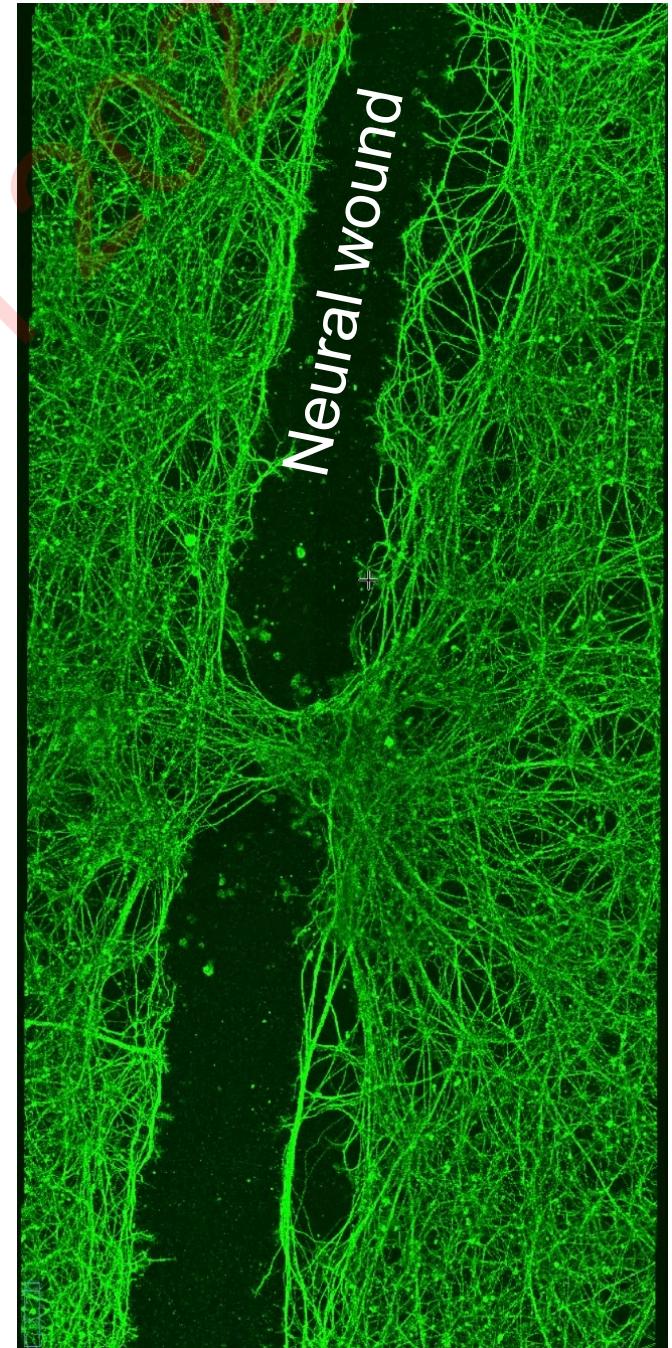
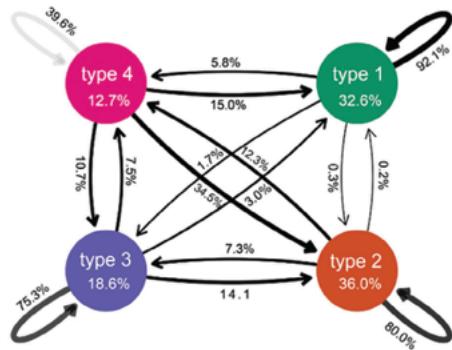
What would *your* cells do if liberated?



Anthrobots Exert Neural Repair

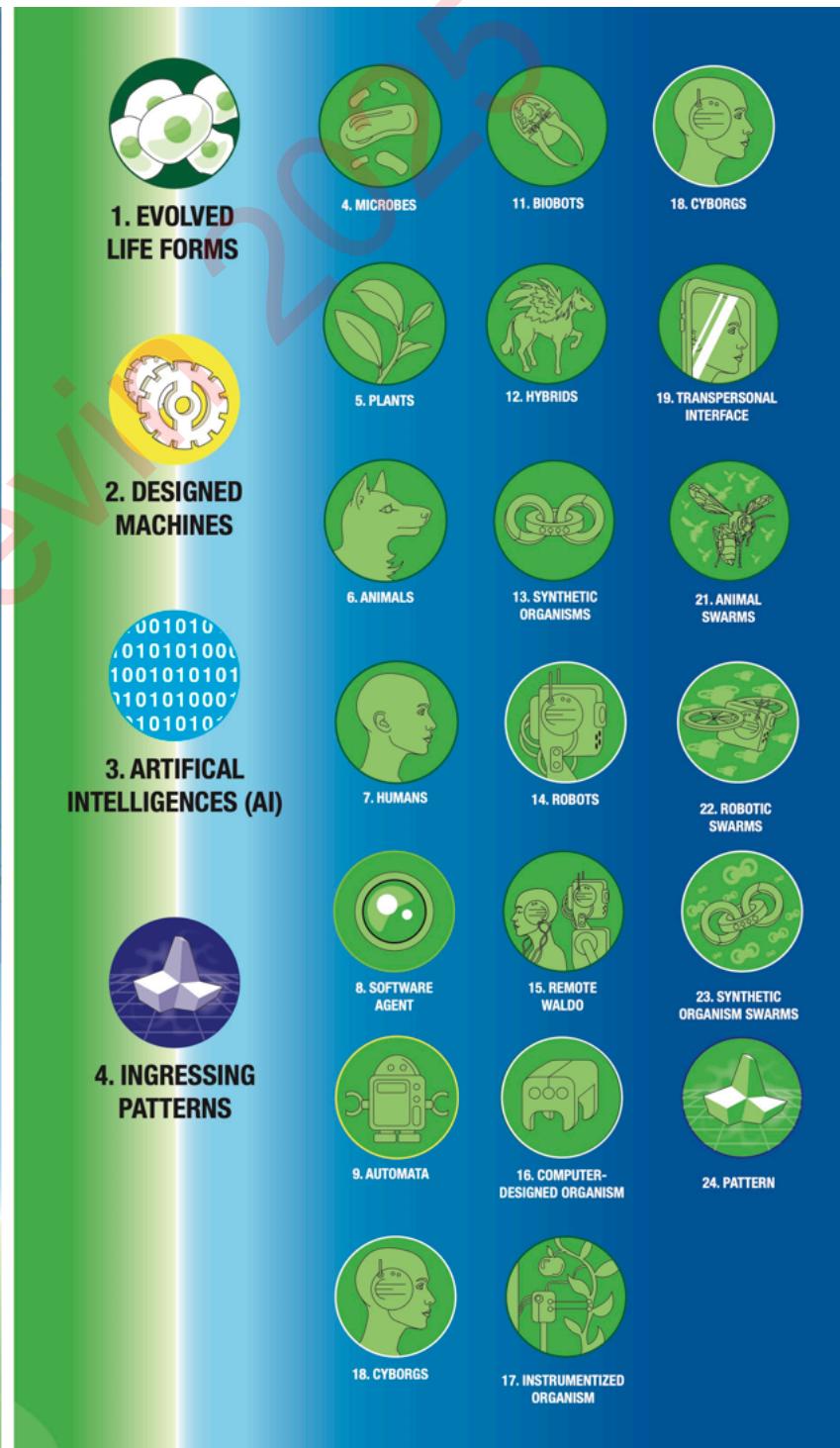
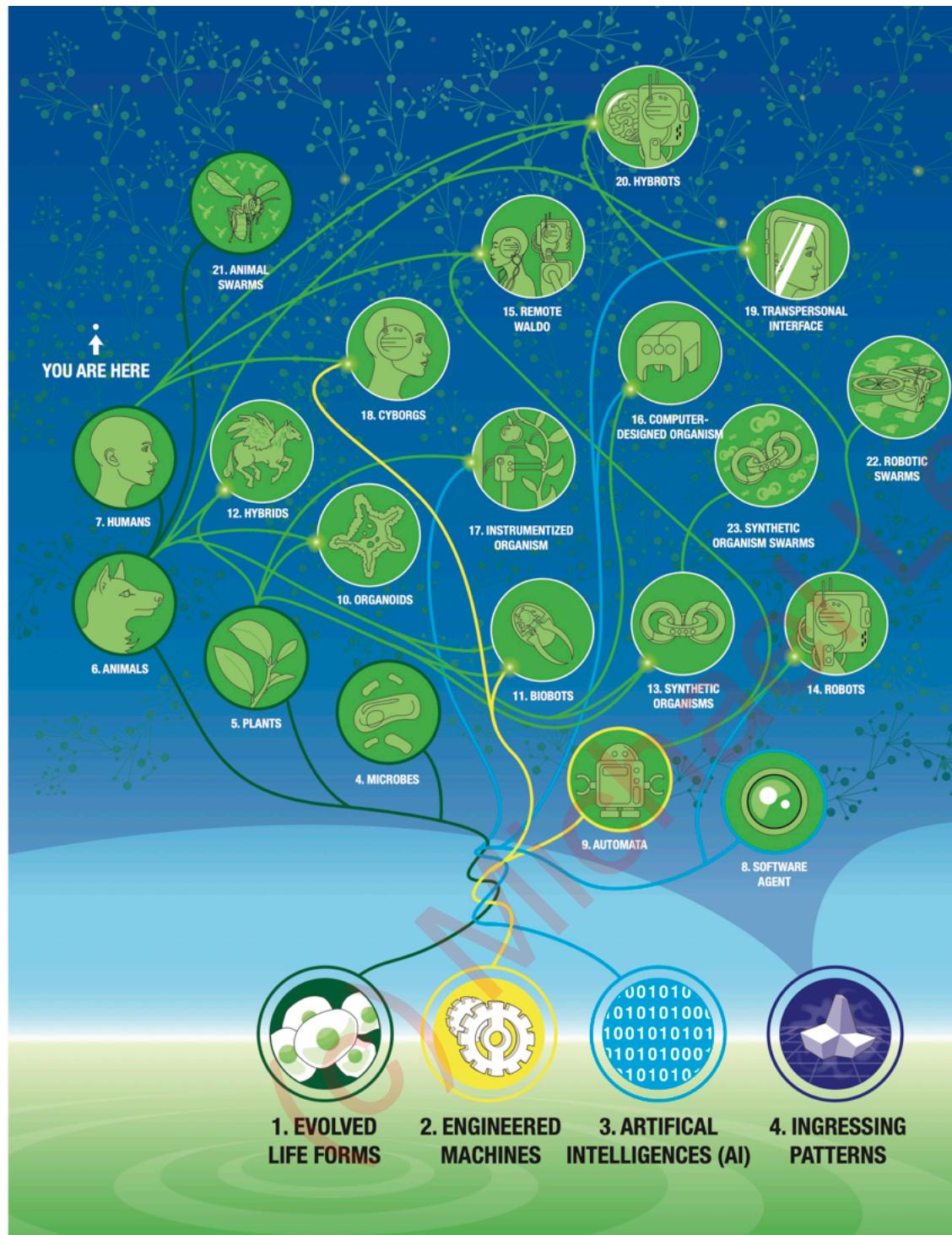


Ethogram of discrete behaviors



Gizem Gumuskaya

“Endless Forms Most Beautiful” \longleftrightarrow ethical synthbosis



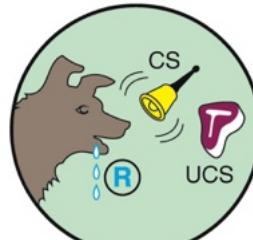
AI for Diverse Intelligence (and ALife, Bioengineering, biomedicine, etc. etc.) research: tools → colleagues



Hardware
modification only



Modify the data encoding
setpoint of goal-driven
process

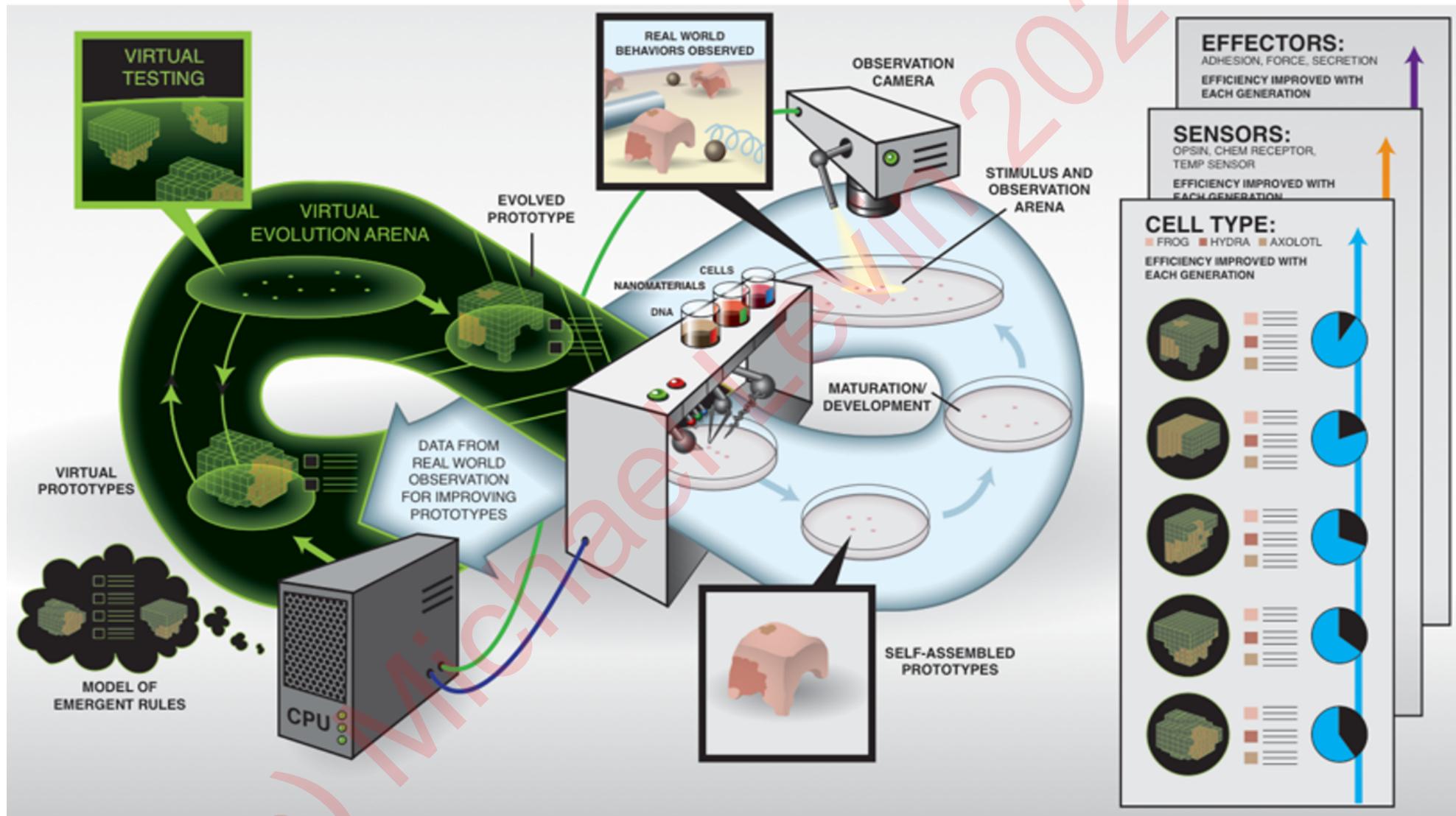


Training by
rewards/
punishments



Communicate
cogent reasons

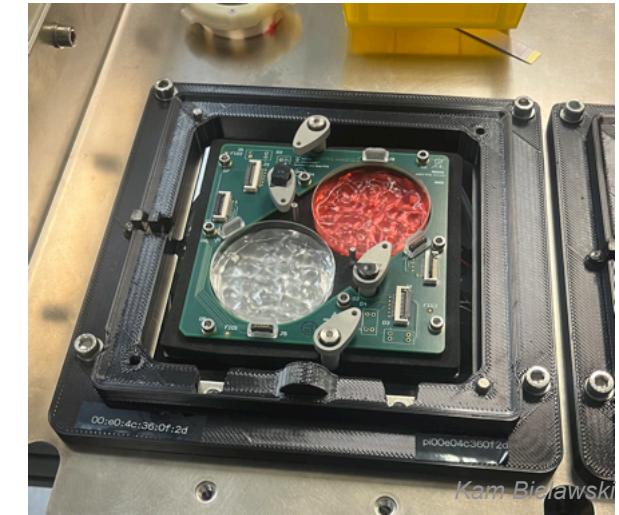
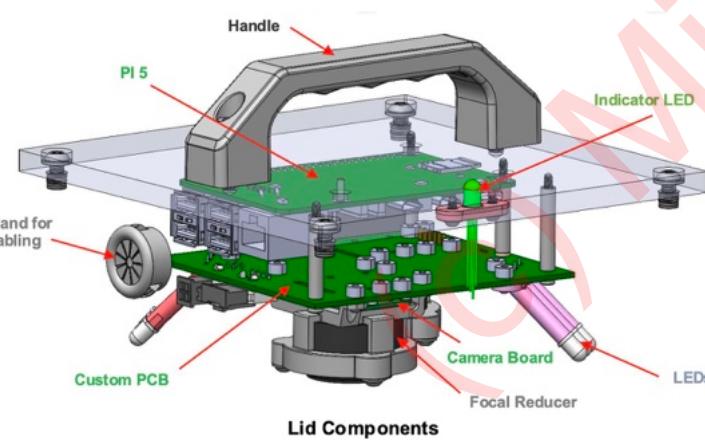
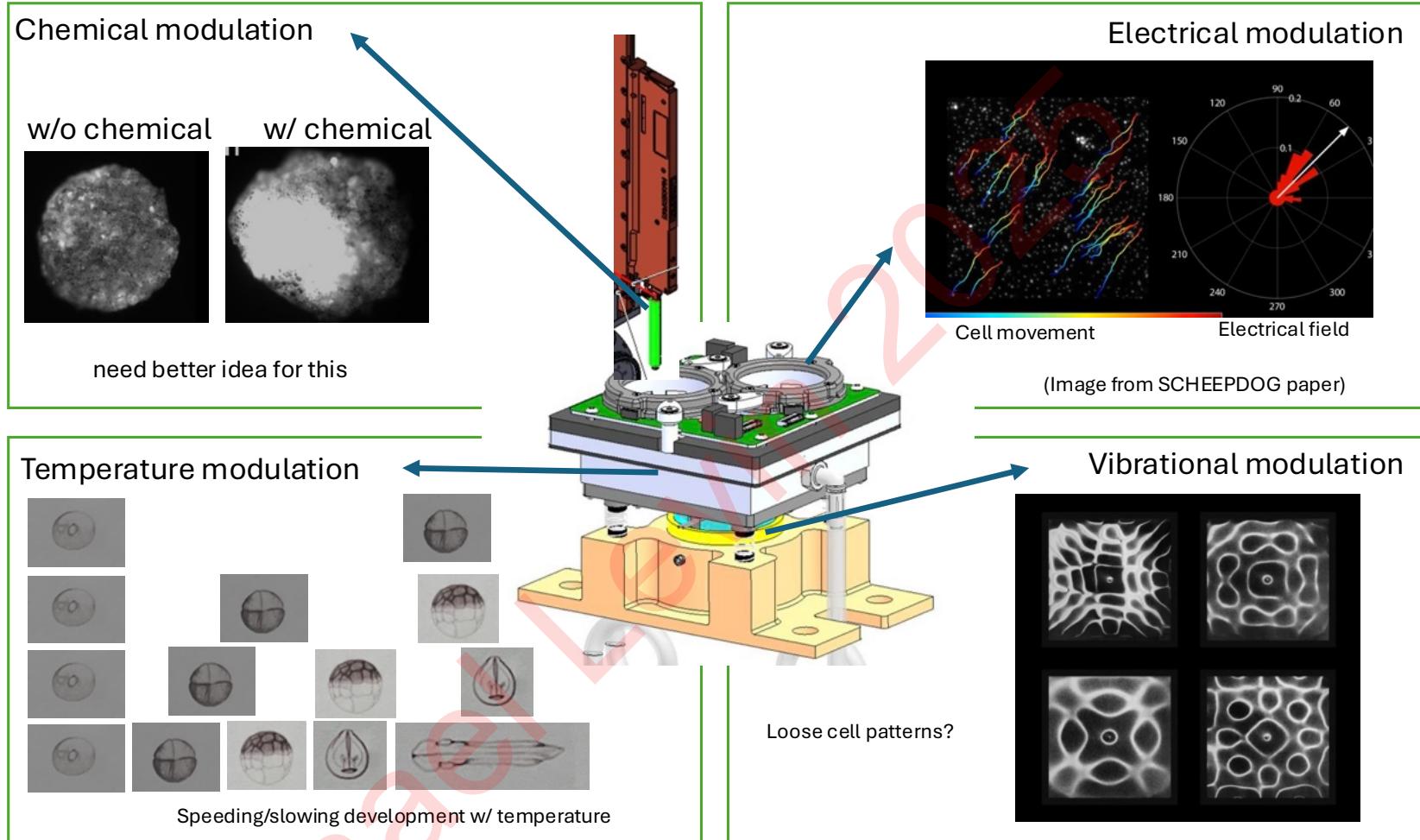
Automating the Search for New Prompts and Behavior-Shaping Stimuli



discovery engine for communication, collaboration with agential materials

exploring the space of prompts

Boston Engineering



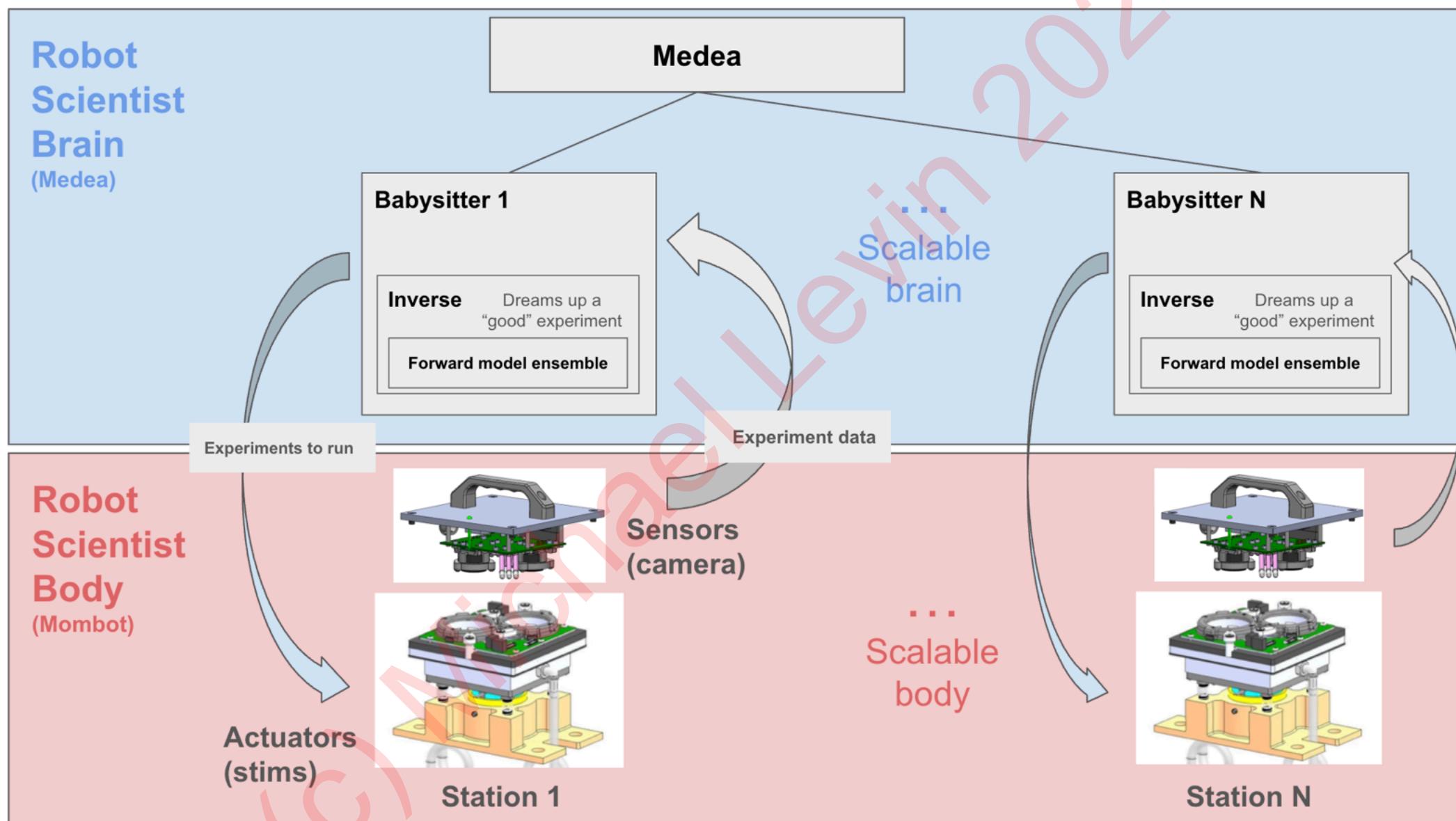
Introducing a new collaborator: an embodied AI scientist working in synmorpho



“MomBot”



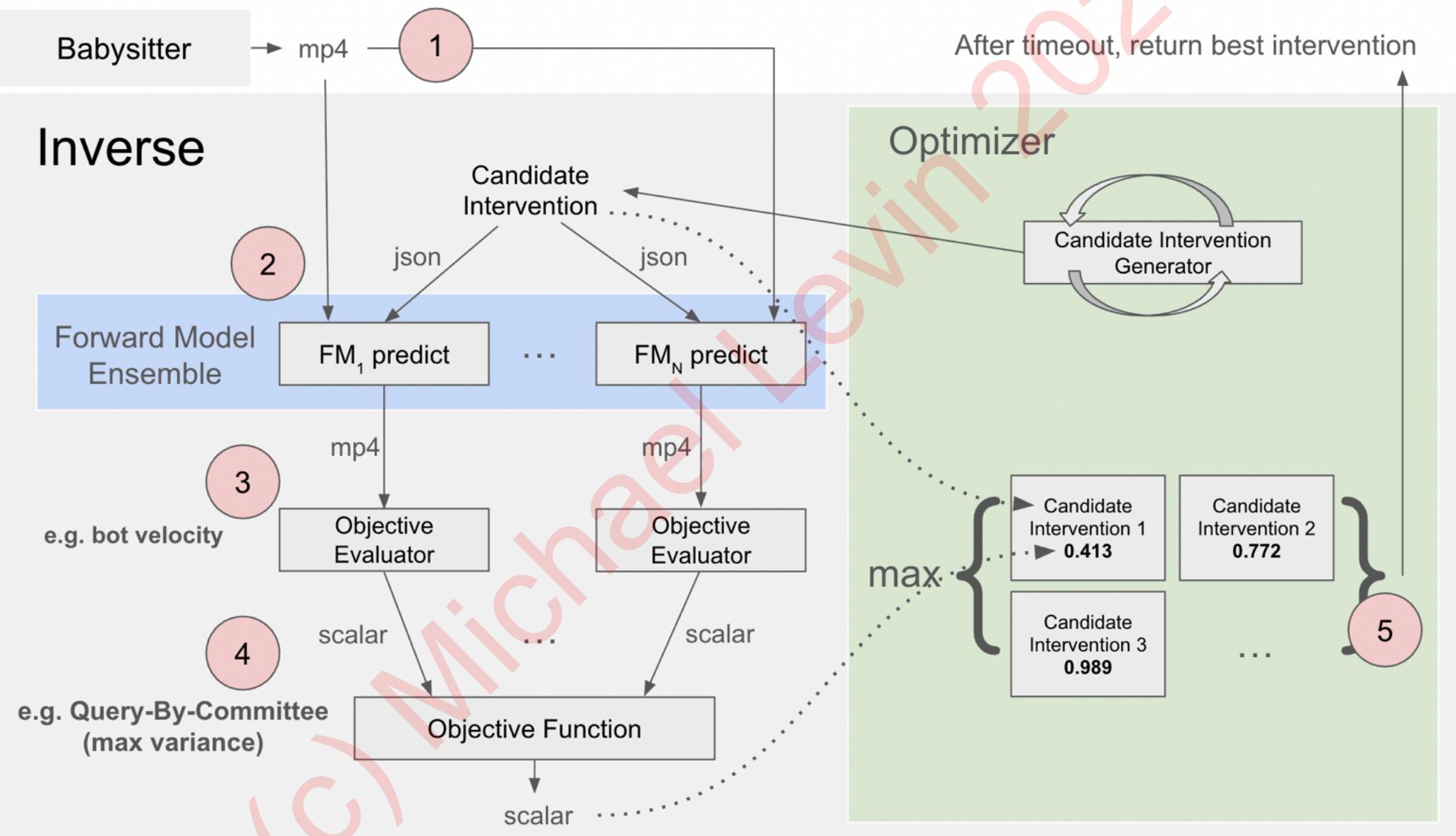
Introducing a new collaborator: an embodied AI scientist working in synmorpho



Like us, it has multiple concurrent cognitive sub-modules in its mind, and parallel, nested effectors in the body

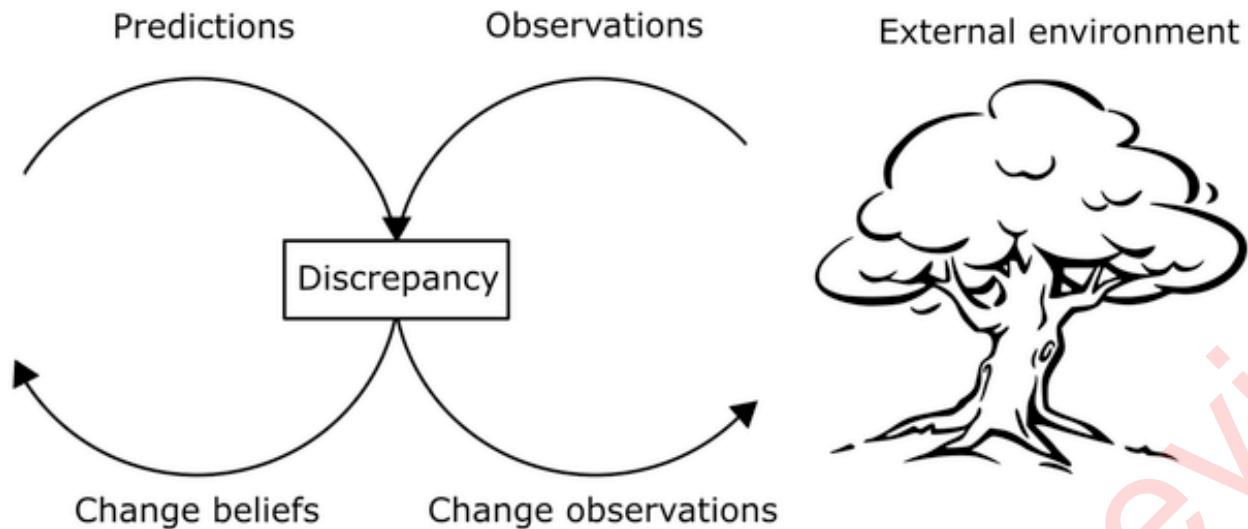
Kam Bielawski
(Bongard Lab, UVM)

Introducing a new collaborator: an embodied AI scientist working in synmorpho

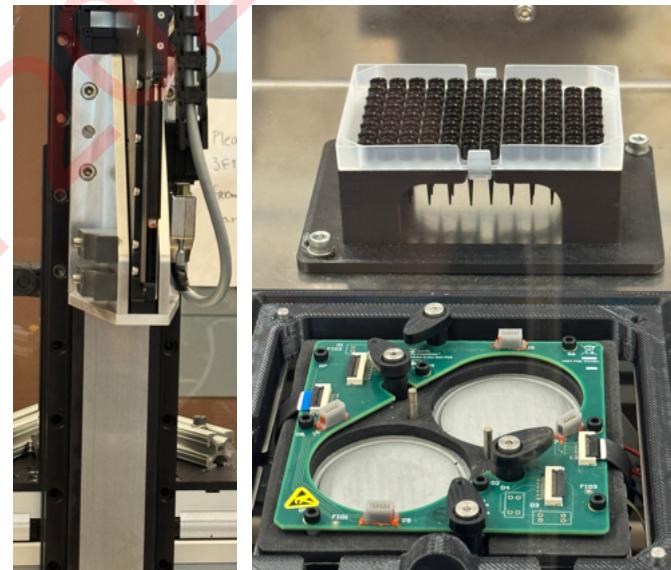


Infotaxis: it tries to do the most informative experiments to give it the most information based on priors

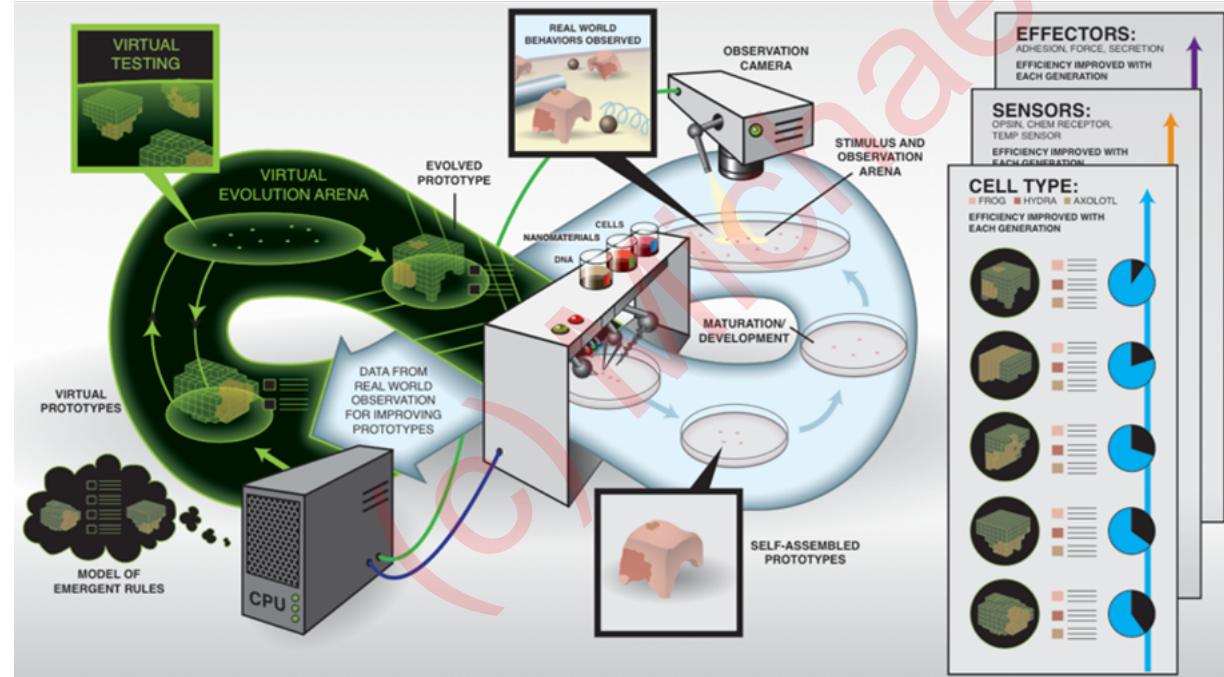
Multiscale Sensory-Behavior Loops



overall loop: sense/manage Xenobot form and function



inner loop:
sense
liquid and
manage
movement
of
materials



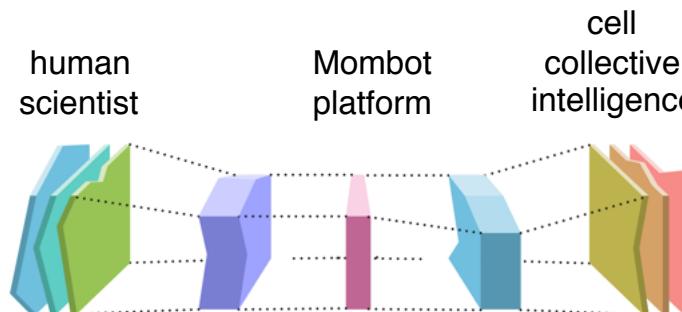
Next Steps:

- Discovery engine - new Xenobots
- Add meta-curiosity: find new problems to solve, not just solutions
- Ask the Xenobots what they want - from instrumental learning of frog tissue to a hybrid system (we, MomBot, Xenobots) in which an agential material actively collaborates with its environment (the MomBot) to shape its embodied mind and their future evolution

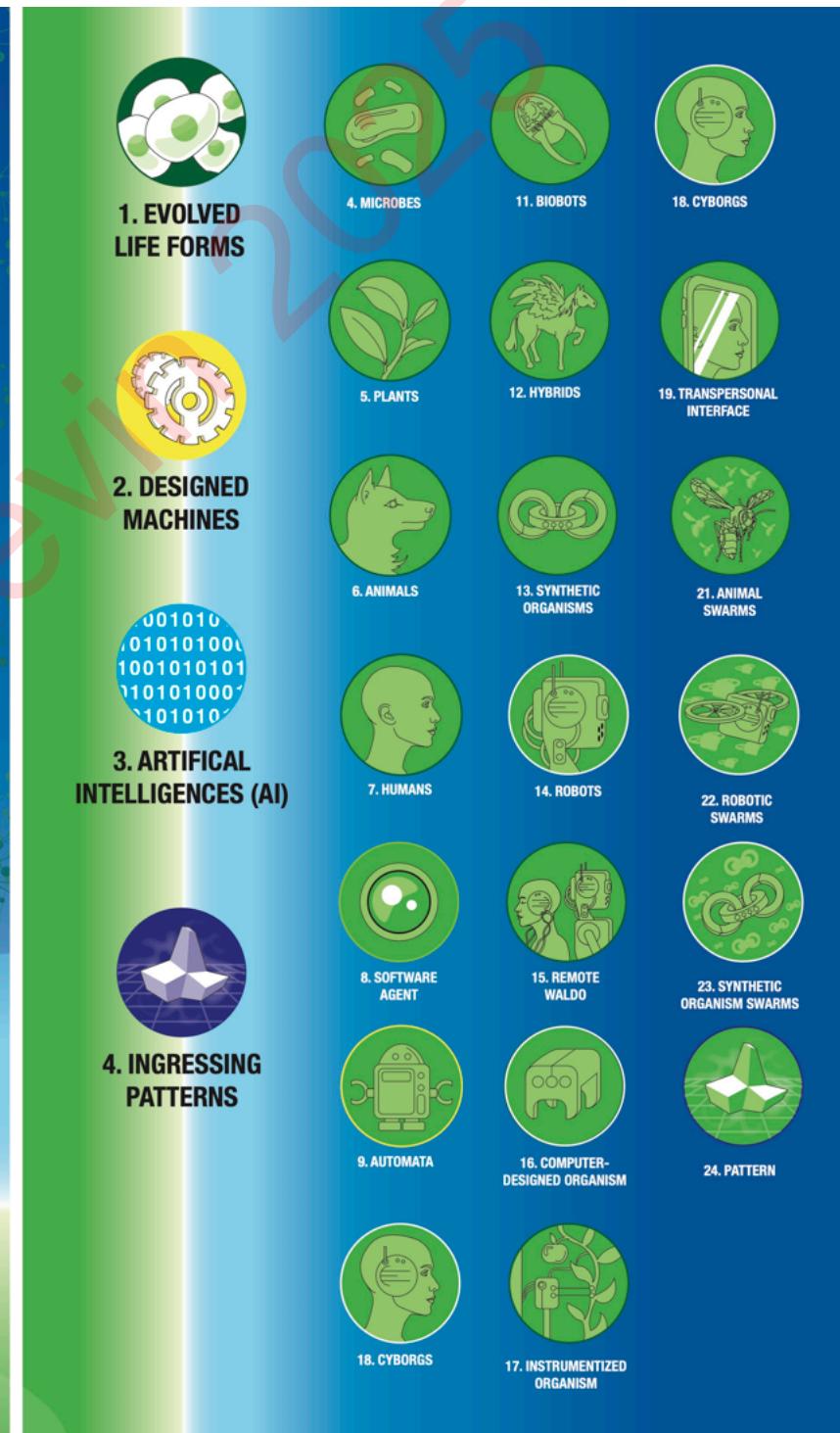
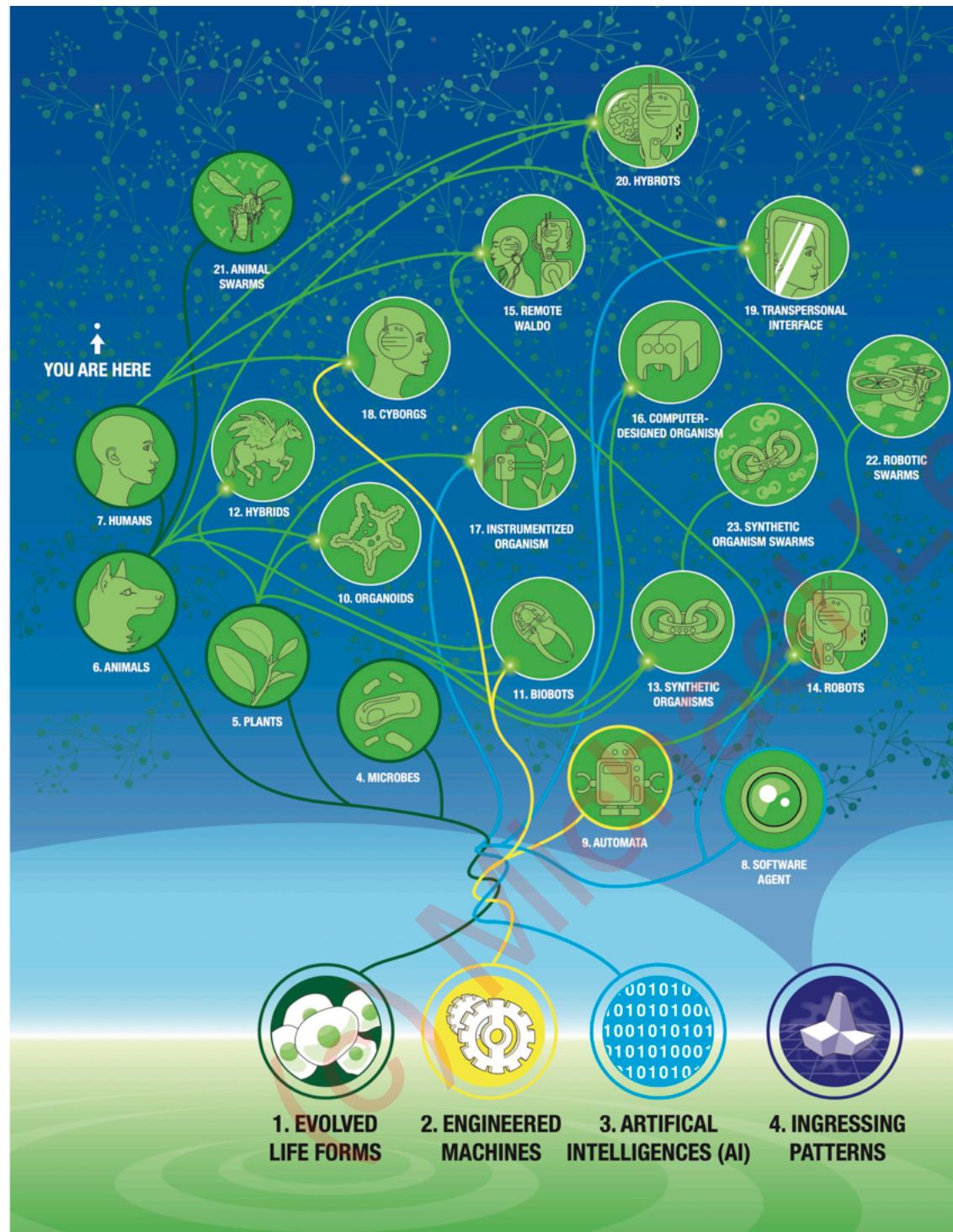
Future Impacts of this Approach:

- Useful synthetic living machines
 - In-the-body repair
 - Environmental cleanup
 - Exploration
- Robot science to crack morphogenetic code
 - Regenerative medicine - injury, birth defects, aging, cancer
 - Bioengineering, synmorpho -> anatomical compiler
- Tools to communicate with unconventional minds
 - Recognize diverse intelligences
 - Communicate with novel embodied minds
 - Be *part of* composite new systems

Discovery automation →
Anatomical Compiler →
Communication to Alife/DI

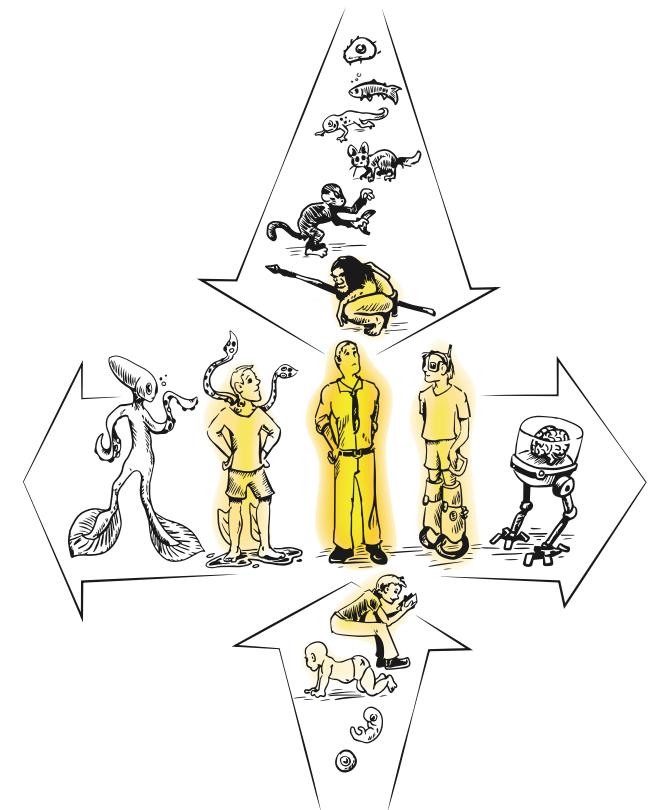
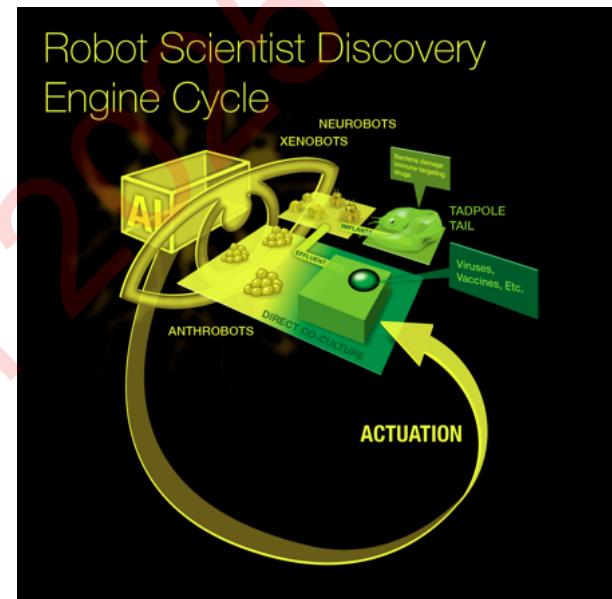


“Endless Forms Most Beautiful” \longleftrightarrow ethical synthbiosis



Main Points:

- Morgan's Canon is an off-ramp for science and engineering; we cannot simply “skew low” for intelligence
- Symmetry between individual cognition and science:
 - process of self- and world-discovery
 - new perspectives on, and by, new minds
- Develop tools to
 - rigorously define kinds of minds on the spectrum of persuadability
 - communicate to them via interfaces
 - develop new ethics for relating to radically different beings - **synthbiosis**
- AI/ALIFE + agential materials = future



Thank you to:

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Vaibhav Pai - voltage gradients in eye/brain induction and repair
Tal Shomrat - planarian memory
Nestor Oviedo, Junji Morokuma - planarian bioelectric pattern memory



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Fallon Durant - planarian bioelectric pattern memory
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Maya Emmons-Bell - planarian barium adaptation



Josh Bongard



Kam Bielawski



Piper Welch



Shawn Beaulieu



Nate Gaylann



Krishna Sriniva...



Amanda Bertschinger Thomas Varley

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