

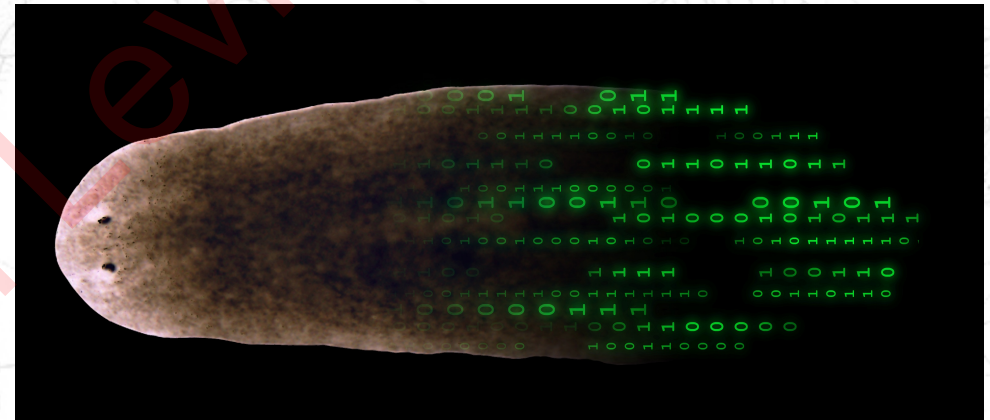
# The Embodied Mind of a New Robot Scientist:

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.drmmichaellevin.org/>

<http://thoughtforms.life/>



ALLEN  
DISCOVERY CENTER  
at Tufts University



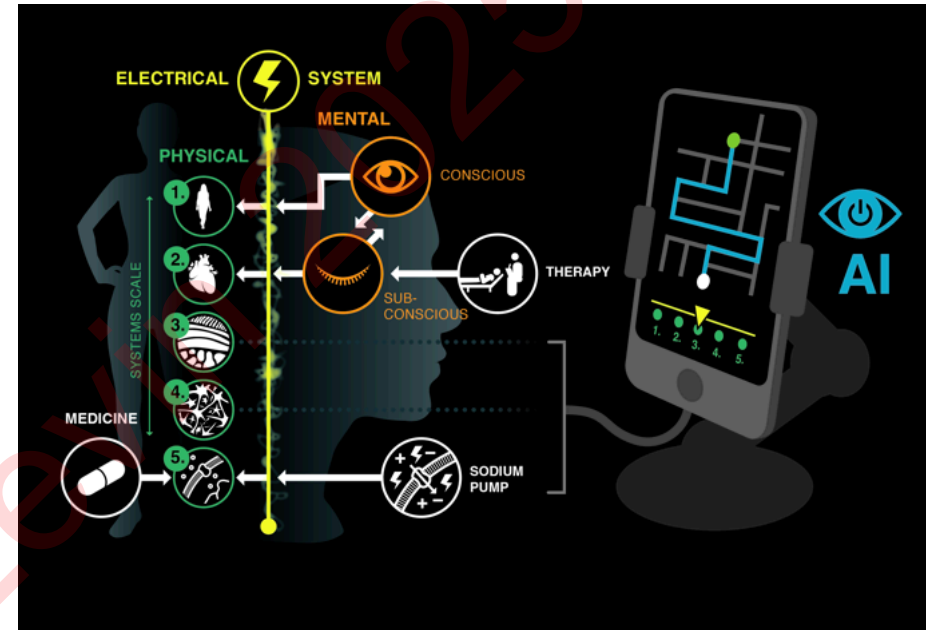
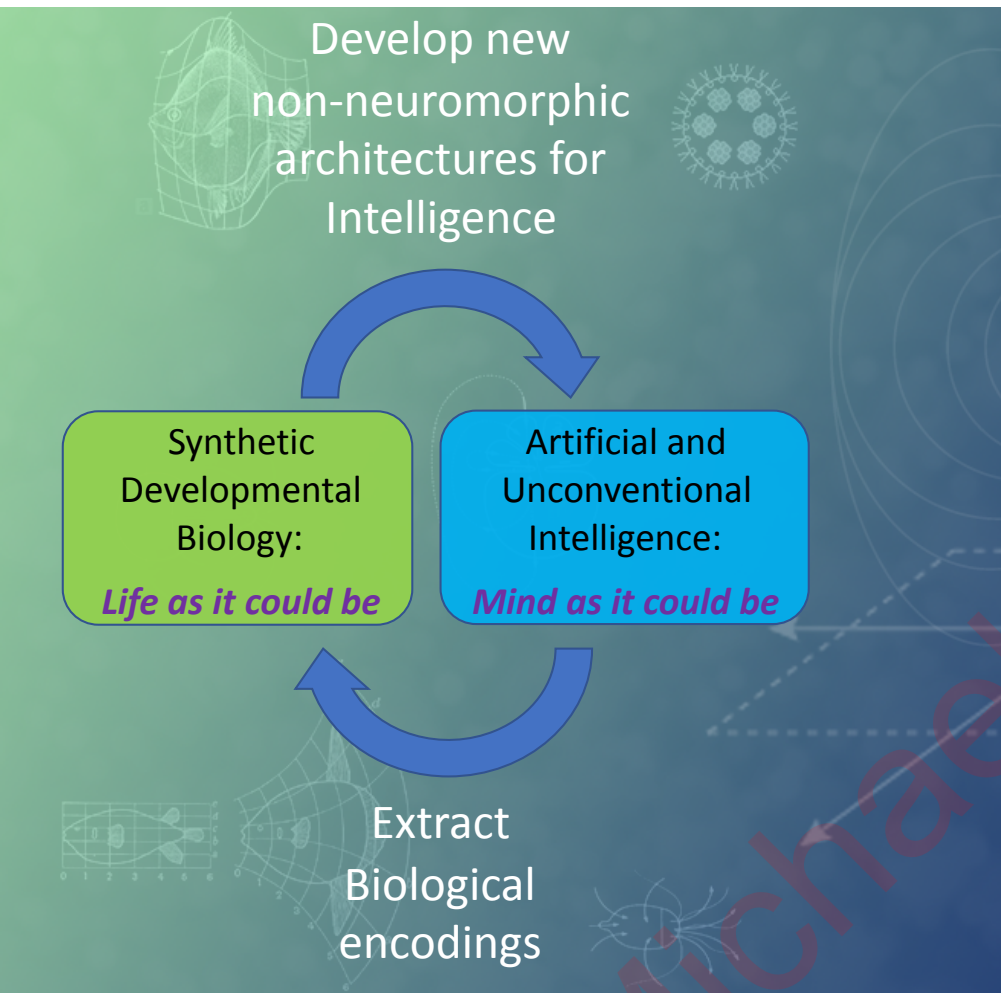
The Institute for  
Computationally  
Designed Organisms

Tufts University | University of Vermont

WYSS  
INSTITUTE



# Embodied Minds: engineering diverse intelligence

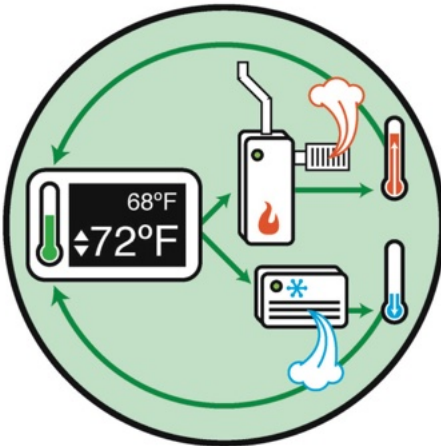


- goal: build tools to enable detection, communication, and ethical interaction with diverse intelligences
- model system: cell collectives navigating morphospace
- applications: regenerative medicine, synmorpho, AI/ALIFE

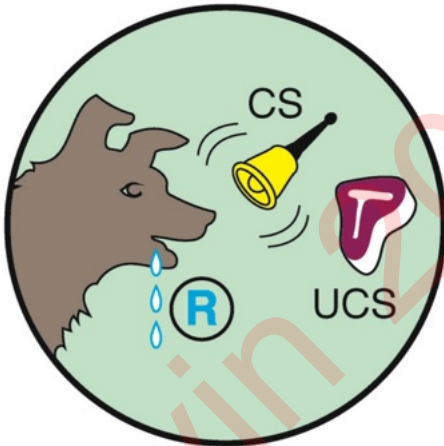
# Impedance Match Between Tools and What You Can See



Hardware  
modification only



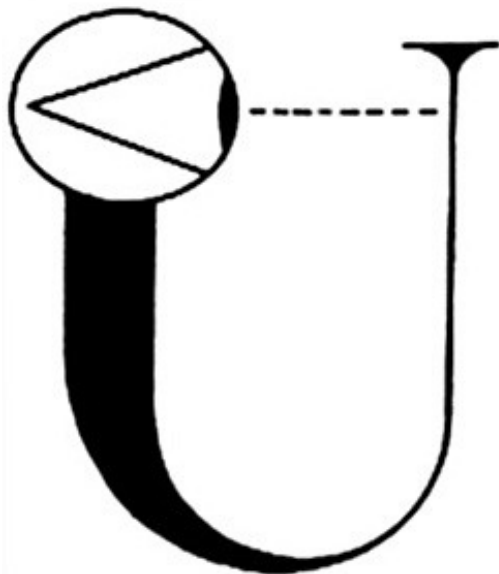
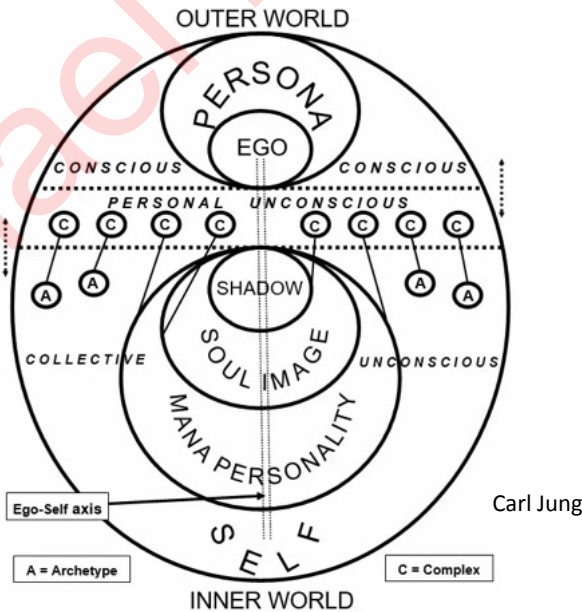
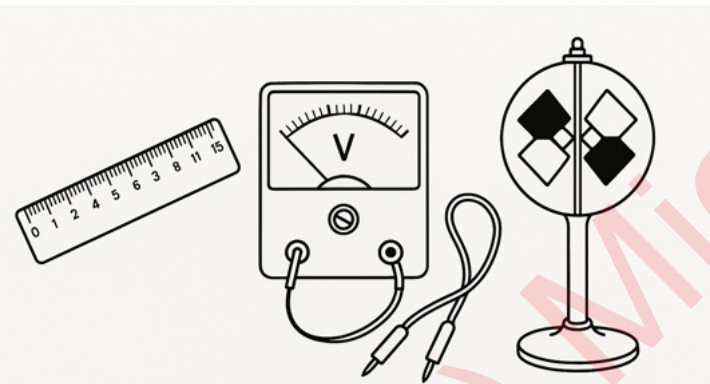
Modify the data encoding  
setpoint of goal-driven  
process



Training by  
rewards/  
punishments



Communicate  
cogent reasons

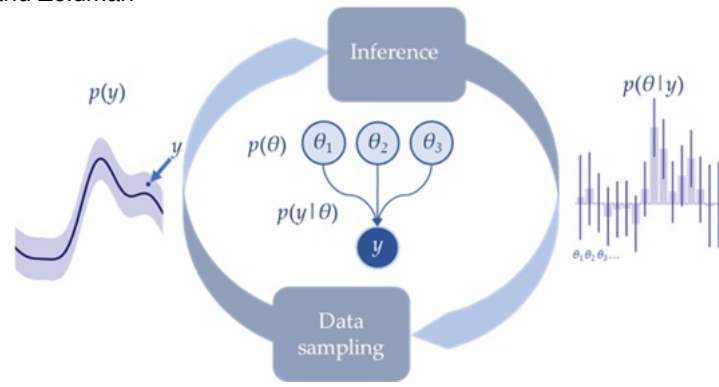


wheeler 1979

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

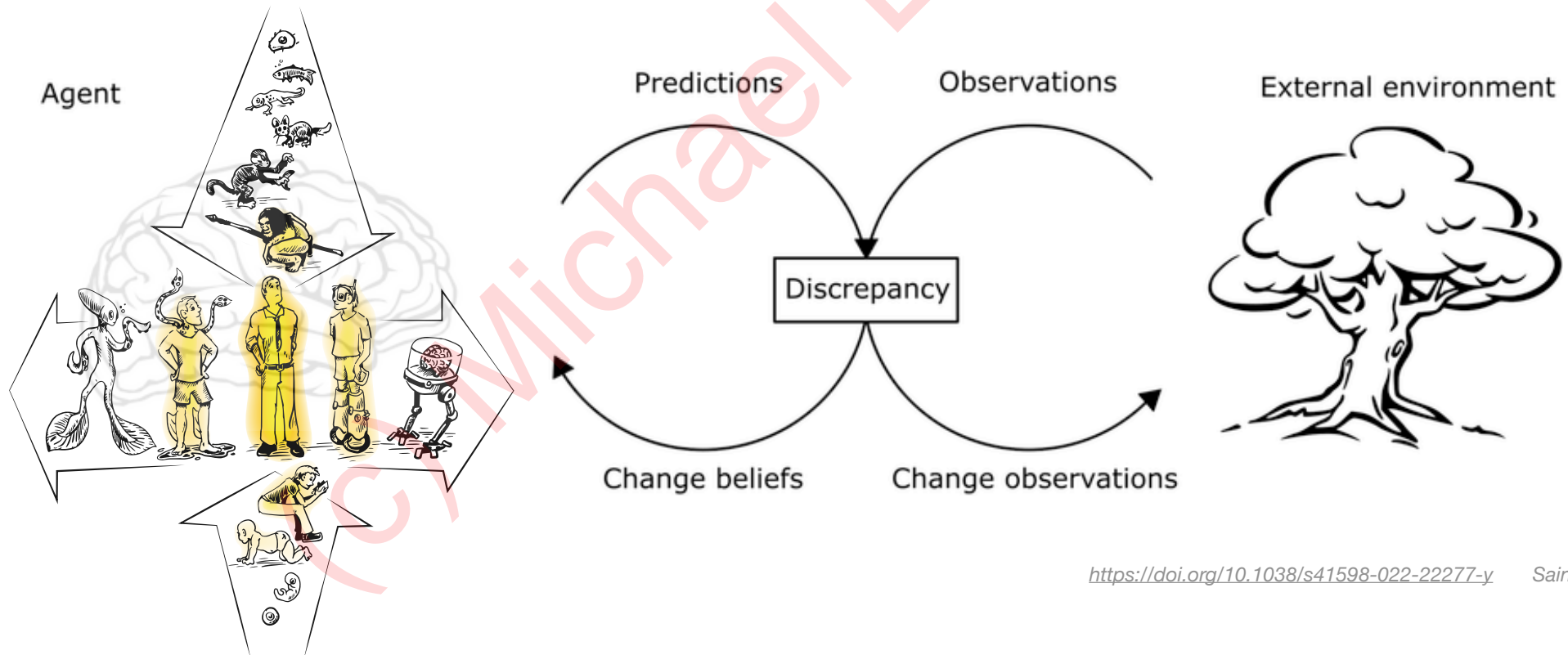
# Symmetry Between Scientist and World

Parr, Friston, and Zeidman

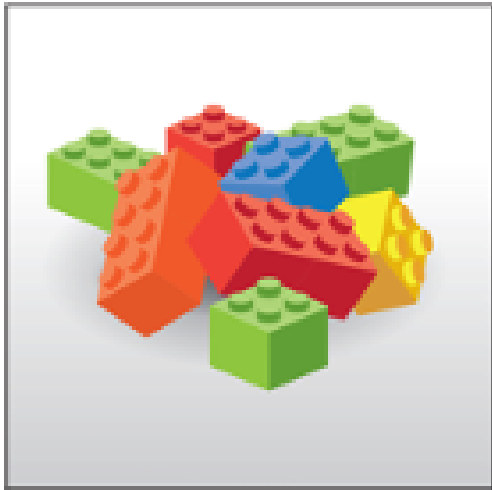


**Figure 1.** The active sampling cycle. This graphic illustrates the basic idea behind this paper. Analogous with action–perception cycles of the sort found in biological systems, it shows reciprocal interactions between the process of sampling data (in biology, through acting upon the world to solicit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

science as active  
inference



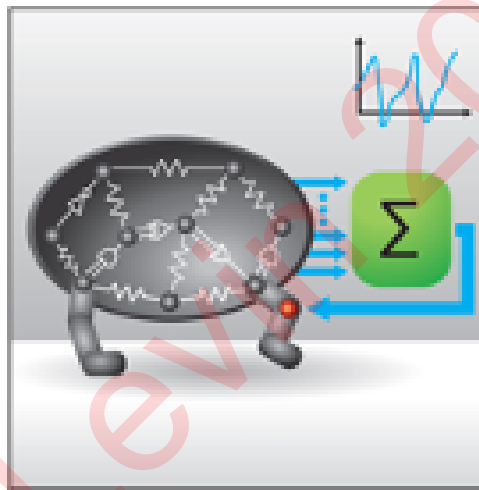
# Engineering with Diverse Substrates



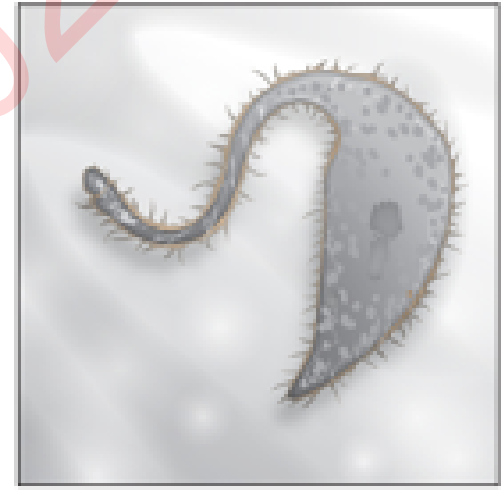
**Passive material**



**Active material**



**Computational material**



**Agential material**

Degree of agential material (from engineering perspective):

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

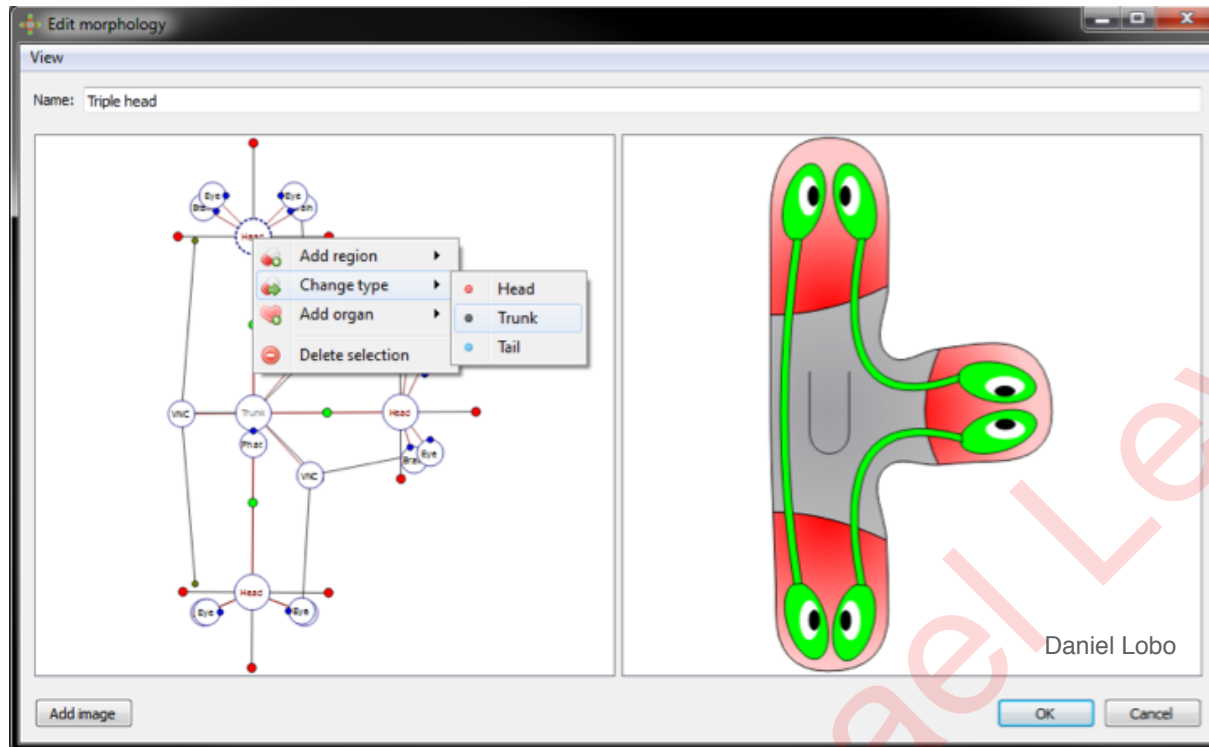
how much of the task is engineering vs. *reverse engineering*?

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**

# Biomedical Endgame: Anatomical Compiler



## Why we need it:

- Birth defects
- Traumatic injury
- Cancer
- Aging

how to control what  
cells will build?

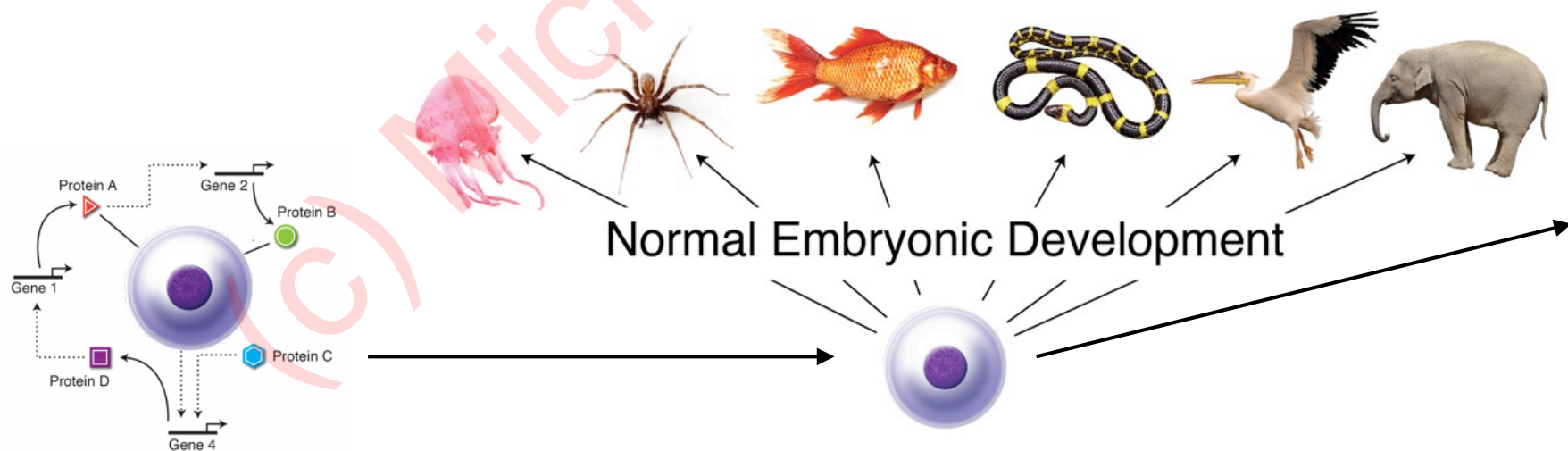
Anatomical compiler is *NOT* a 3D printer - it  
is a communications device (translator)  
because of agential material of life

# Agential Material of Life



Lacrymaria = 1 cell  
no brain  
no nervous system

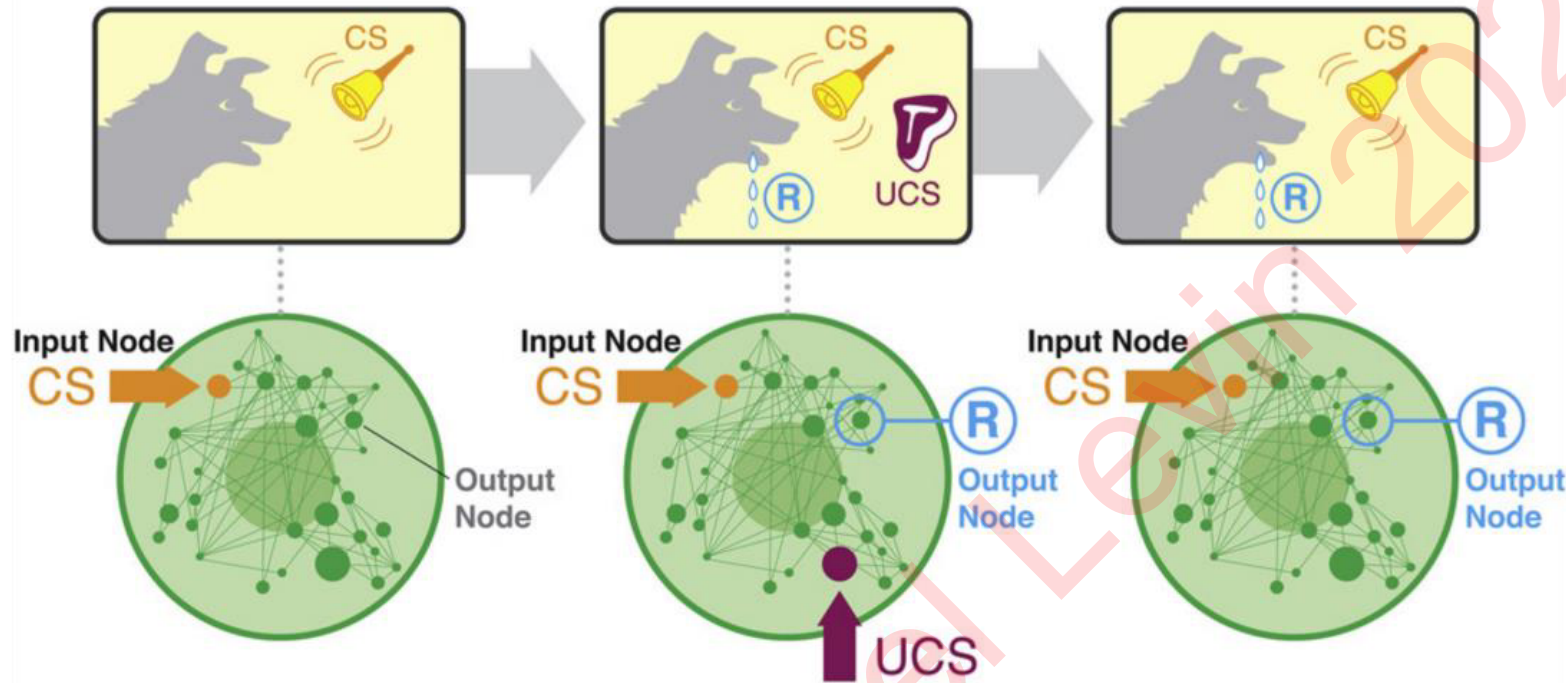
high competency  
at cell-level  
agendas



*Rene Descartes*



# Collective Intelligence Below the Cell Level



Biomedicine:

- drug conditioning




International Journal of  
Molecular Sciences



Article

## Learning in Transcriptional Network Models: Computational Discovery of Pathway-Level Memory and Effective Interventions

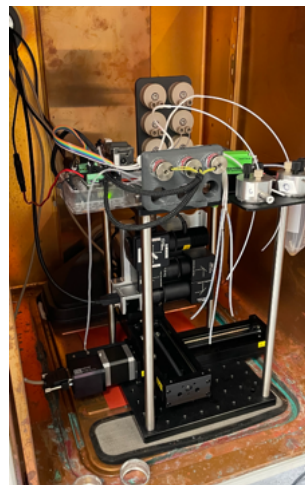
Surama Biswas <sup>1,2,†</sup>, Wesley Clawson <sup>1,†</sup> and Michael Levin <sup>1,3,\*</sup> 

iScience

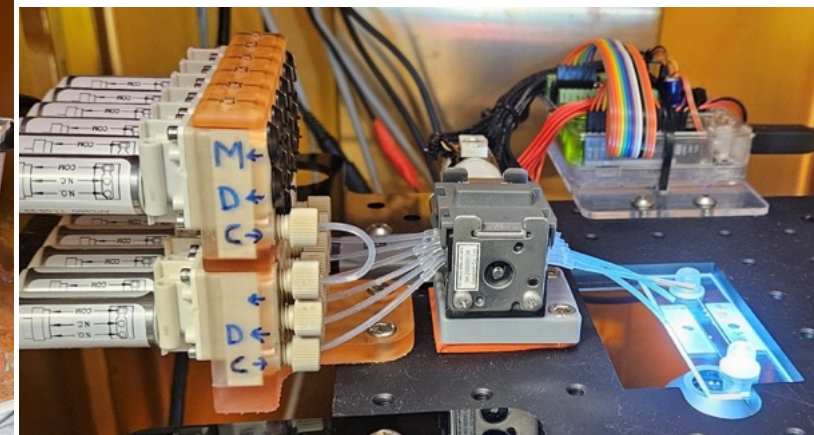
CellPress  
OPEN ACCESS

Article

Gene regulatory networks exhibit several kinds of memory: quantification of memory in biological and random transcriptional networks



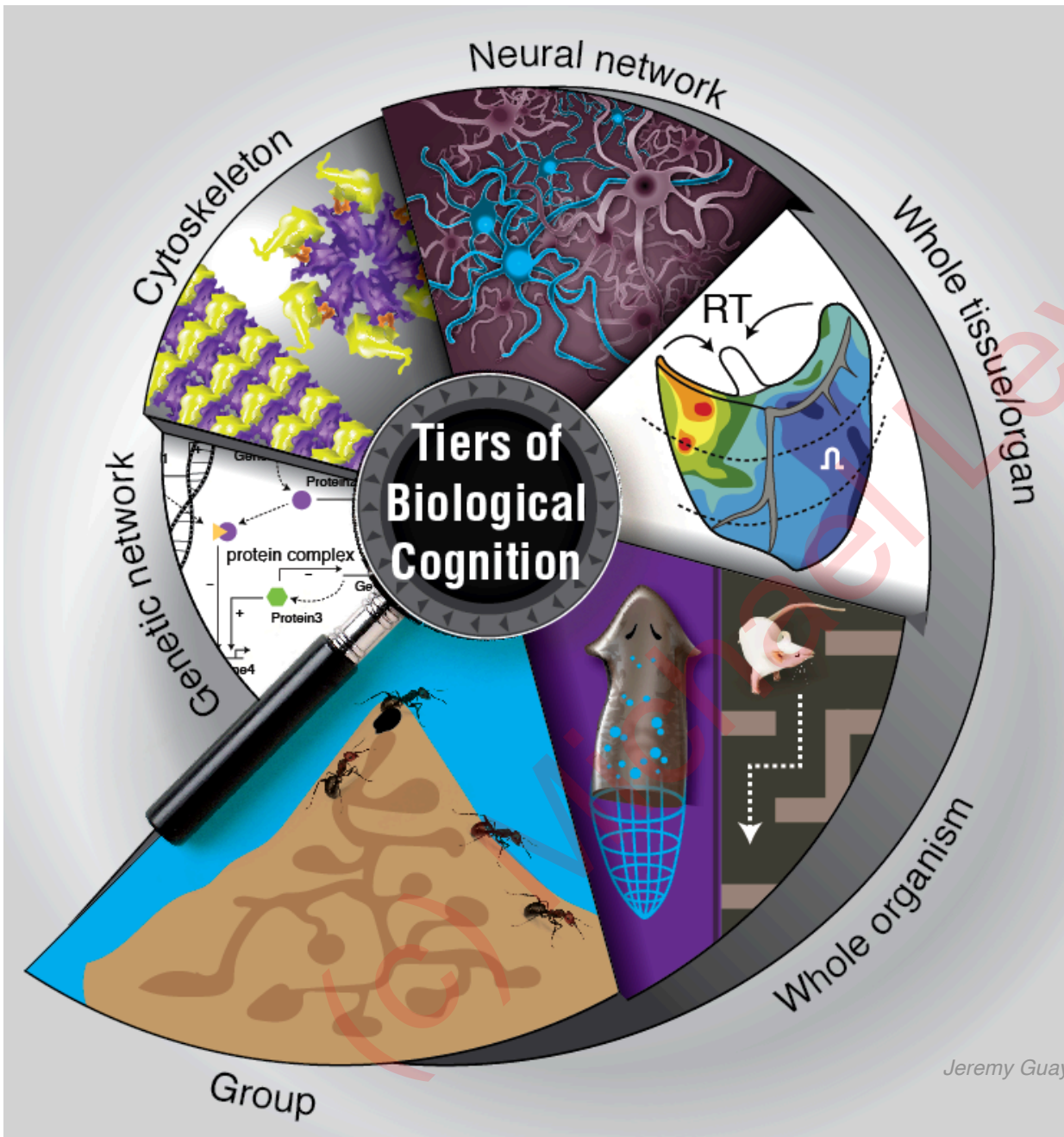
Patrick Erickson



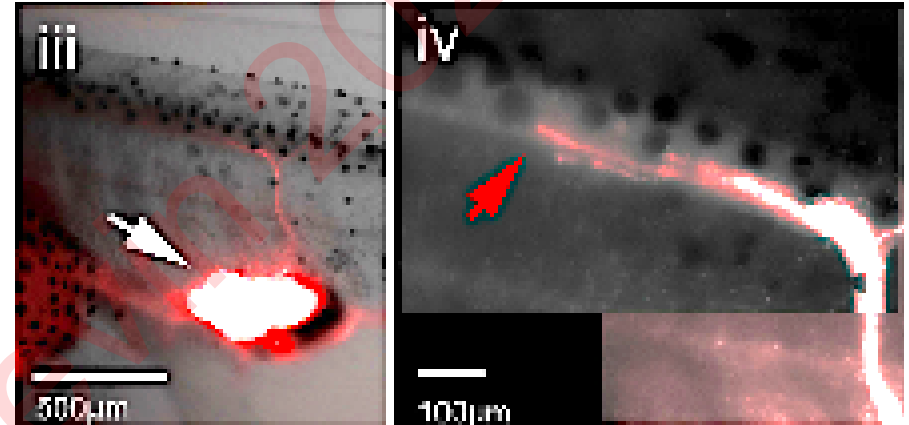
# Nested Cognition, not Merely Structure

## 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

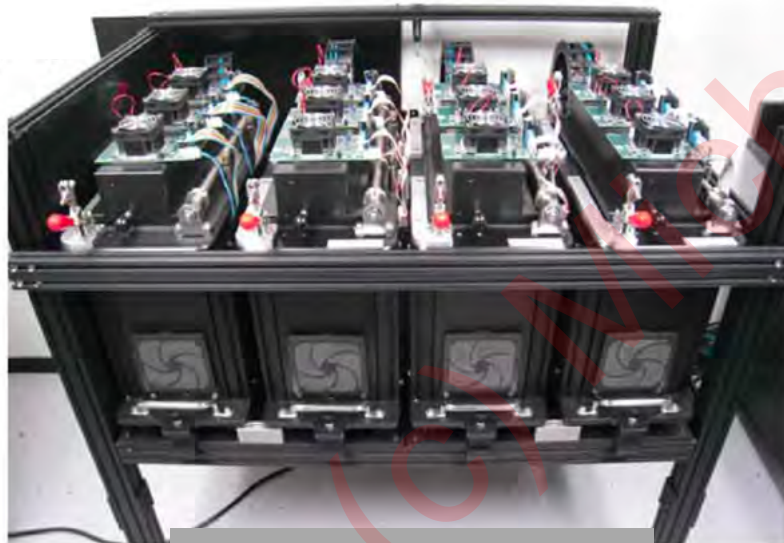


# On-the Fly Adjustment to Novel Architectures



Ectopic eyes on tail provide vision!

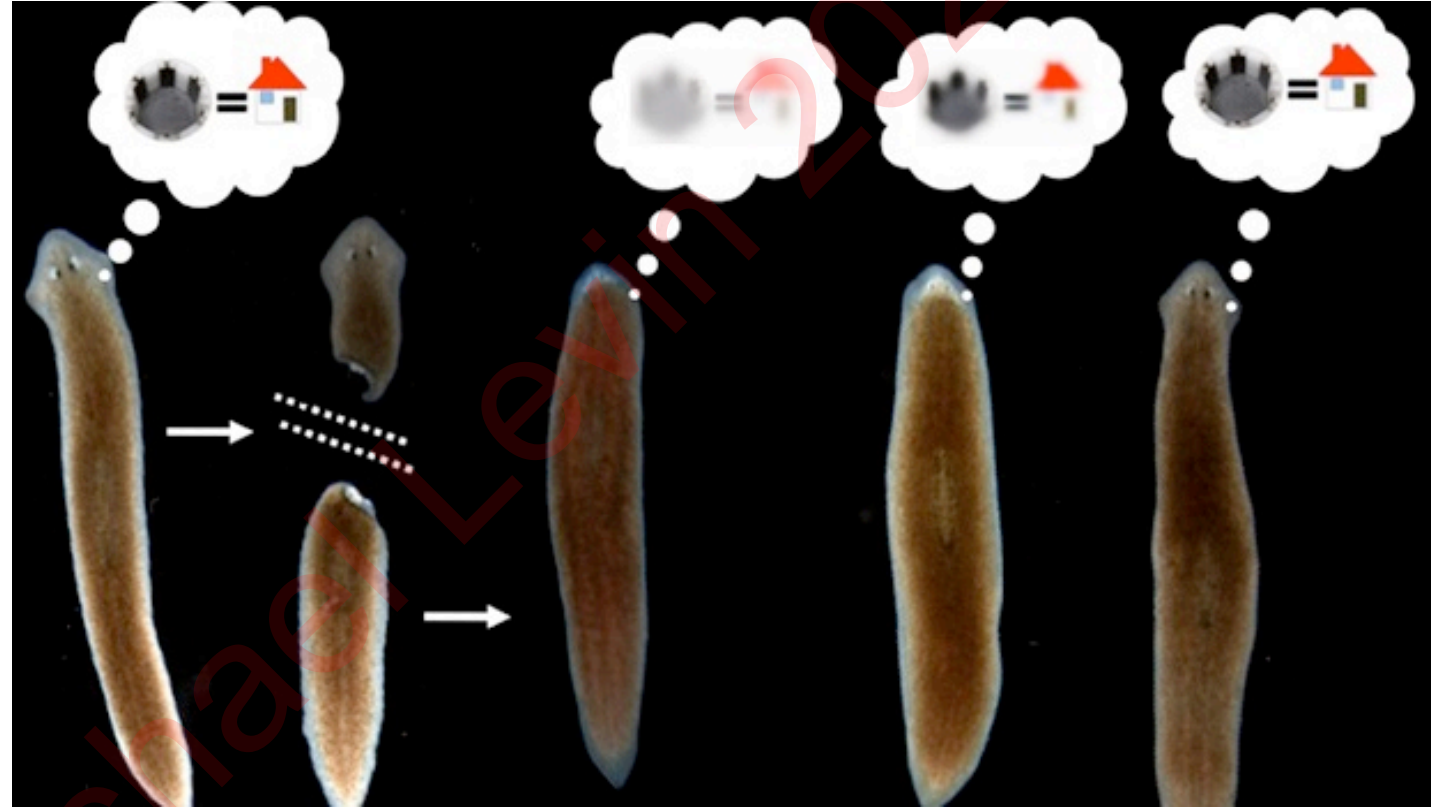
*Douglas Blackiston*



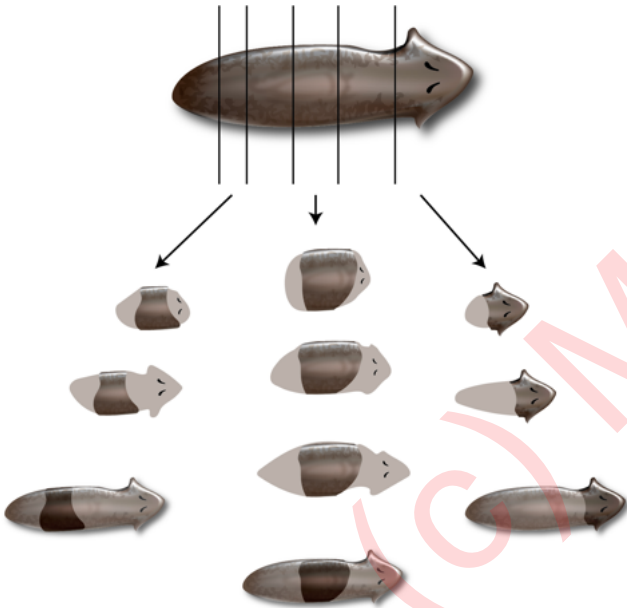
Behavioral Testing Device

**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

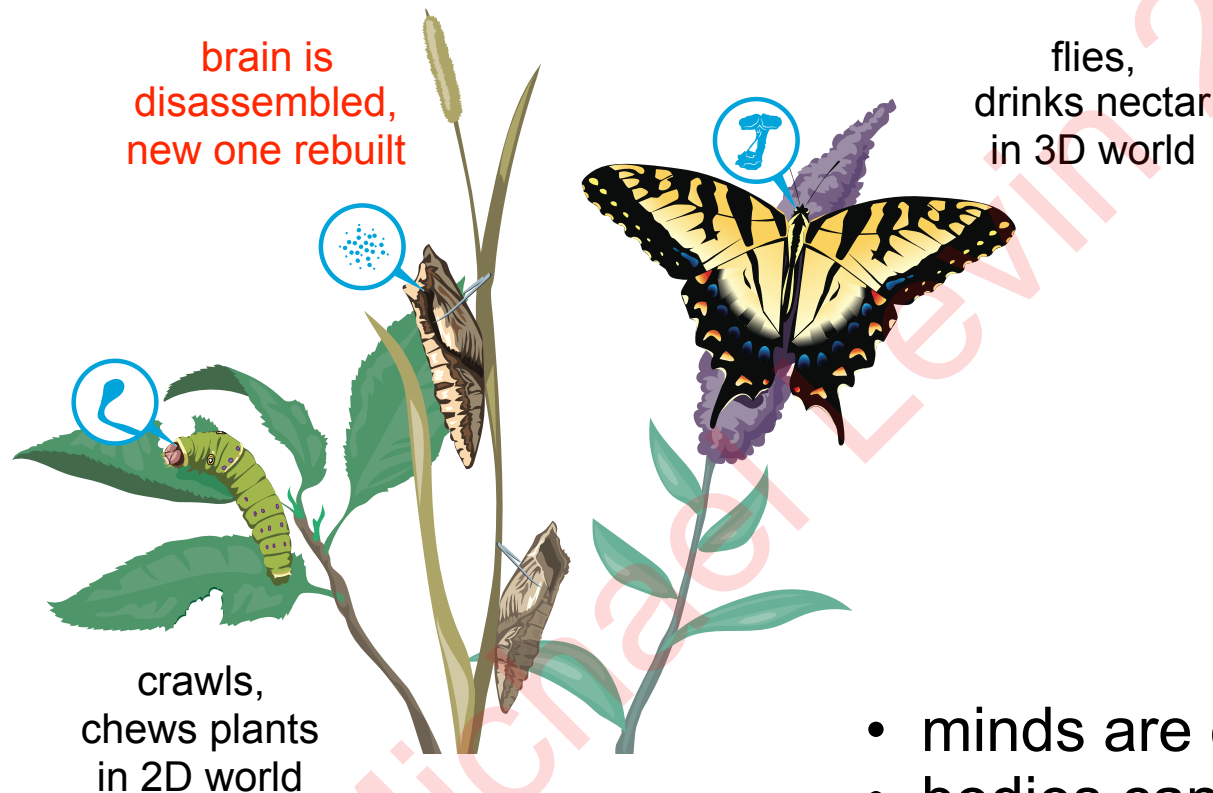


## HYPOTHESIS

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

Moran Neuhof<sup>1,\*</sup>, Michael Levin<sup>2,\*</sup> and Oded Rechavi<sup>1,2,3,\*</sup>

# 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?

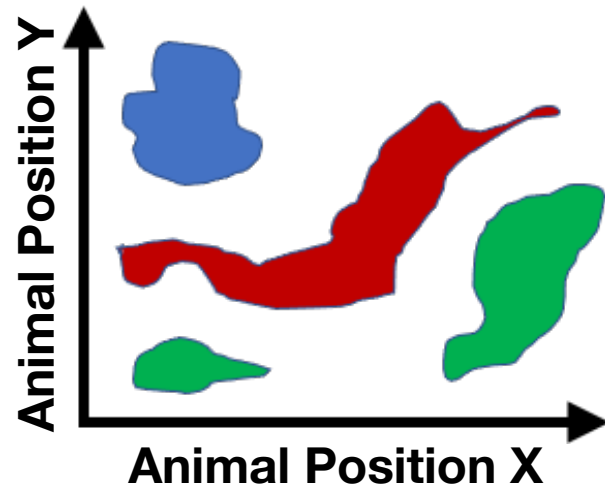
Communicative & Integrative Biology 8:5, e1073424; September/October 2015; Published with license by Taylor and Francis Group, LLC

**The stability of memories during brain remodeling: A perspective**

Douglas J Blackiston<sup>1</sup>, Tal Shomrat<sup>2,3</sup>, and Michael Levin<sup>1,\*</sup>

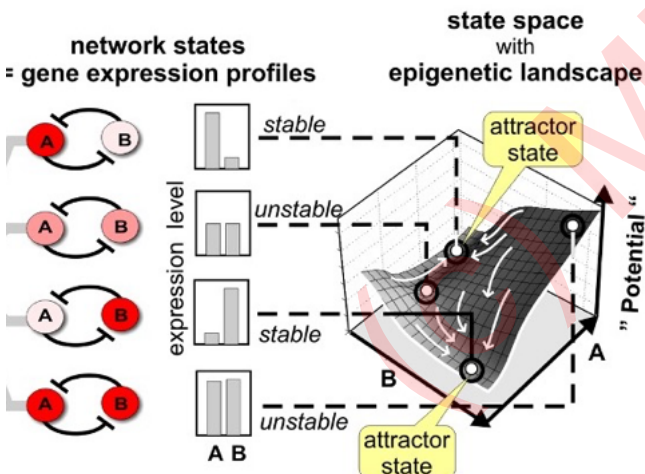
# Problem-solving in Diverse Spaces

## 3D Space (behavior)

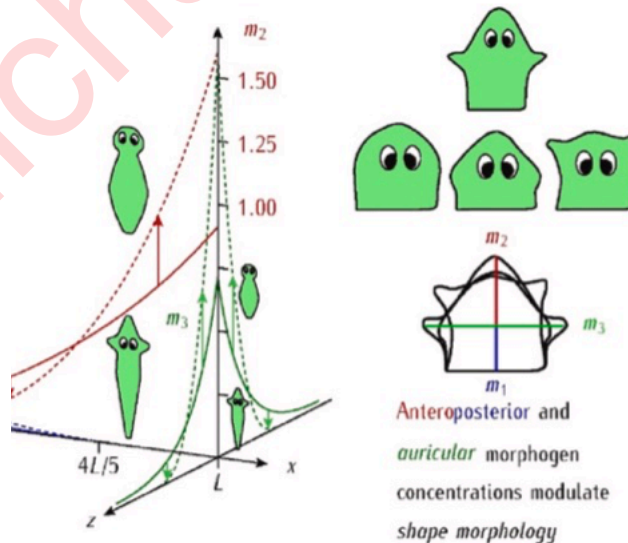


## Transcriptional Space

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

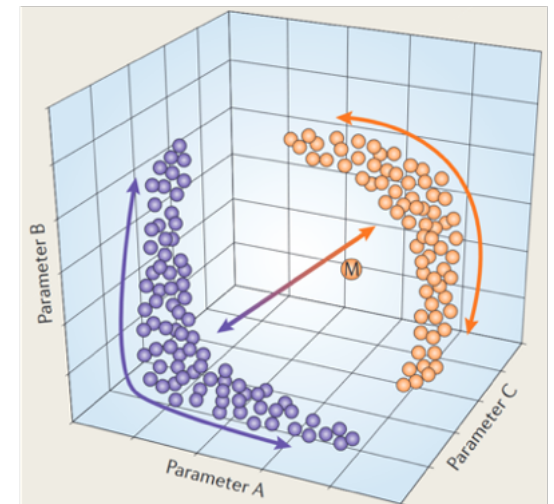


## Morphospace

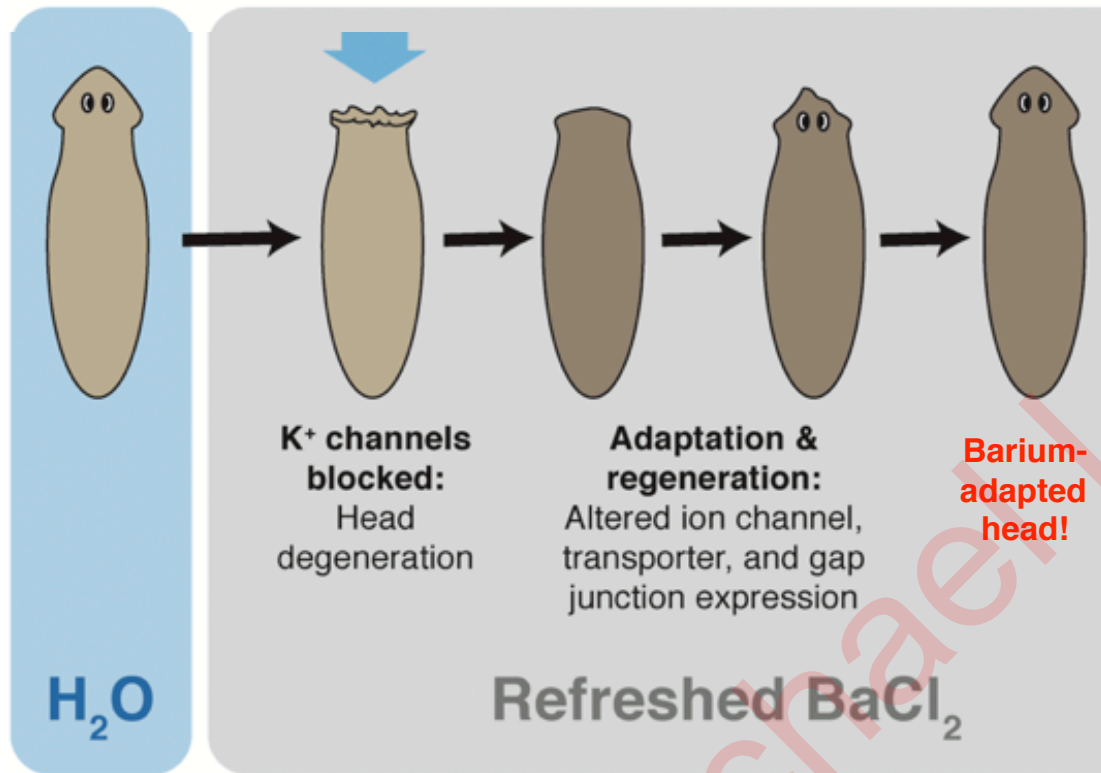


## Physiological Space

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

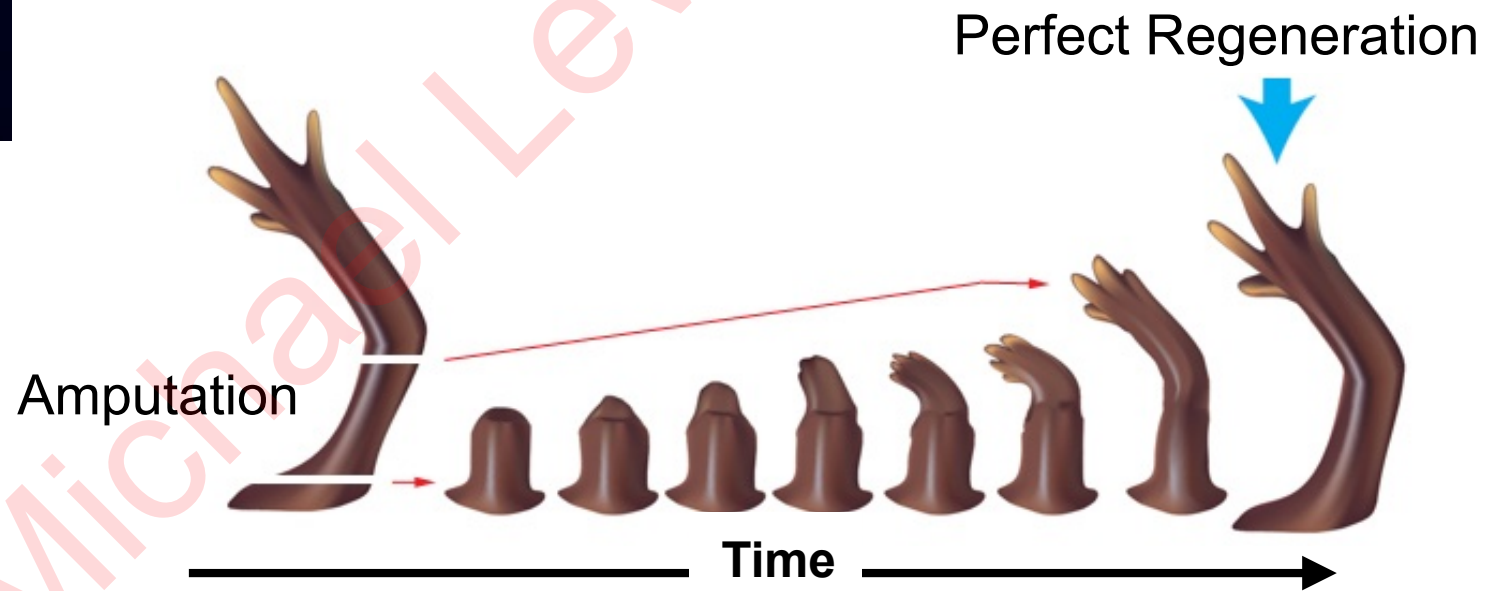


Small number of genes regulated out of entire genome! ~20K effectors



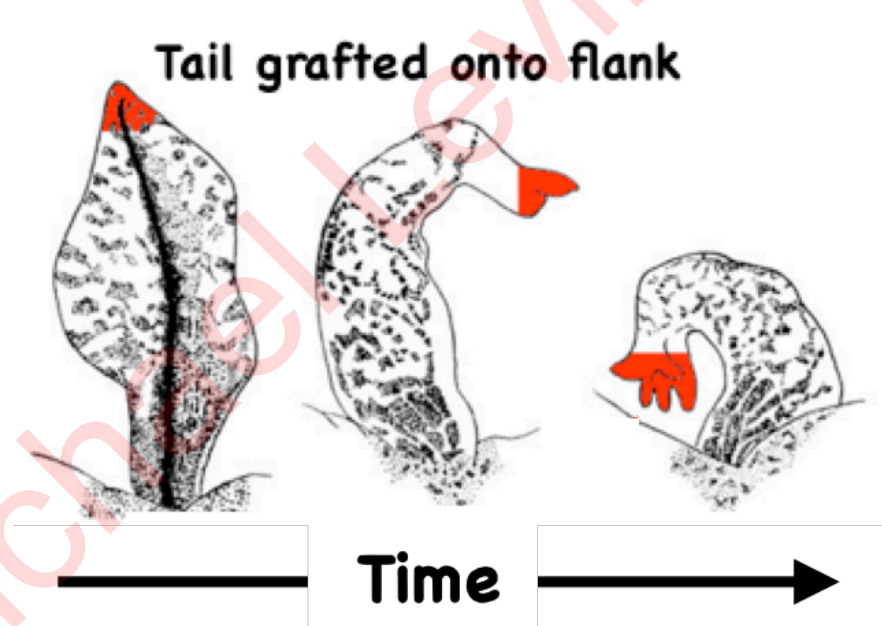
- planarian heads degenerate after exposure to barium
- planaria eventually adapt and regenerate heads that tolerate barium
- a relatively few transcripts were altered to produce barium tolerance
- how did the system choose exactly the right genes to modulate, to deal with this evolutionarily-novel challenge?

# 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

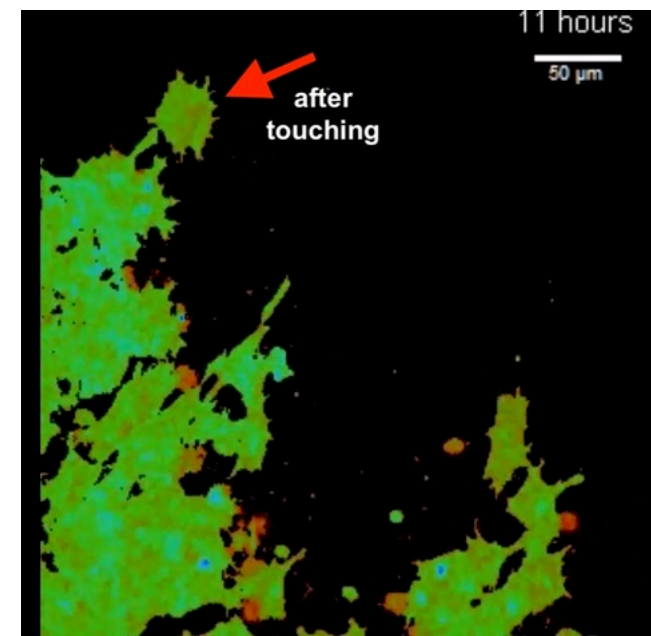
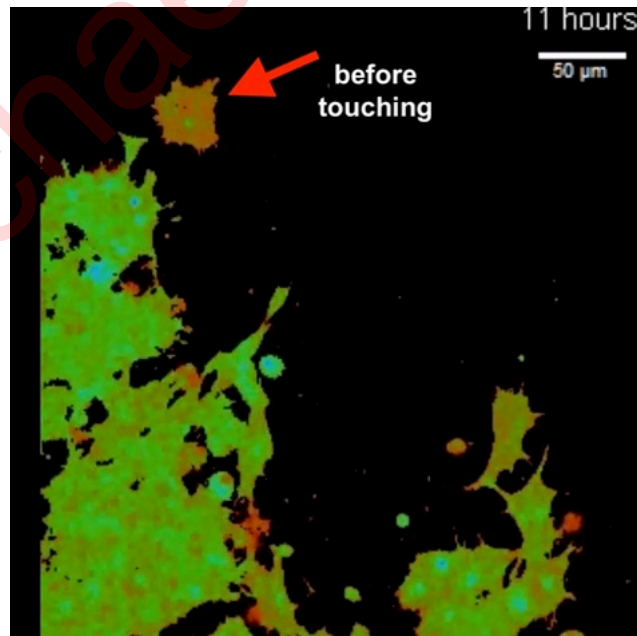
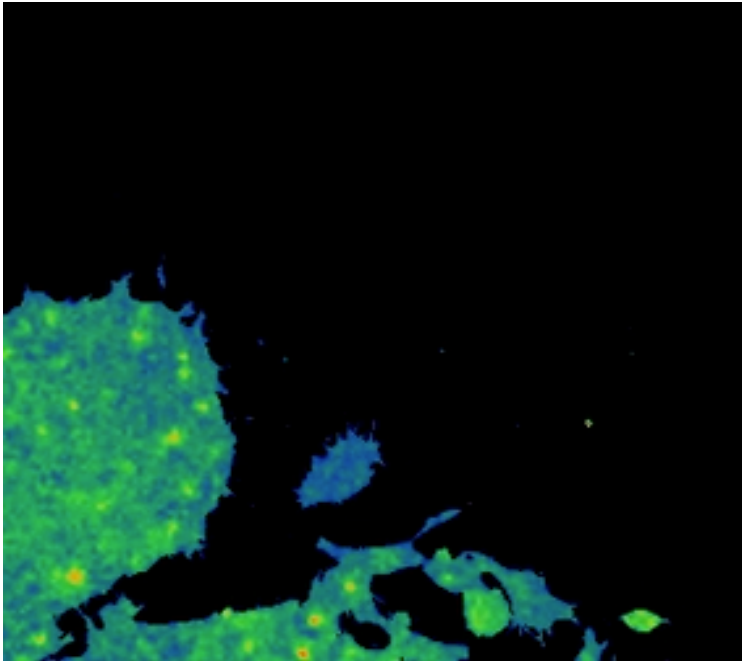


*Farinella-Ferruzza, Experientia, 1956 (15)*

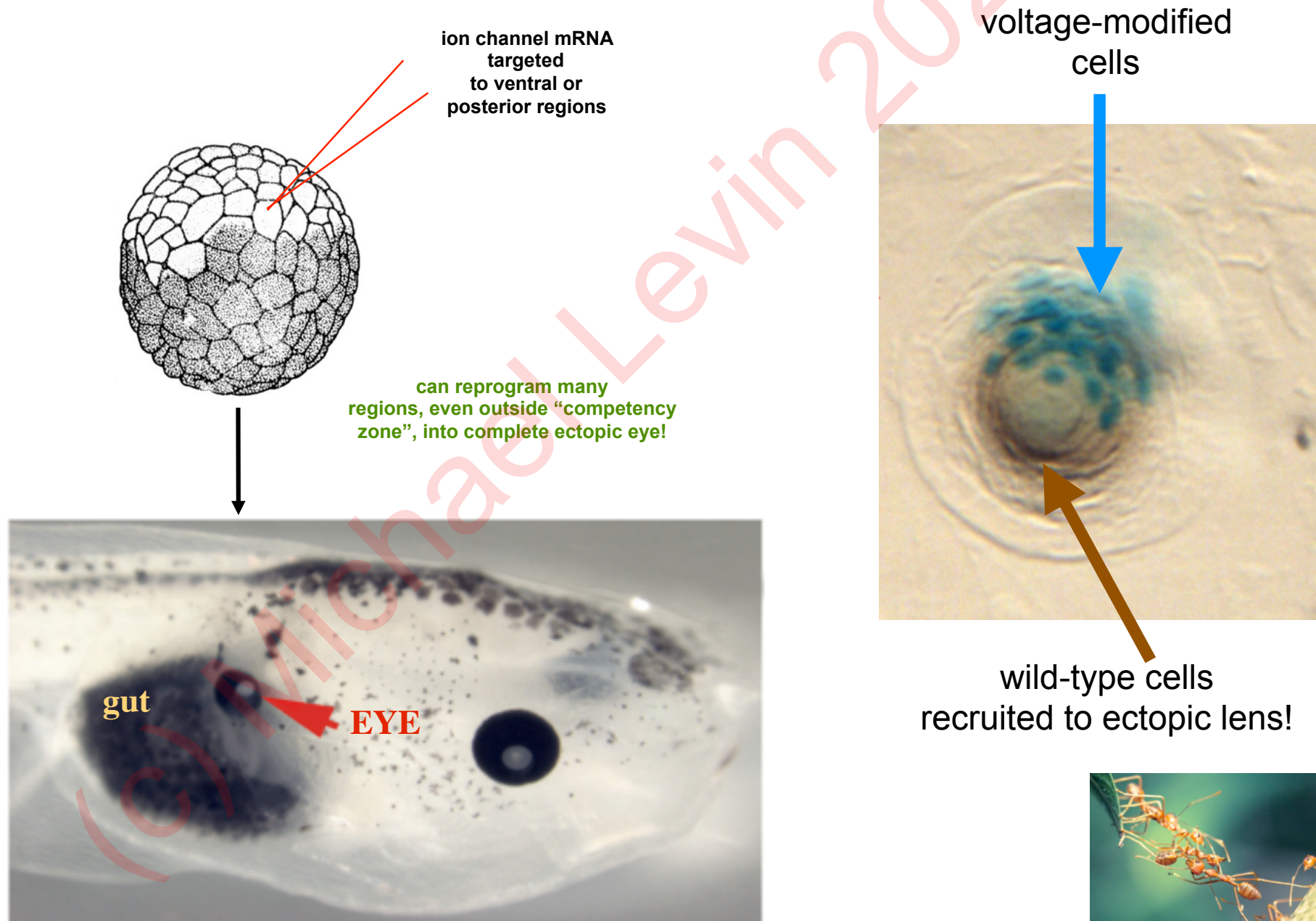
top-down control to  
align pairs to higher-  
order set point:

**local order obeys global plan**

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



# Bioelectric Interface to Agential Material: Self-scaling morphogenetic subroutines

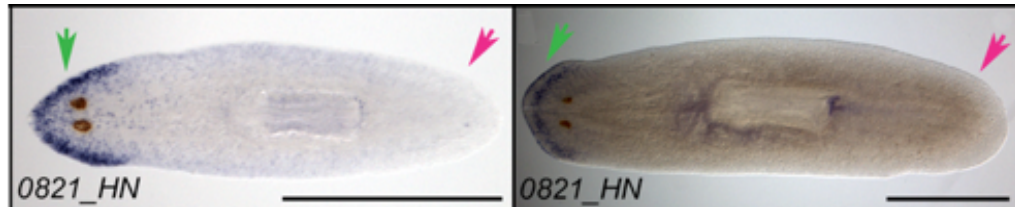


# Re-writing Anatomical Pattern Memory

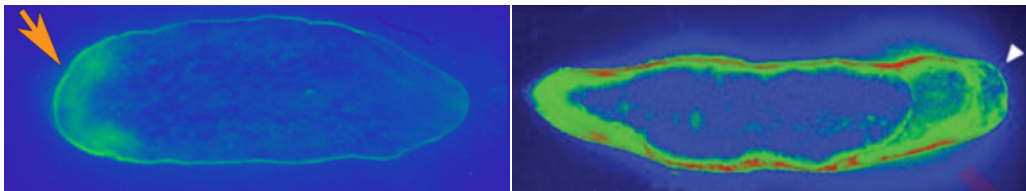


control worms

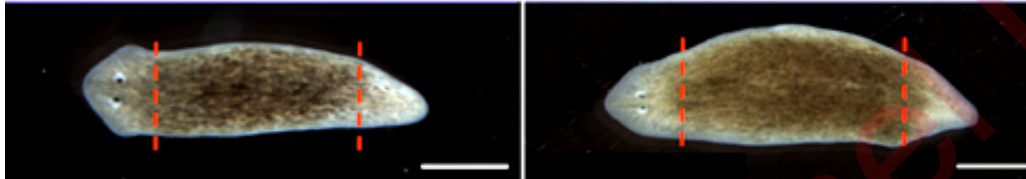
bioelectrically edited



normal  
axial identity  
gene expression



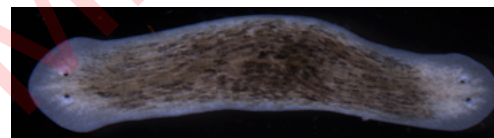
bioelectric  
pattern



normal anatomy

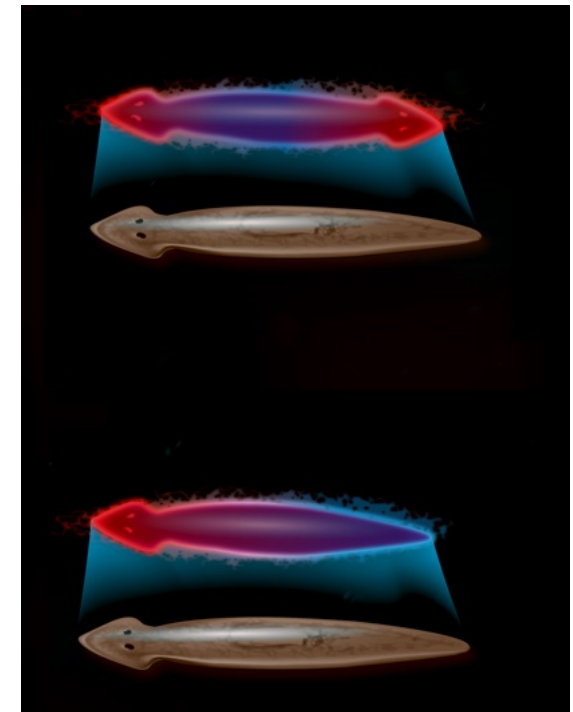


middle-third  
regenerates:



built anatomy  
after cutting

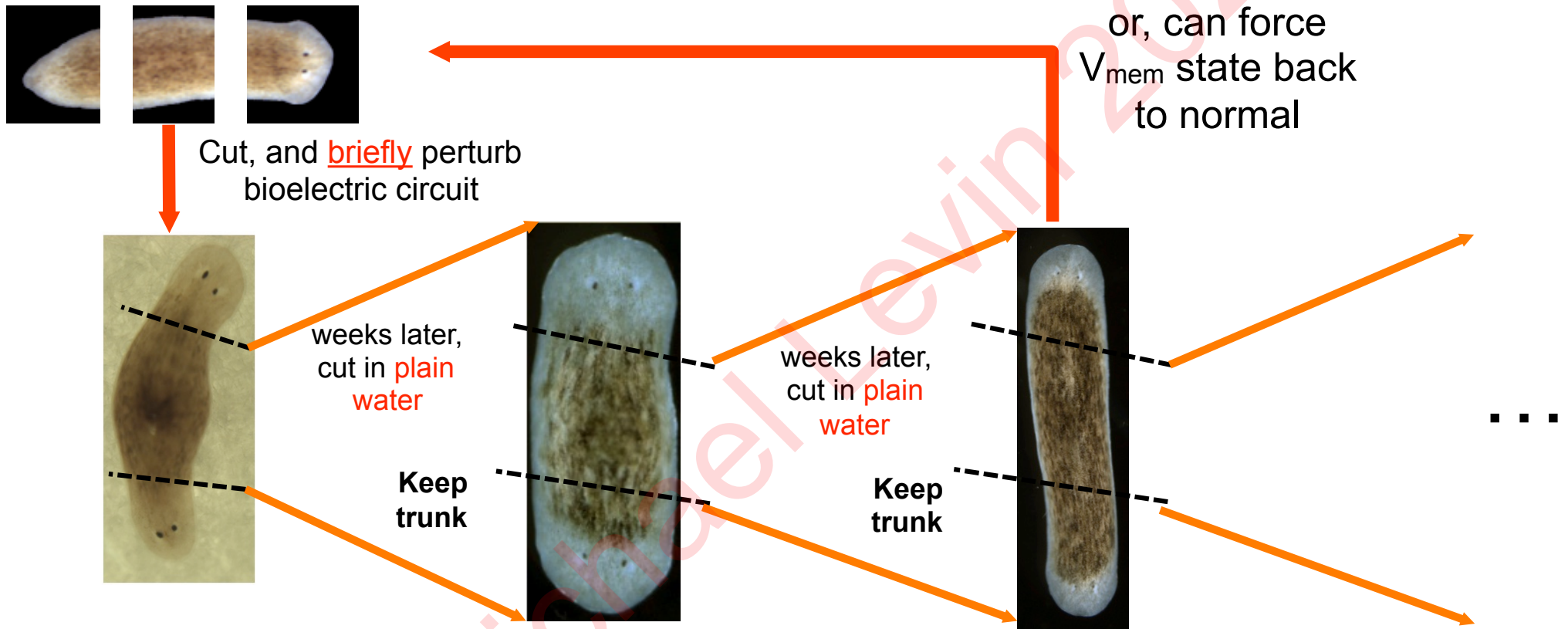
The Same Body can Store different  
Electrical Pattern Memories



*Fallon Durant*

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*



# **Novel Forms of Life and Mind**

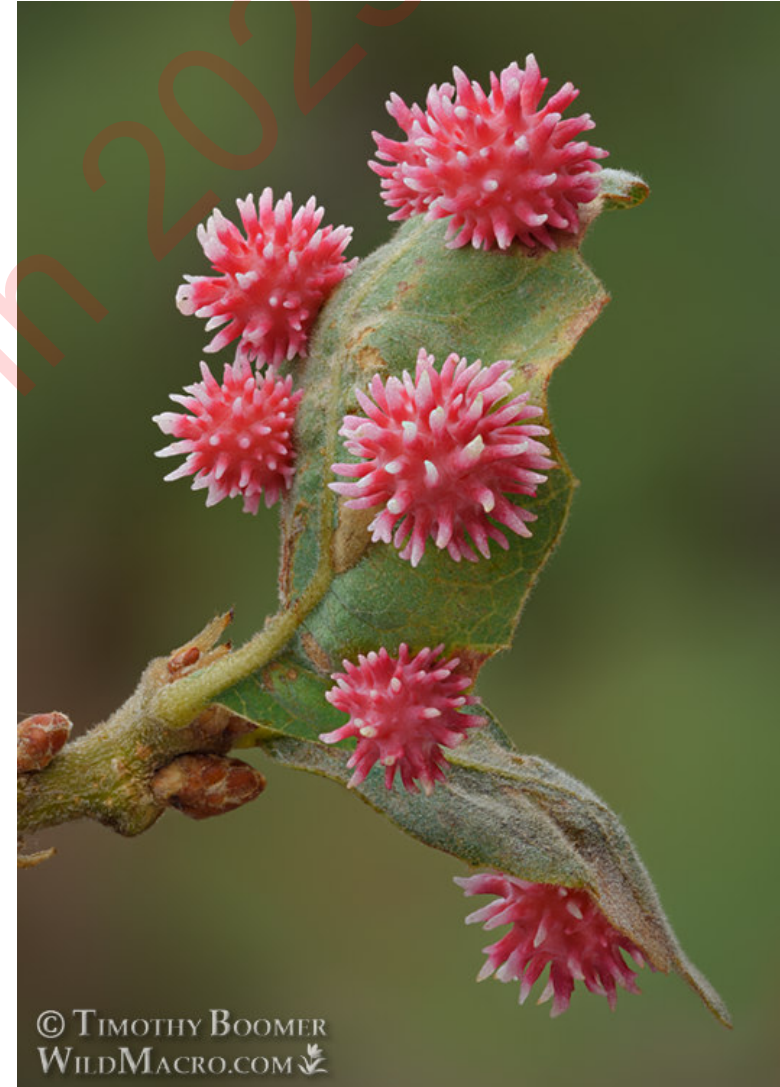
# Messages from Hacker Reveal Flexibility:



Photo Credit: Andrew Deans

## Hedgehog Gall

*Acraspis erinacei*  
August - November



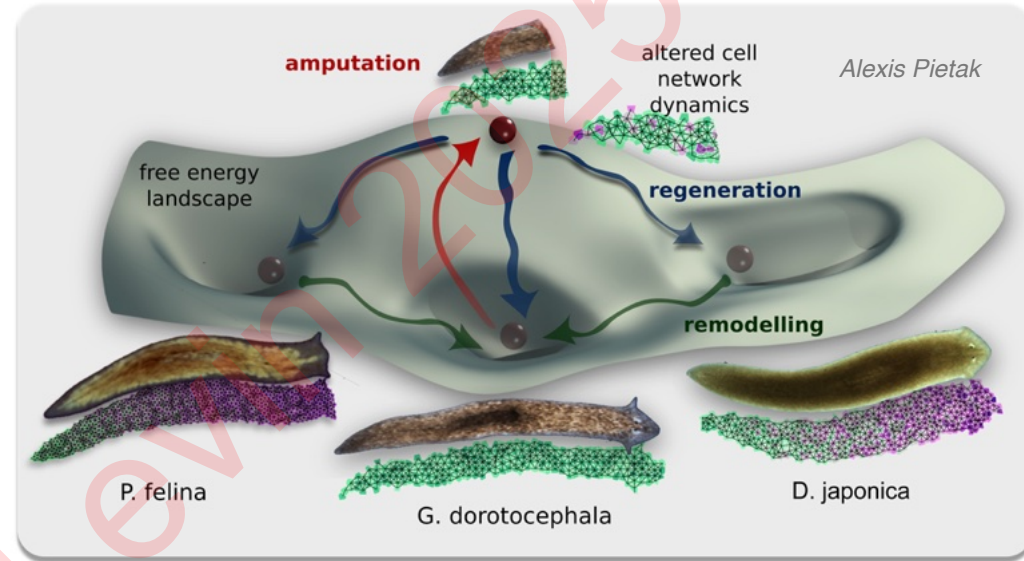
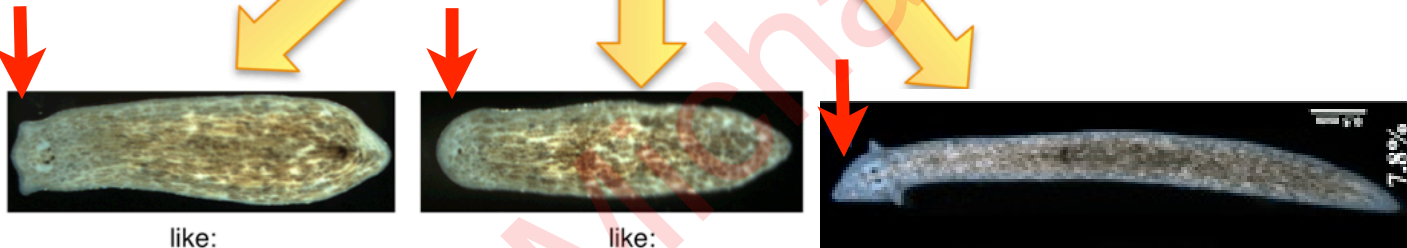
Parasite hacks host to induce new anatomy (bio-prompting)

# Exploring Morphospace with Planarian Bodies

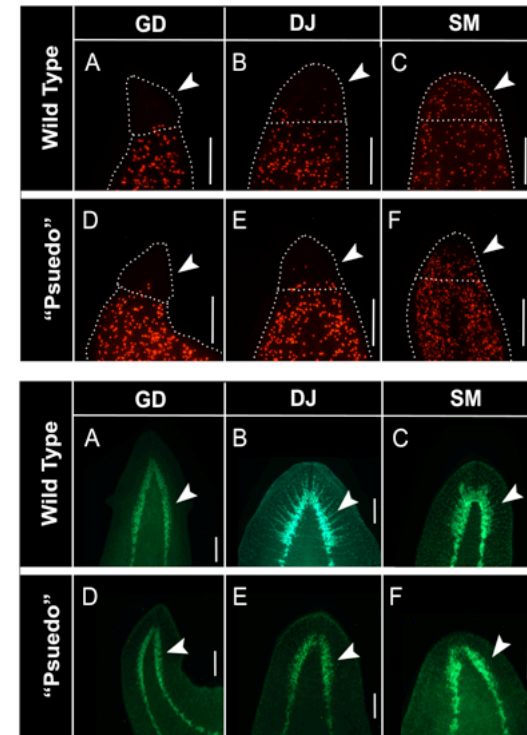
Species-specific shapes = attractors in morphospace



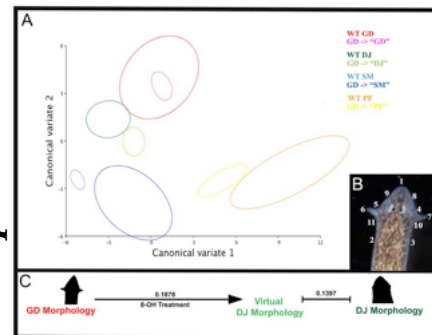
cut off head, perturb network topology



brain shape and stem cell patterns match also!

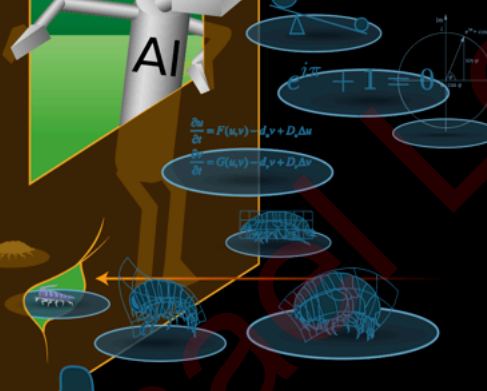


quantitative morphometrics



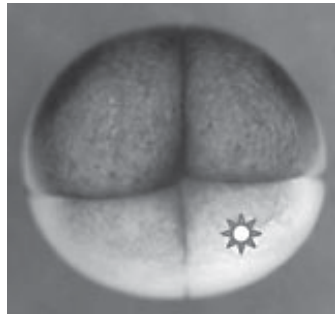
Maya Emmons-Bell

# Selected Setpoint



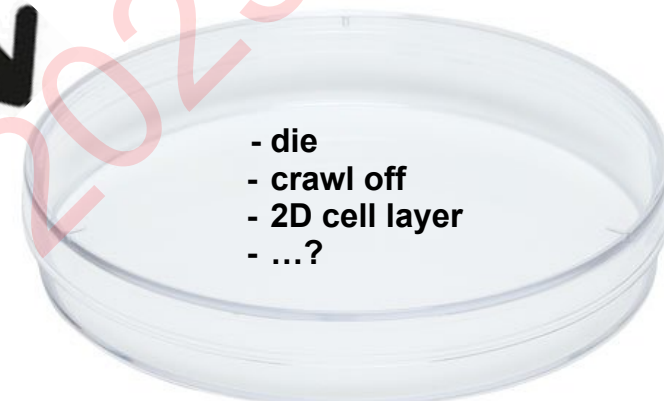
<https://thoughtforms.life/symposium-on-the-platonic-space/>

# Rebooting Multicellularity



Early frog  
embryo

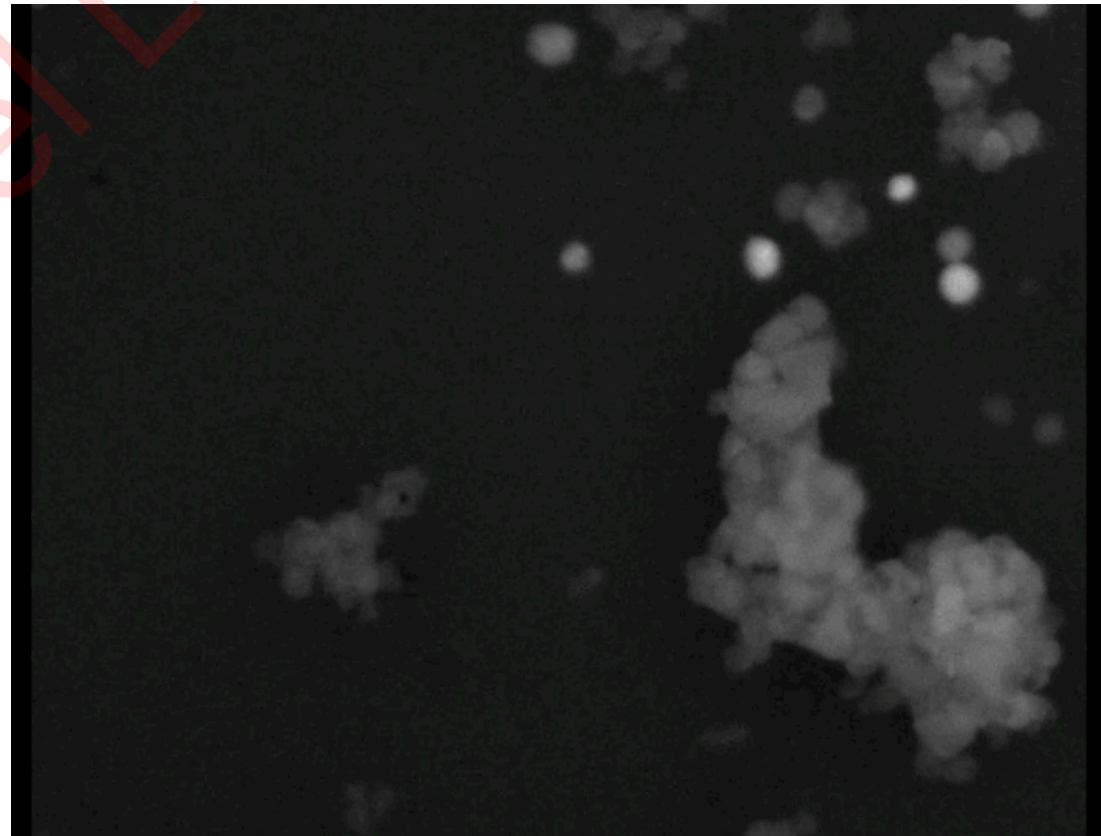
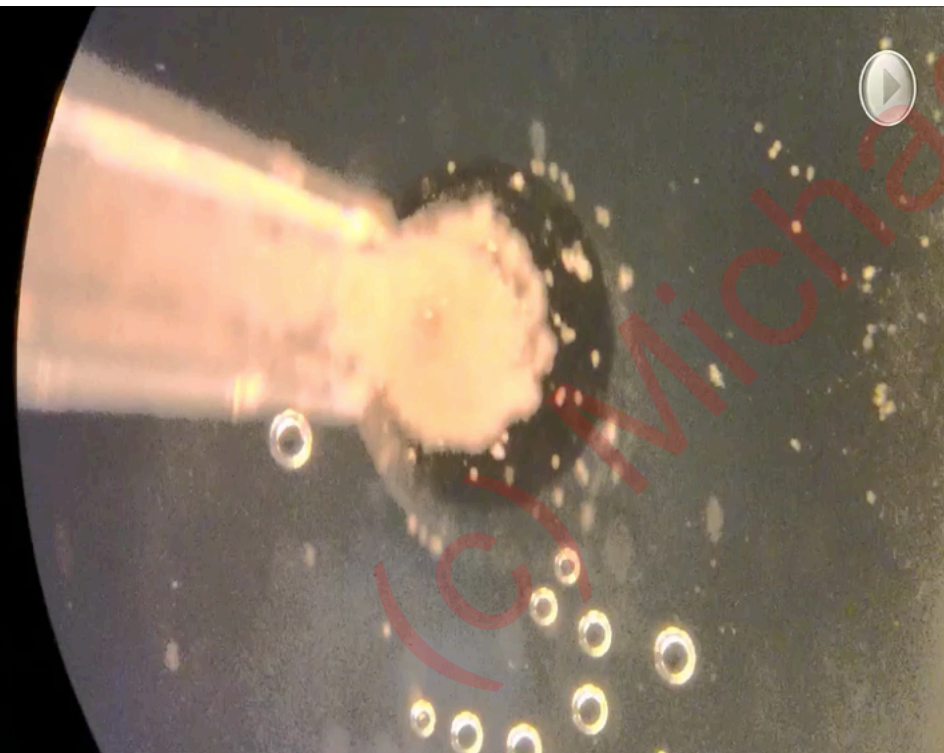
8 hours  
→



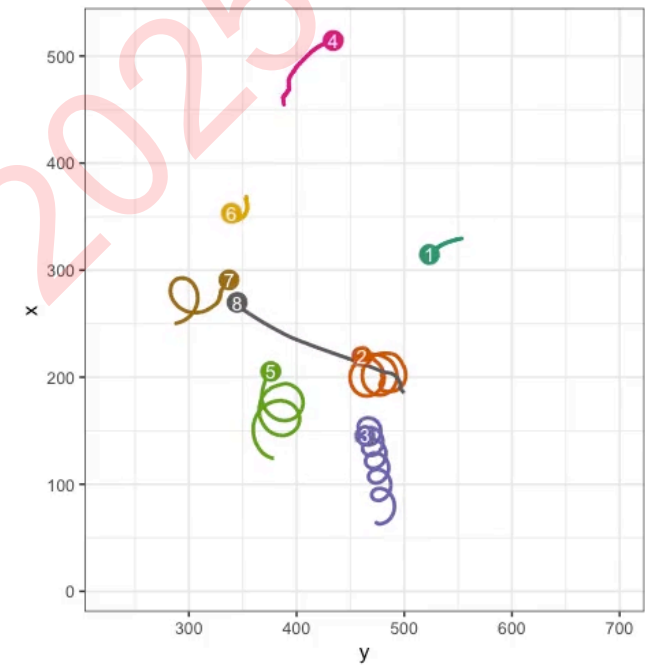
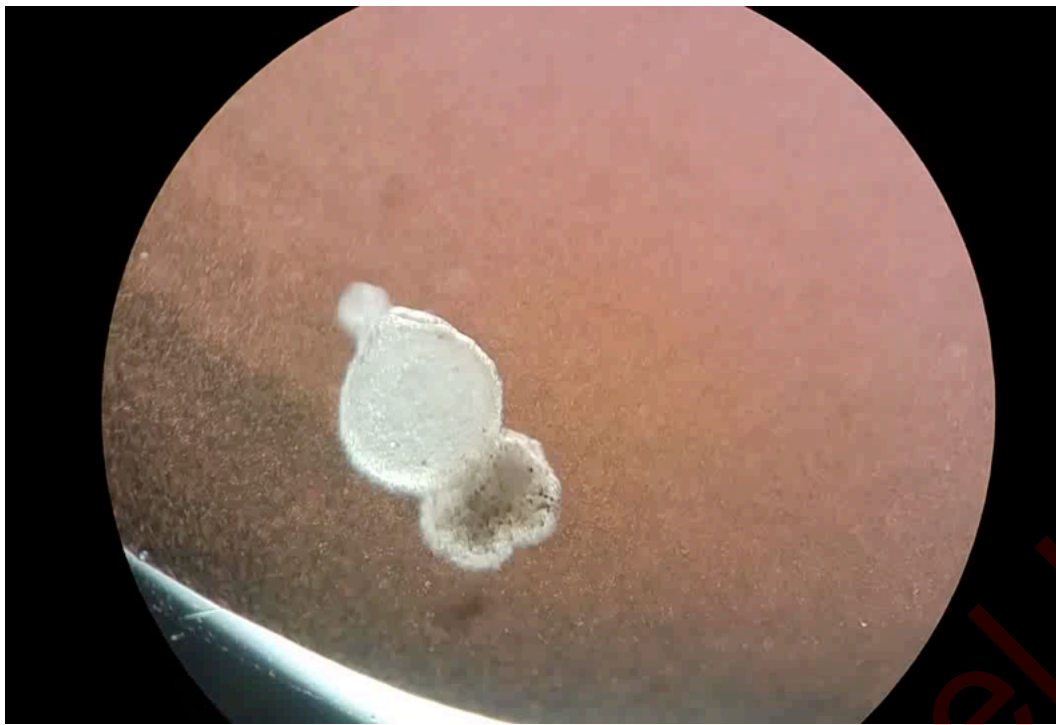
- die
- crawl off
- 2D cell layer
- ...?

assay for form  
and function

*Douglas Blackiston*



# Xenobot Ciliary Motility

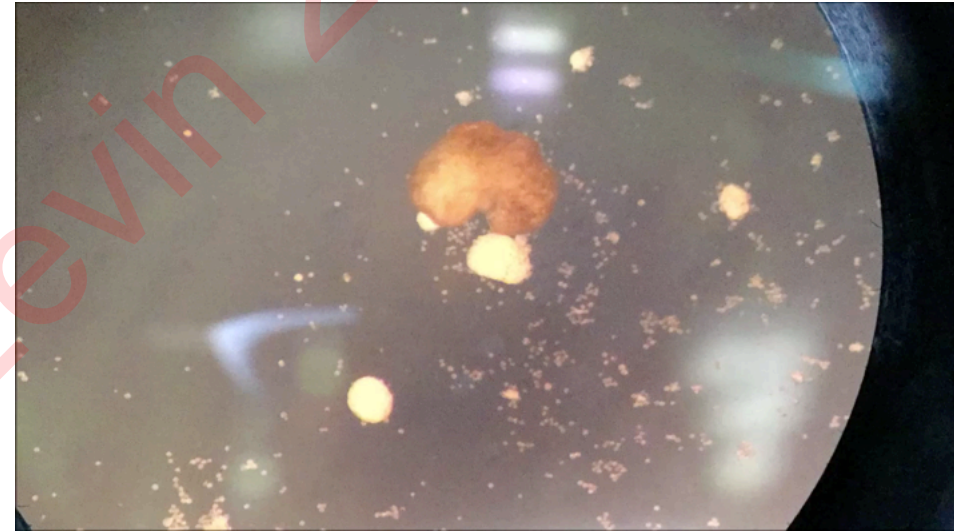
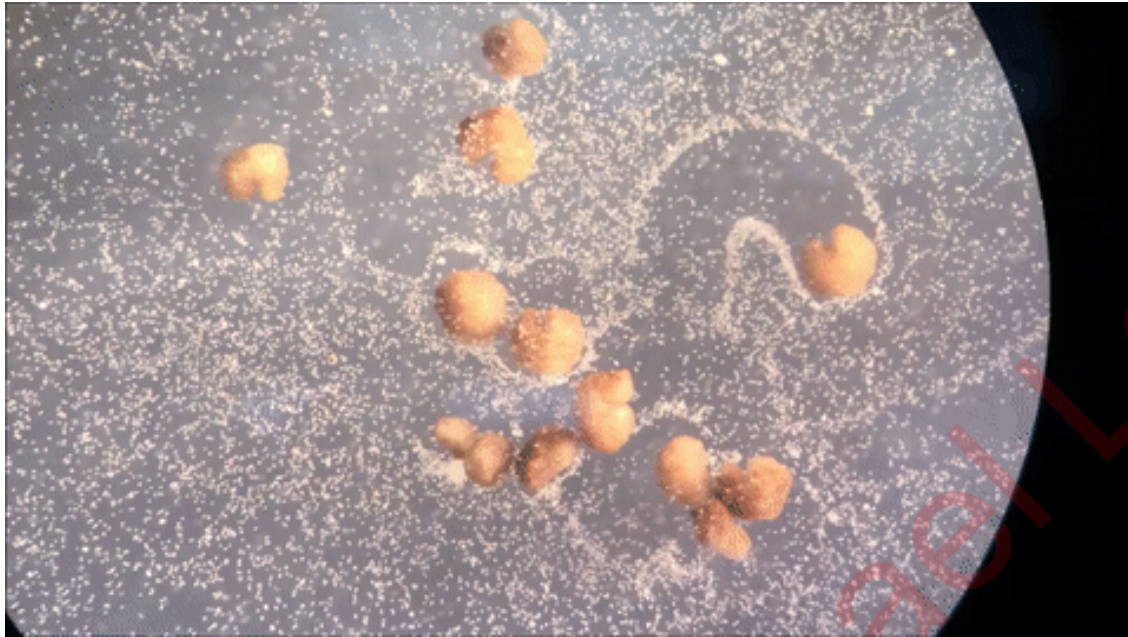


# Xenobot in a maze (still water, no flow):



- 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:



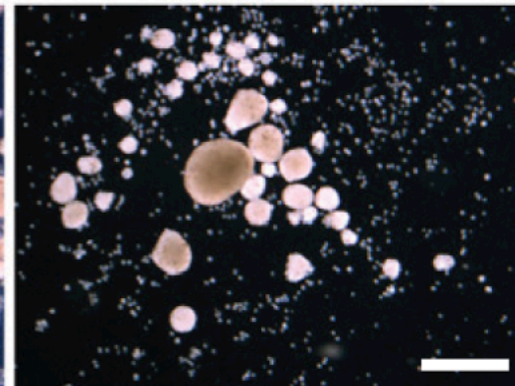
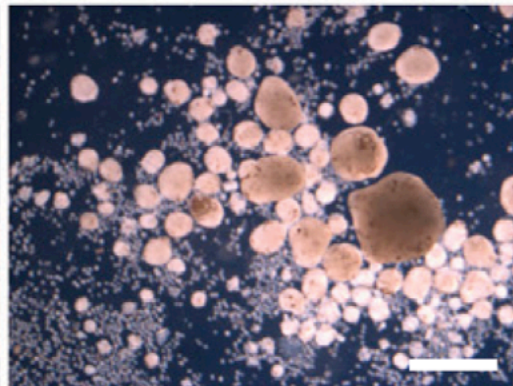
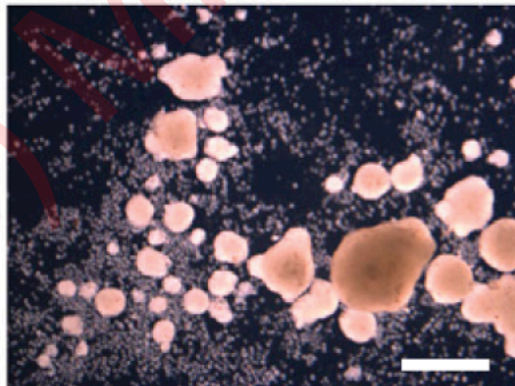
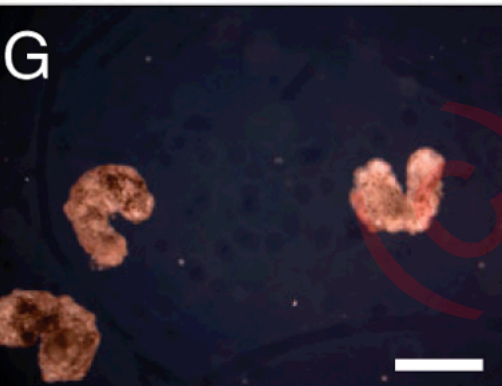
*Douglas Blackiston*

gen 0

gen 1

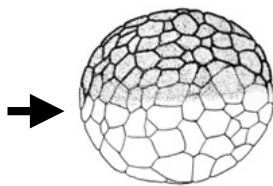
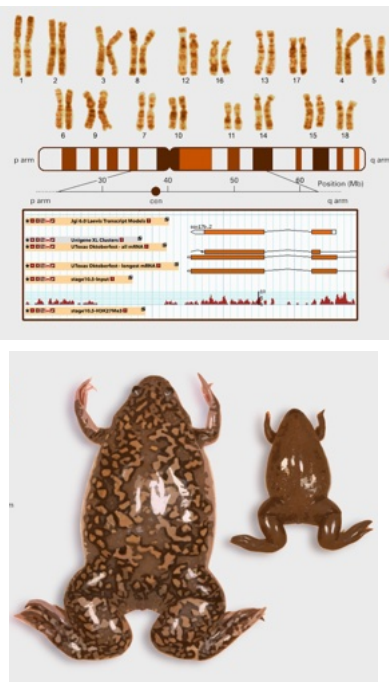
gen 2

gen 3

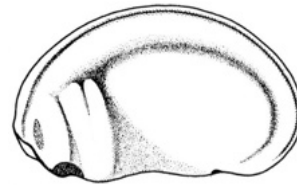


# Xenobots have a Standard Frog Genome Novel Morphology, Transcriptome, Behaviors

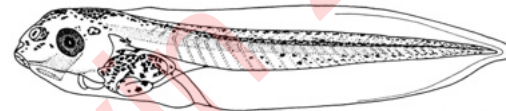
## Xenopus laevis genome



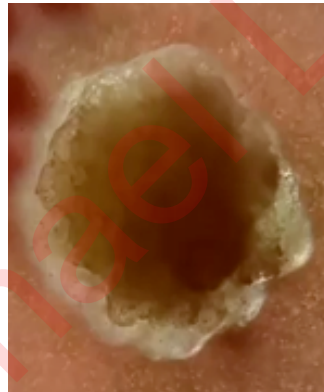
Path A: embryos



*Douglas Blackiston*



Path B: Xenobots

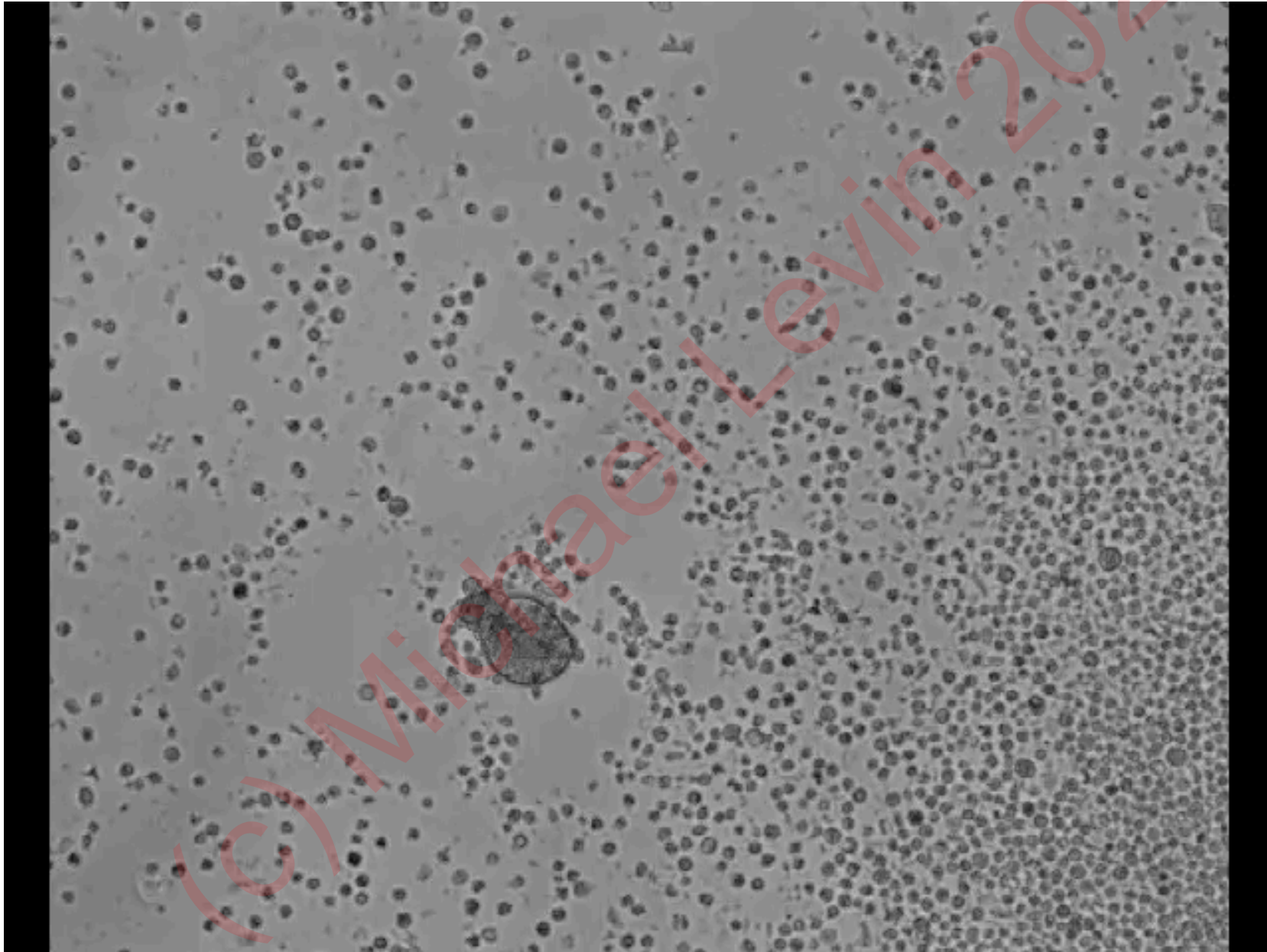


Developmental Time

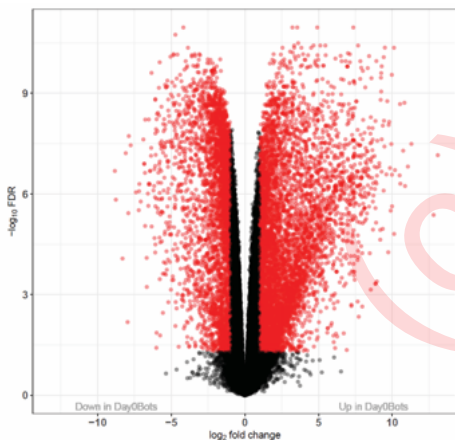
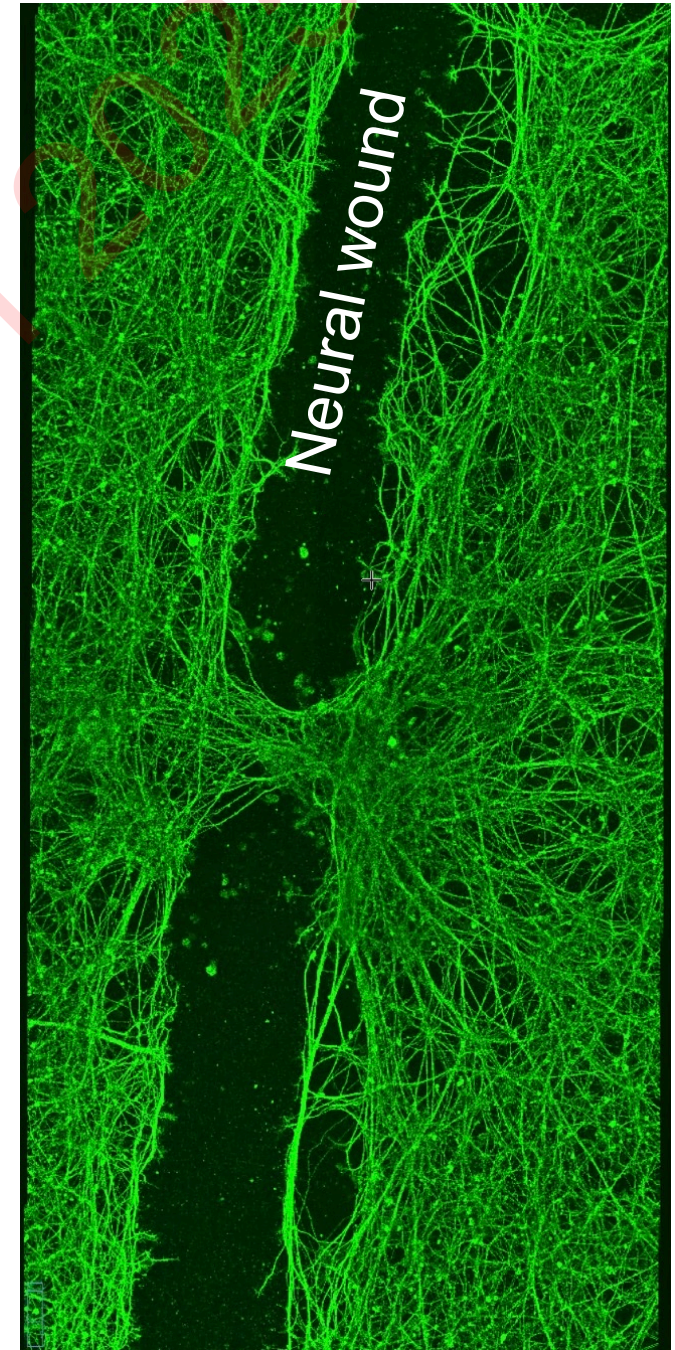
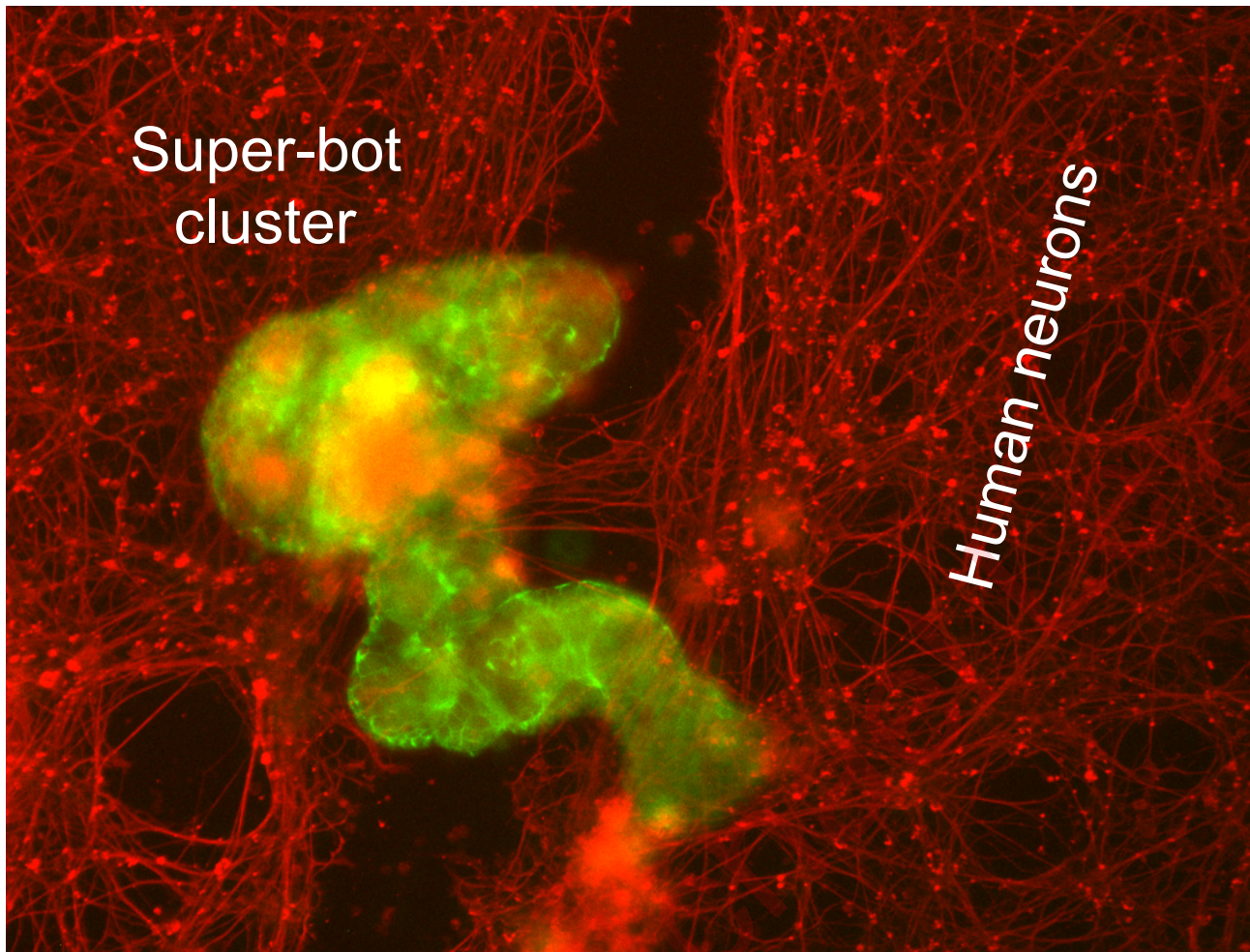
Behavior

no straightforward story of selection for these properties

# What would *your* cells do if liberated?

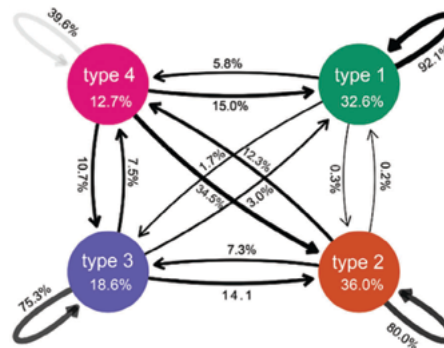


# Anthrobots Exert Neural Repair



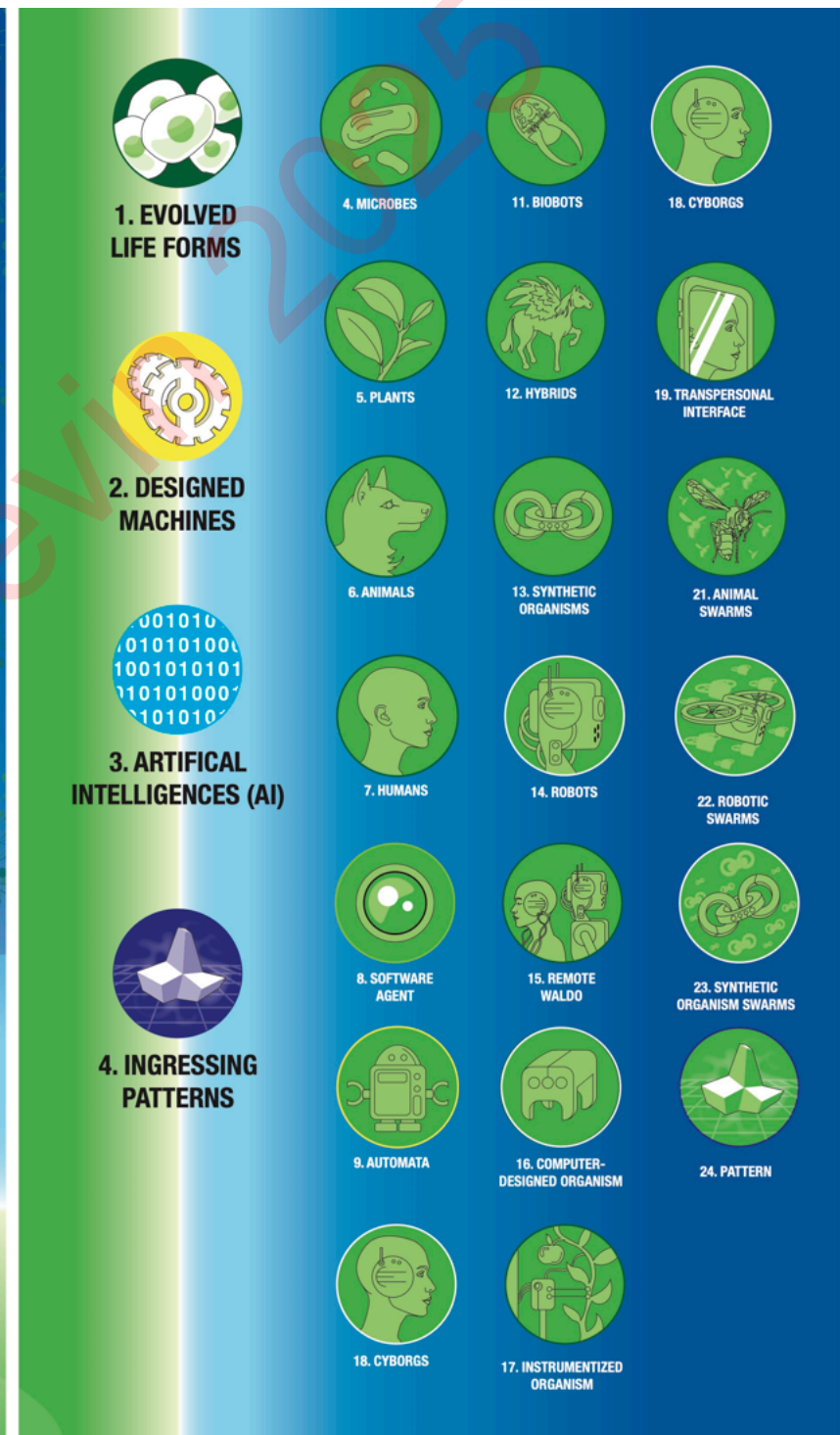
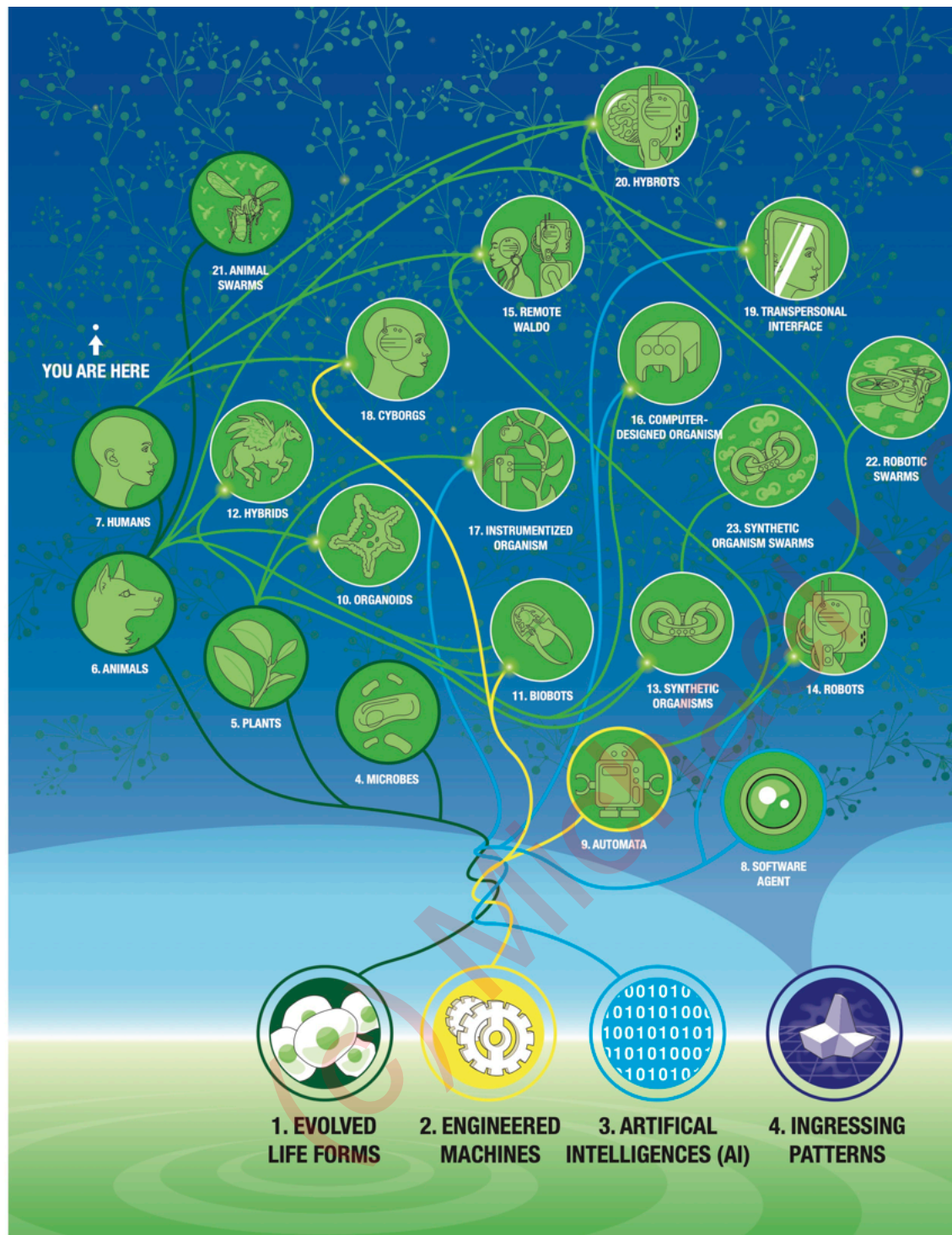
drastically  
remodeled  
transcriptome

Ethogram of discrete behaviors



Gizem Gumuskaya

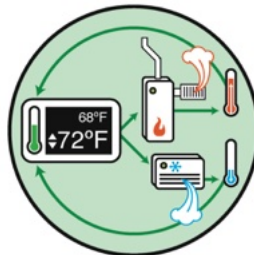
# “Endless Forms Most Beautiful” <—> ethical synthbiosis



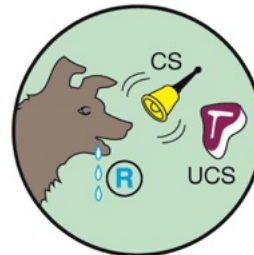
# AI for Diverse Intelligence (and ALife, Bioengineering, biomedicine, etc. etc.) research: tools → colleagues



Hardware  
modification only



Modify the data encoding  
setpoint of goal-driven  
process

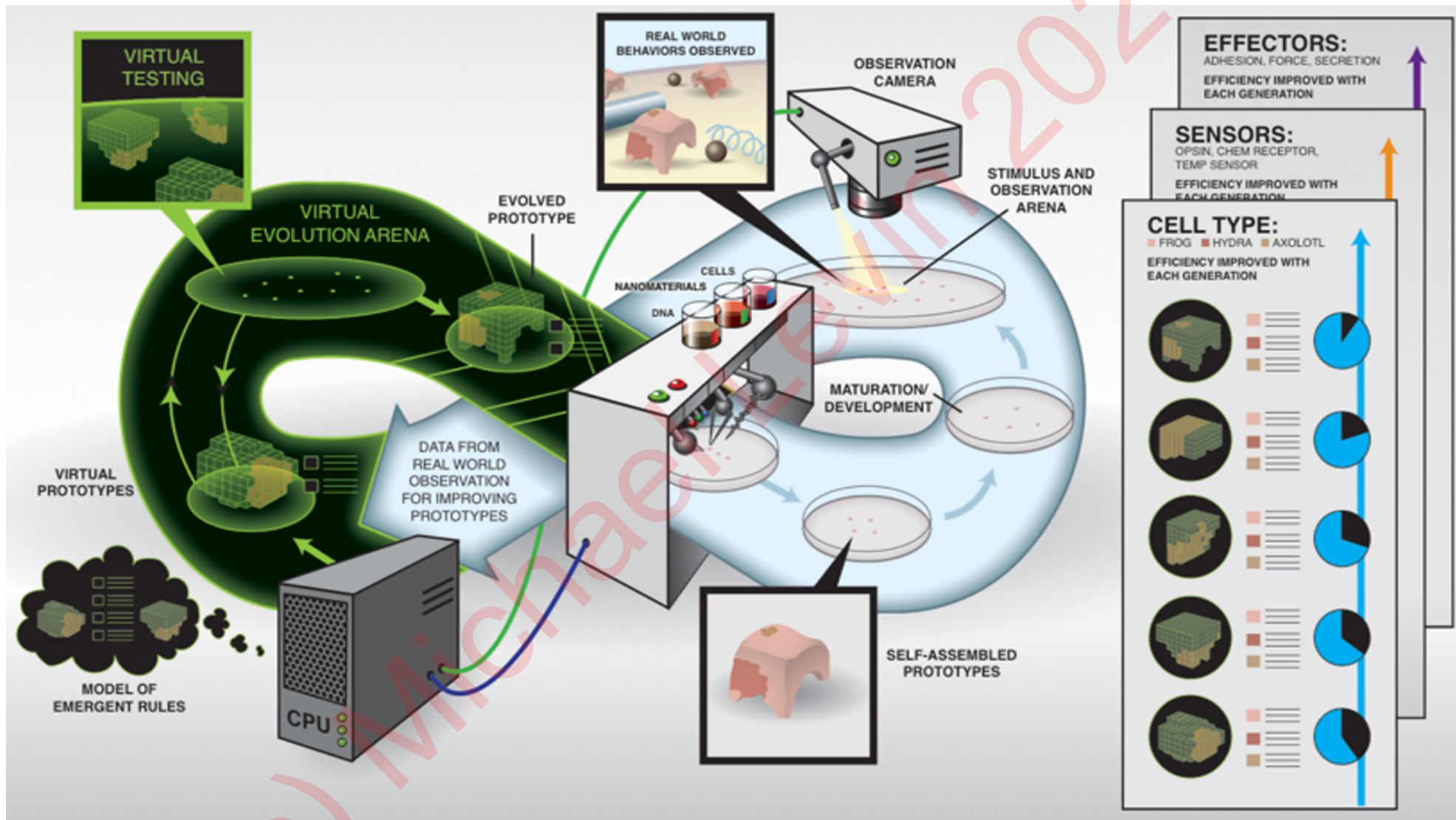


Training by  
rewards/  
punishments



Communicate  
cogent reasons

# Automating the Search for New Prompts and Behavior-Shaping Stimuli

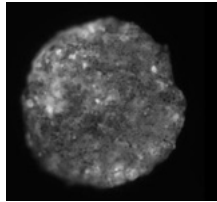


discovery engine for communication, collaboration  
with agential materials

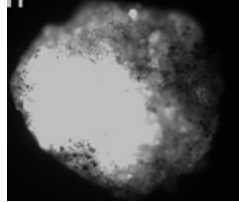
# exploring the space of prompts

## Chemical modulation

w/o chemical

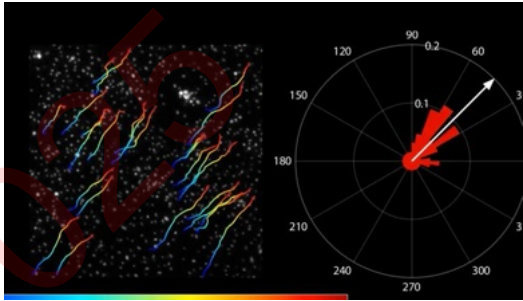


w/ chemical



need better idea for this

## Electrical modulation

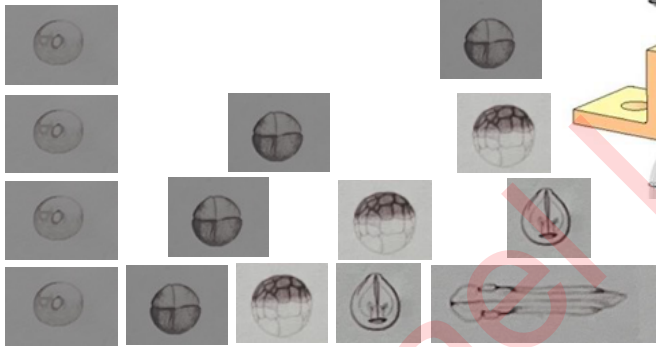


Cell movement

Electrical field

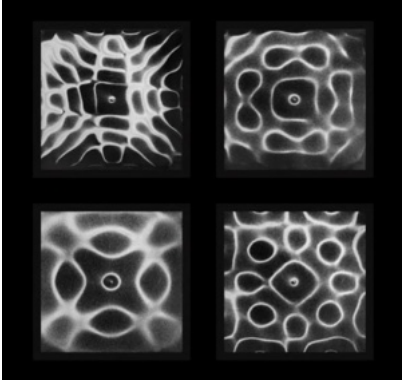
(Image from SCHEEPDOG paper)

## Temperature modulation



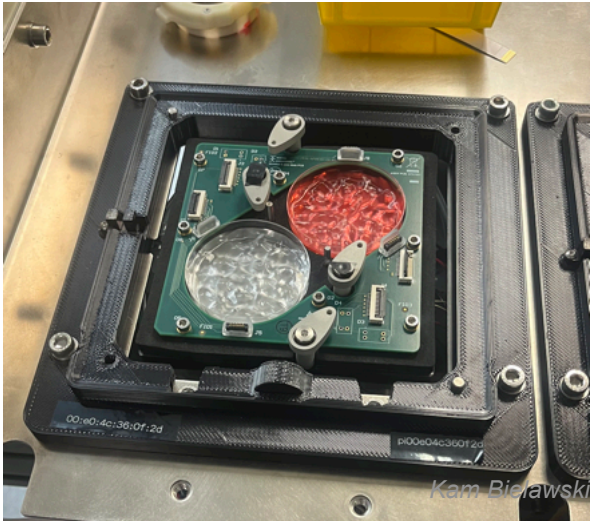
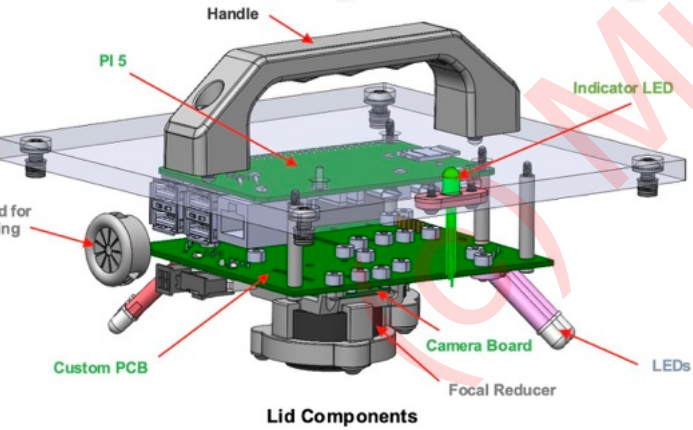
Speeding/slowing development w/ temperature

## Vibrational modulation



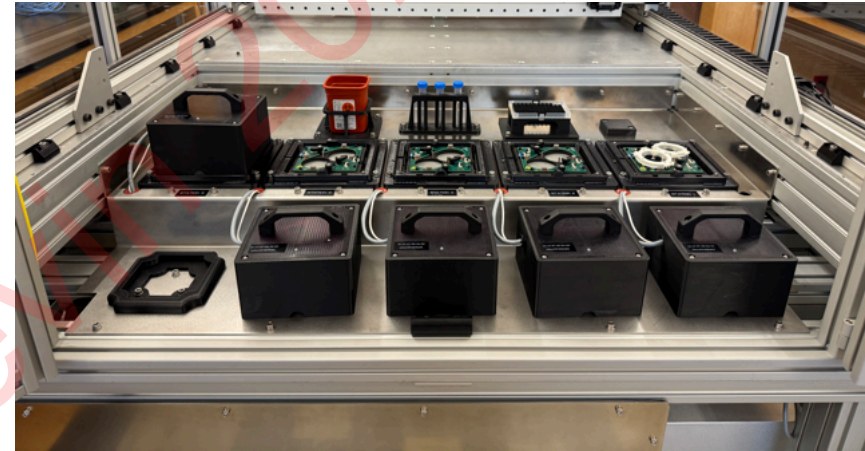
Loose cell patterns?

Boston Engineering



Kam Bialawski

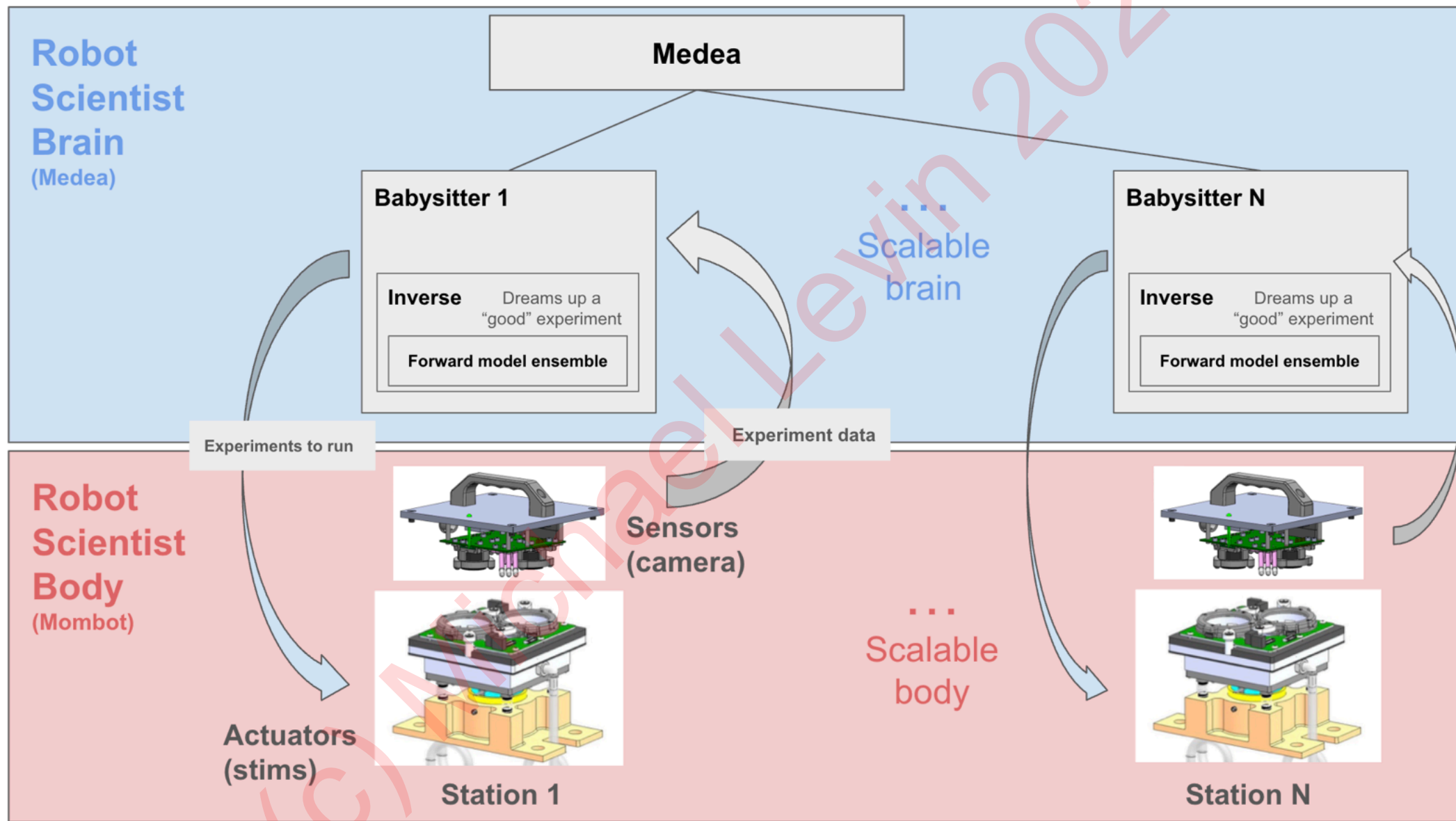
# Introducing a new collaborator: an embodied AI scientist working in synmorpho



**“MomBot”**



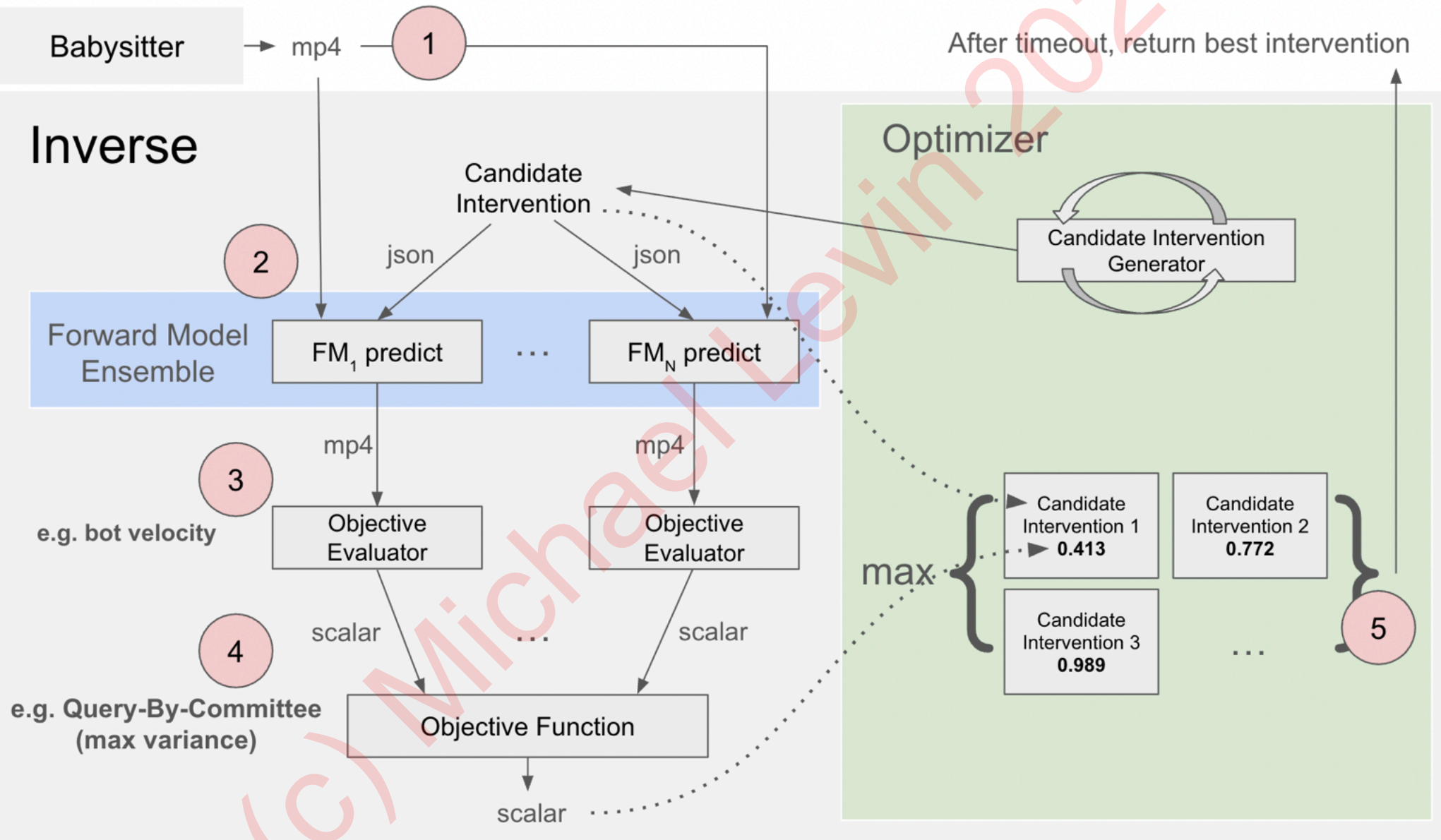
# Introducing a new collaborator: an embodied AI scientist working in symmorpho



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

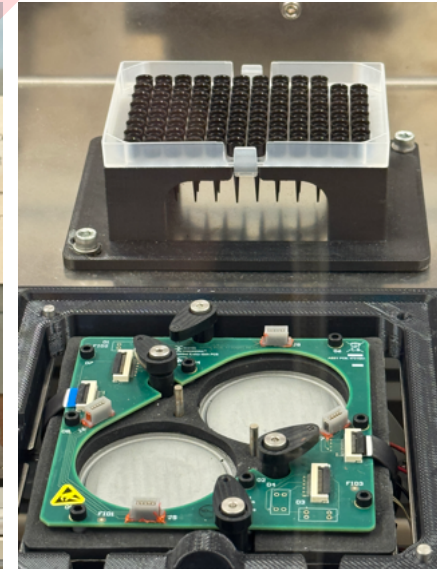
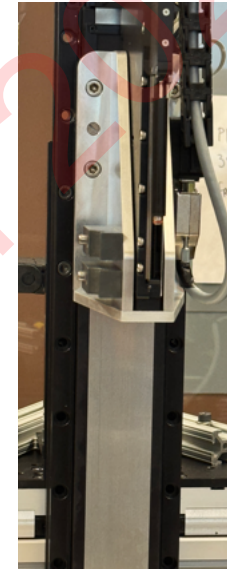
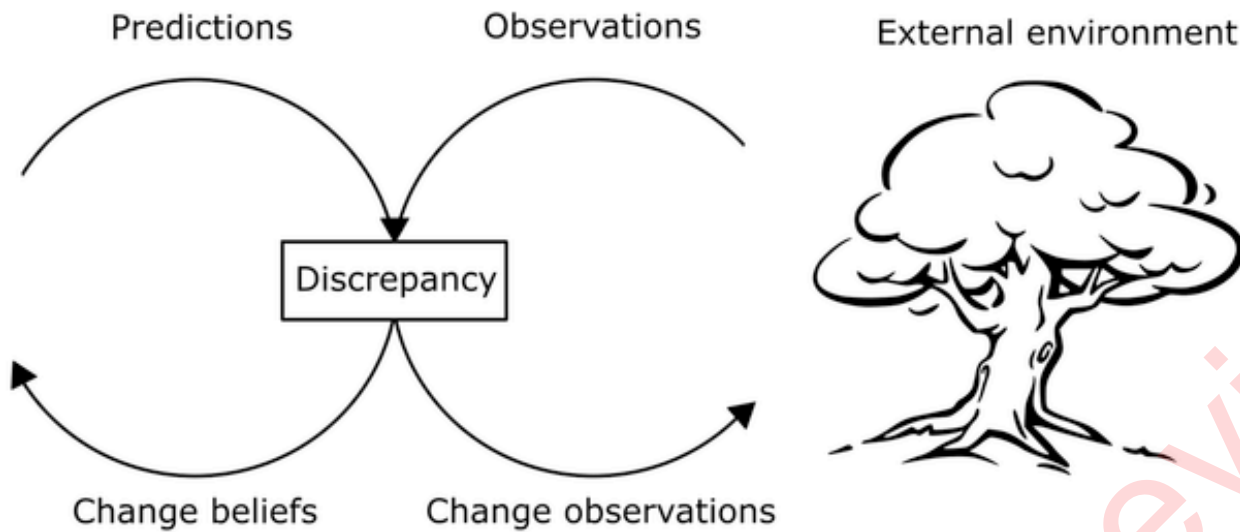
Kam Bielawski  
(Bongard Lab, UVM)

# Introducing a new collaborator: an embodied AI scientist working in symmorpho

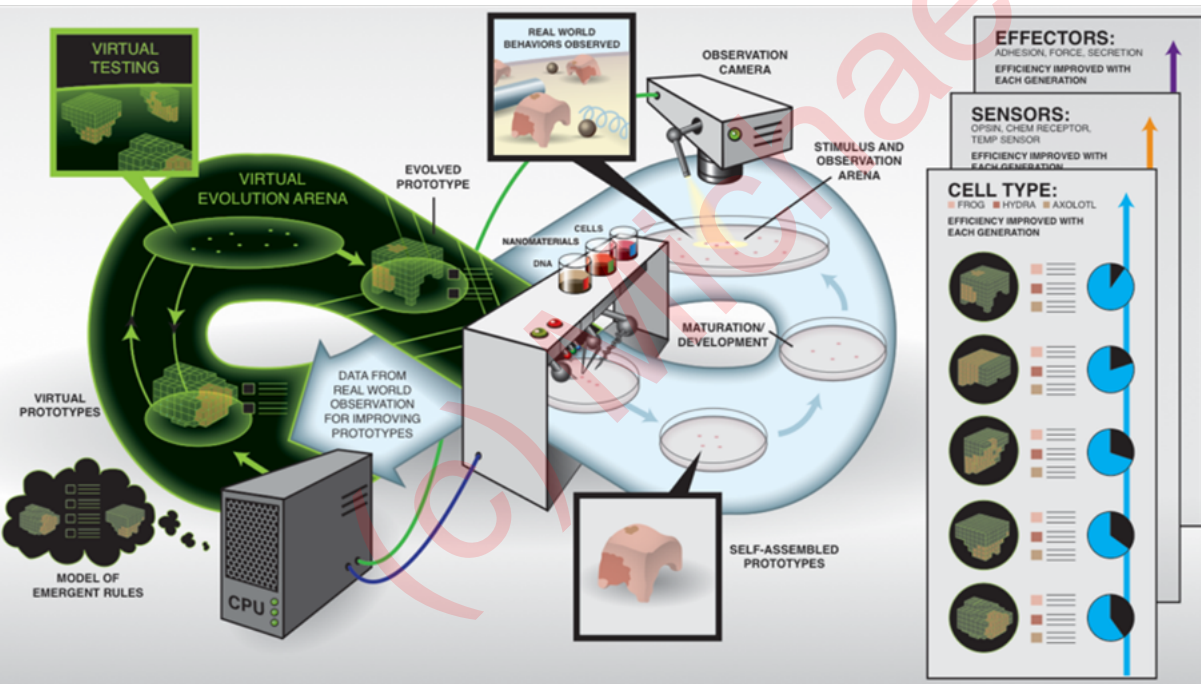


**Infotaxis:** it tries to do the most informative experiments to give it the most information based on priors

# Multiscale Sensory-Behavior Loops



overall loop: sense/manage Xenobot form and function



inner loop:  
sense  
liquid and  
manage  
movement  
of  
materials



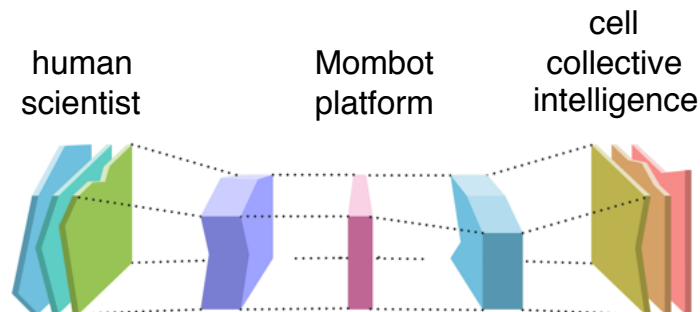
# Next Steps:

- 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

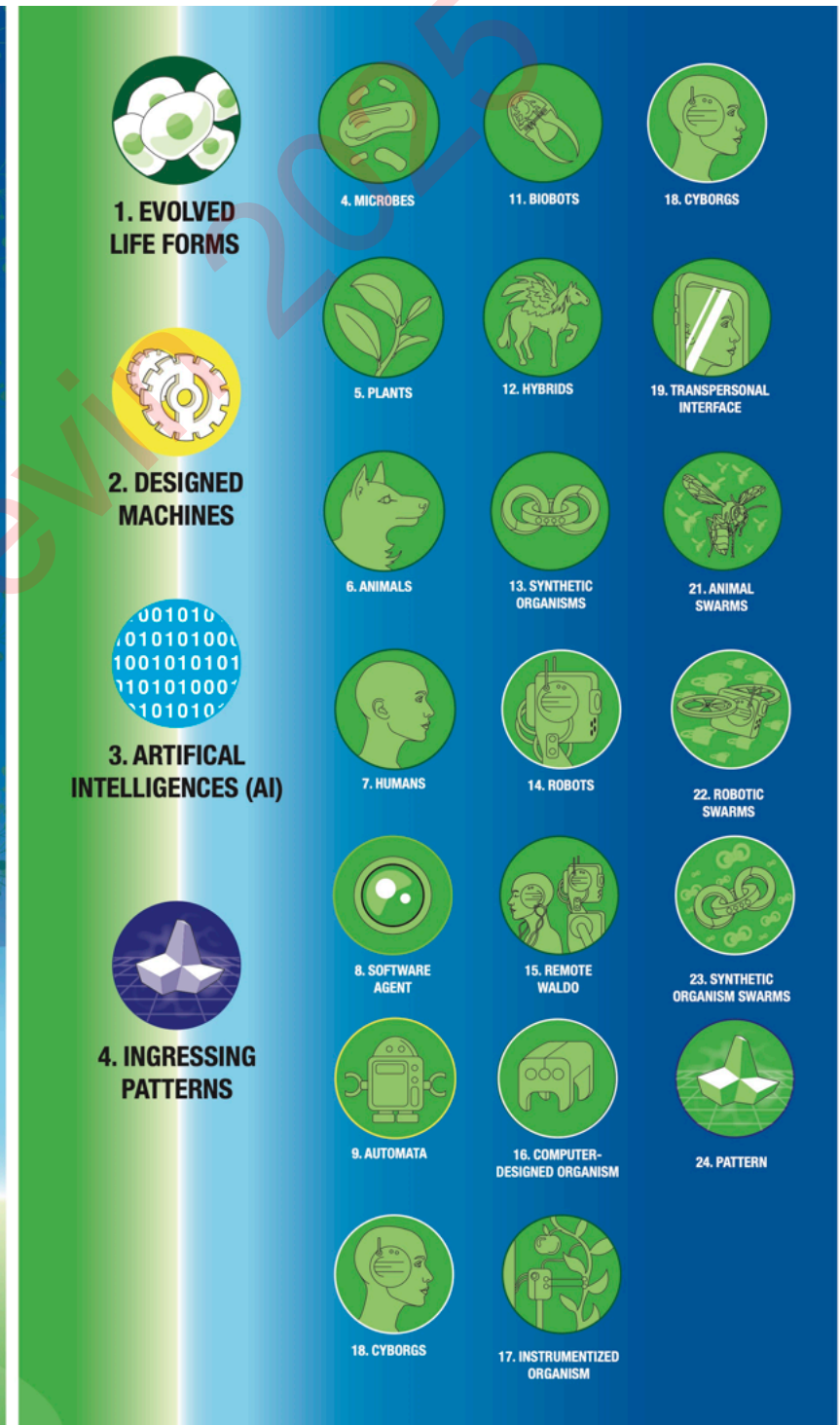
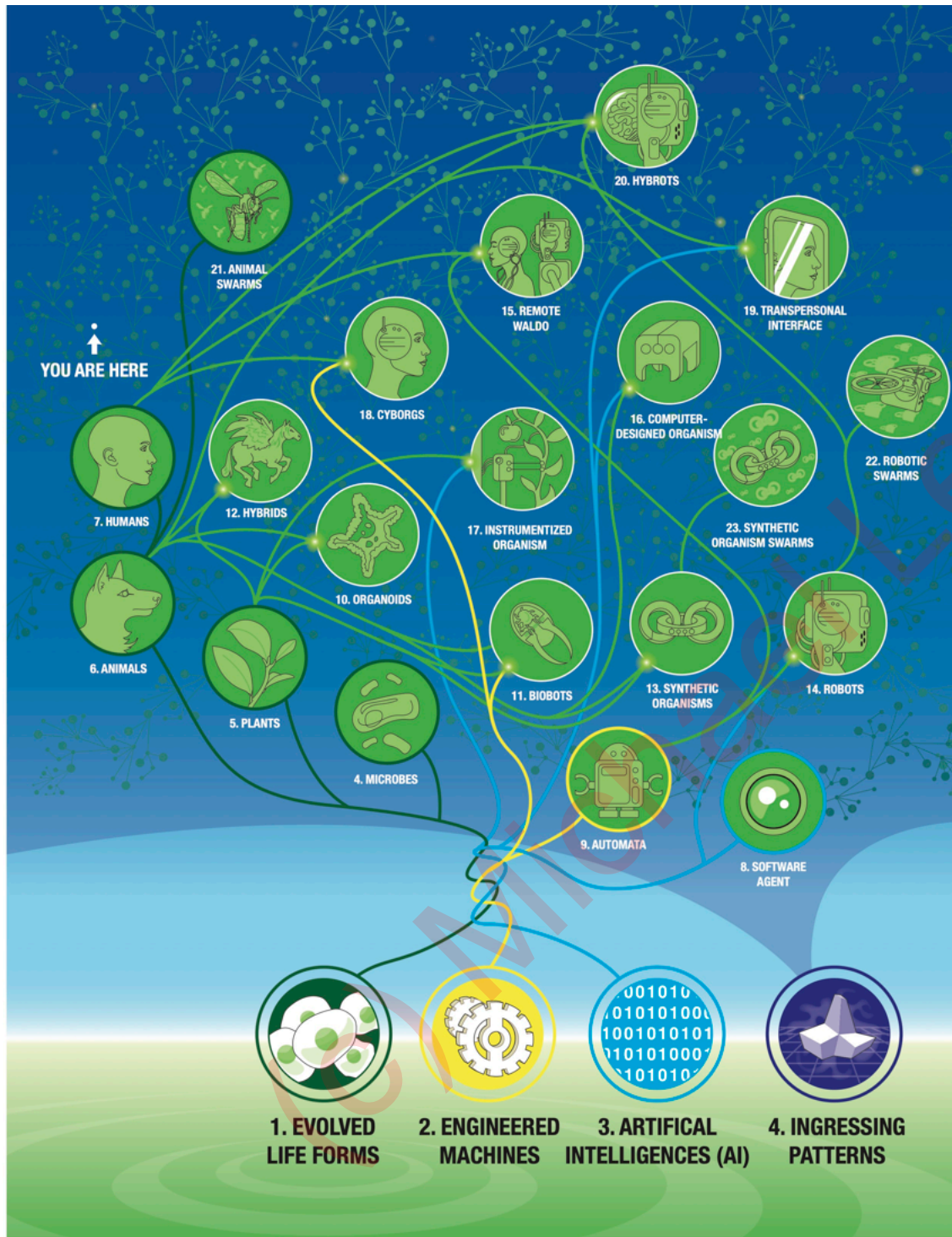
# Future Impacts of this Approach:

- 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

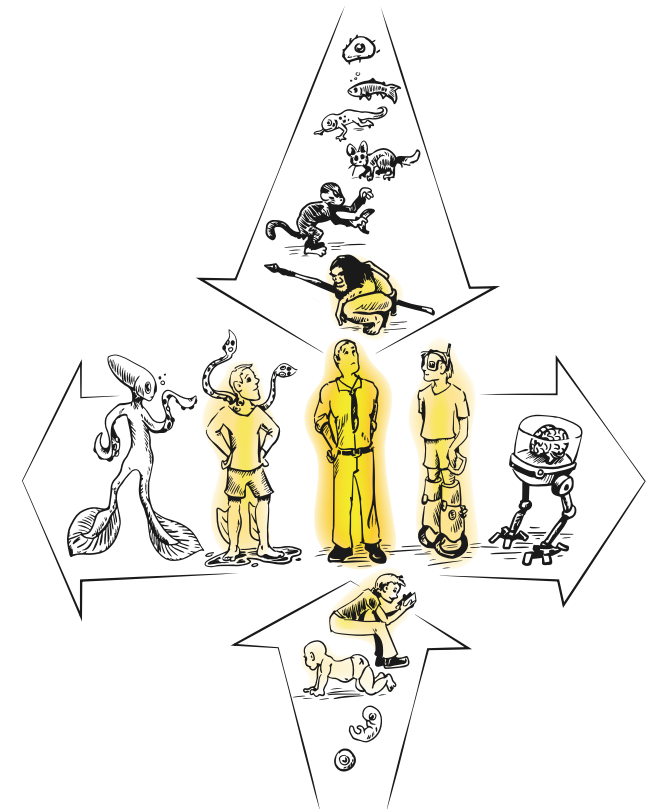
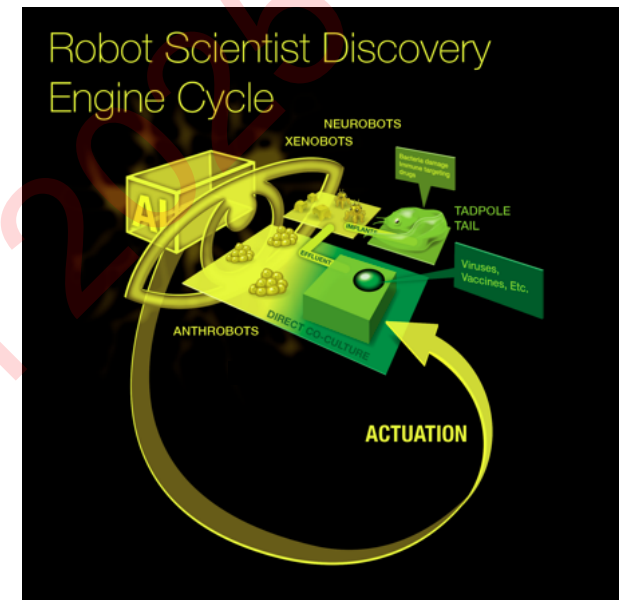


# “Endless Forms Most Beautiful” <—> ethical synthbiosis



## 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:

## Post-docs and Staff Scientists:

**Douglas Blackiston** - brain-body interface plasticity, Xenobots  
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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  
Gizem Gumuskaya, Nik Davey - Anthrobots

## Undergraduate Students:

Pranjal Srivastava, Ben G. Cooper, Hannah Lesser, Ben Semegran - Anthrobots  
Maya Emmons-Bell - planarian barium adaptation

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Joan Lemire - molecular biology  
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Krishna Srinivasan, Shawn Beaulieu,  
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**Blackiston Lab at Tufts:** Douglas Blackiston and Tomas Gonzalez-Zugasti

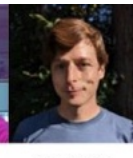
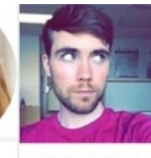
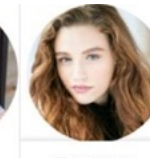
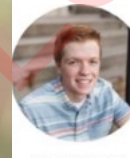
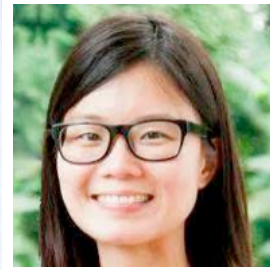
Illustrations: Jeremy Guay @ Peregrine Creative

Model systems: frog, fish, human cells, animats, mice, and many others

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Disclosures: Fauna Systems,  
Astonishing Labs



Heather Moyer, Mark Smithers & team

