Technological Approach to Mind Everywhere:

TAME = a framework for Diverse Intelligence research based on a goal-directedness in unconventional Agents

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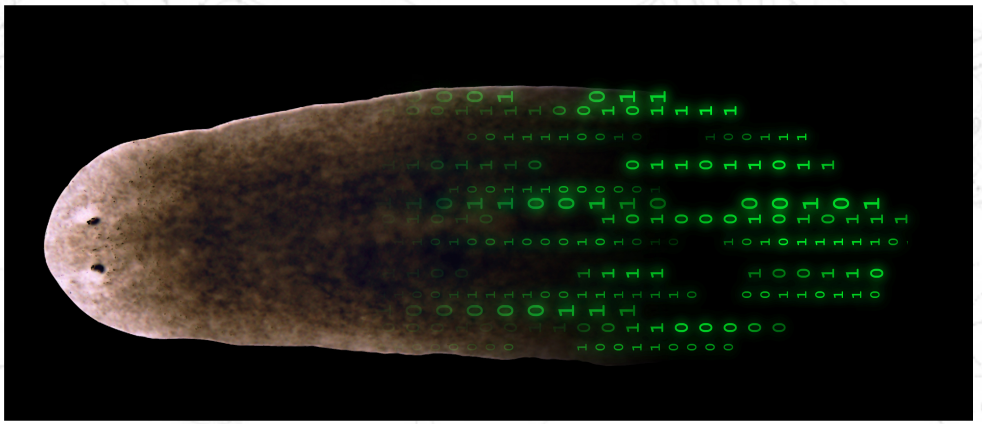

ALLEN DISCOVERY CENTER at Tufts University

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Main Points:

- How much intelligence/agency/cognition a system has - framed as an engineering problem, not just philosophy. I propose an empirical approach, using appropriate levels of cognitive concepts to better predict/control complex living systems.

- Diverse Intelligences can be directly compared with respect to the spatio-temporal scale of the **goals** they are capable of working towards: the "cognitive light cone" model.

- Synthetic bioengineering provides an astronomically large option space for new bodies and new minds, without standard evolutionary back-stories - novel beings impact understanding of evolution, genomes, etc.

- The study of morphogenesis as an unconventional collective intelligence (solving problems in morphospace) operating via developmental bioelectricity provides a new window on cognitive (goal) scaling.

Framework Goal:

- enable comparison of truly diverse intelligences regardless of composition or origin story
    - familiar creatures - us, apes, birds
    - weird creatures (colonial organisms, swarms)
    - synthetic biology - engineered new life forms
    - AI
    - exo-biological agents (Earth is N=1)
- moves experimental work forward

Outline:

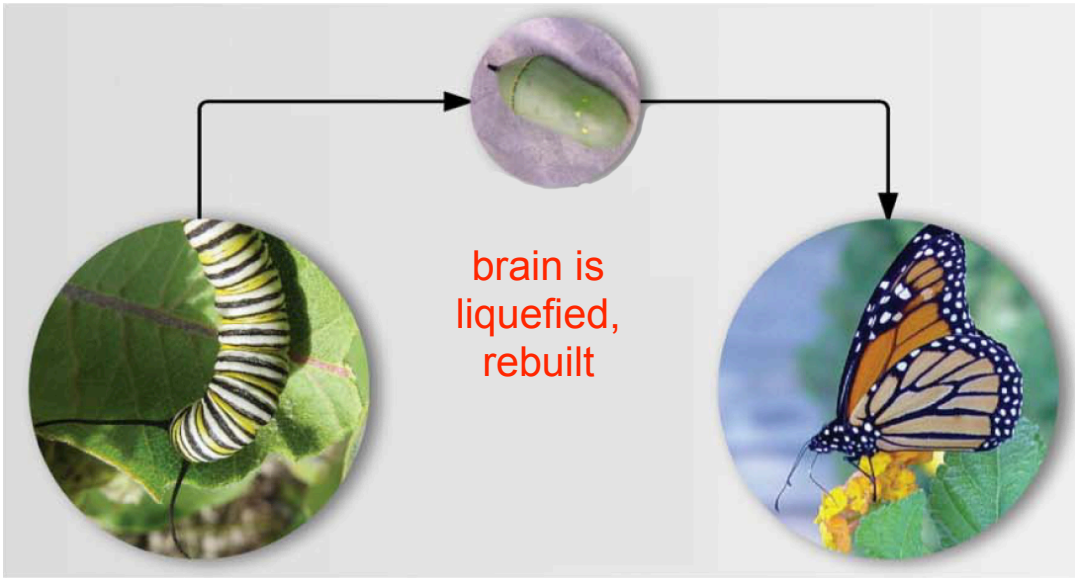
- Intro: broadening cognitive science
  - plastic subject of intelligence
  - expand the option space of model systems

- Technological Approach to Mind Everywhere
  - philosophical principles
  - specific hypothesis for defining Selves
  - specific hypothesis for multi scale cognition

- Model systems and data:
  - morphogenesis as a collective intelligence
  - Xenobots - a novel proto-organism

Changing the Subject (of Intelligence)

The Self is the subject/owner of complex memories, credit assignment, goals
it changes on evolutionary, but also ontogenetic, timescales



crawls,
chews plants

flies,
drinks nectar

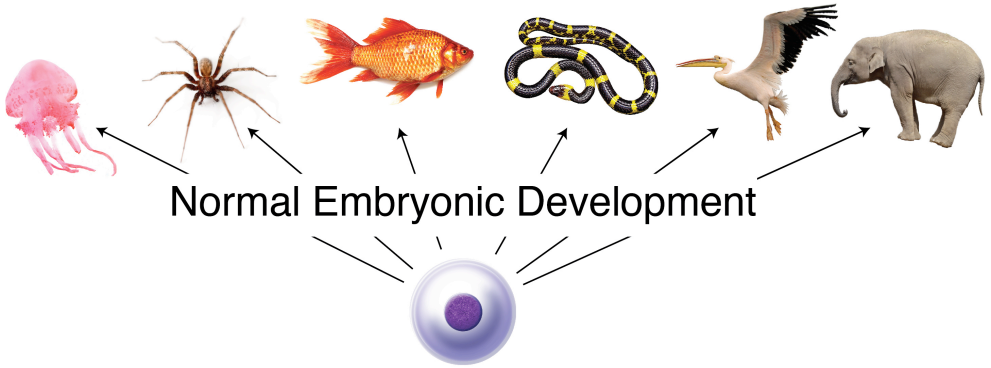
Communicative & Integrative Biology 8:5, e1073424; September/October 2015; Published with license by Taylor and Francis Group, LLC

The stability of memories during brain remodeling: A perspective

Douglas J Blackiston[1], Tal Shomrat[2,3], and Michael Levin[1,*]

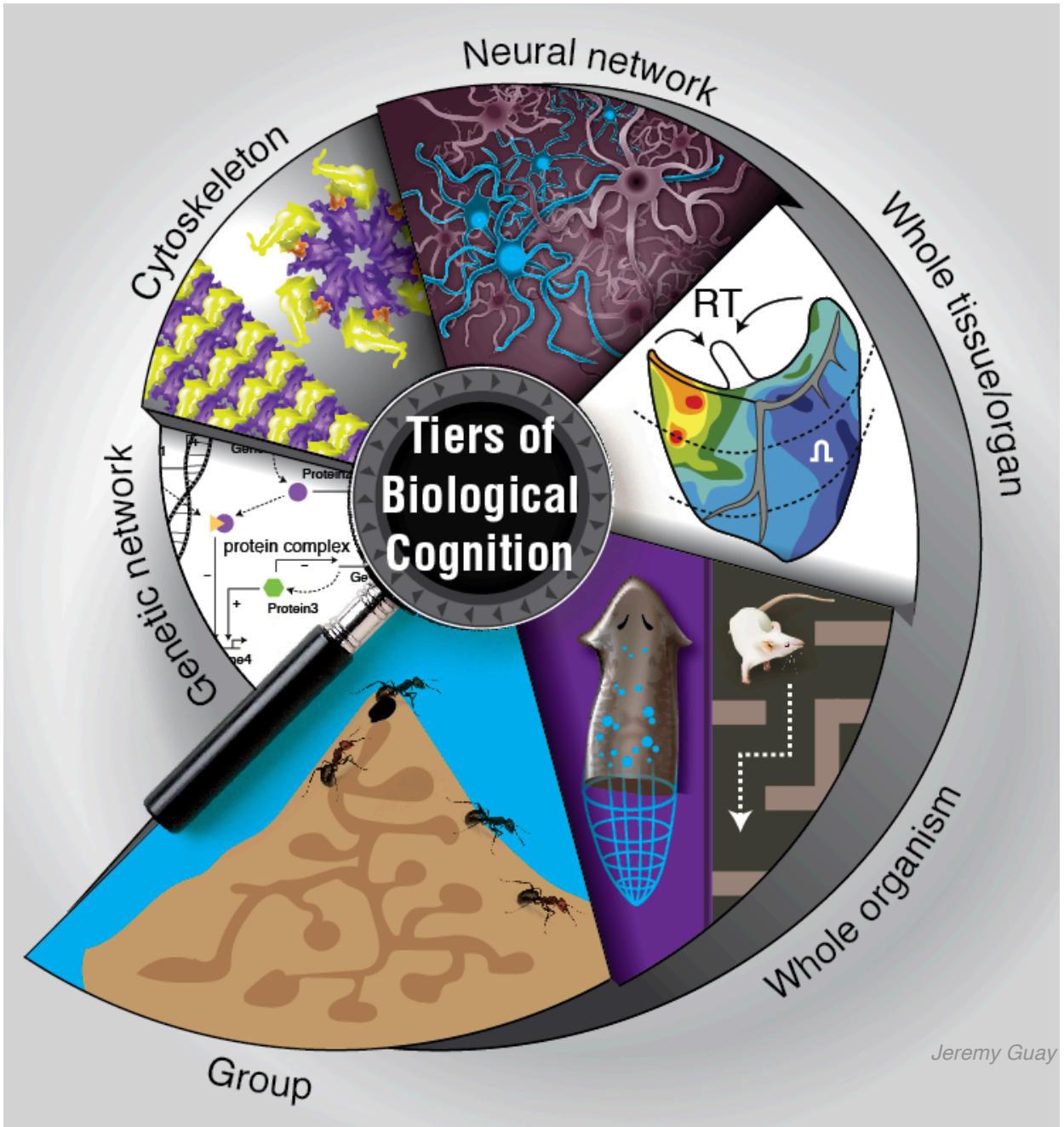
- minds are embodied
- bodies can change drastically

Ontogeny recapitulates phylogeny



- we all make the journey across the Cartesian cut – from "just physics" of single cell (egg) biochemistry to conscious being

Nested Cognition

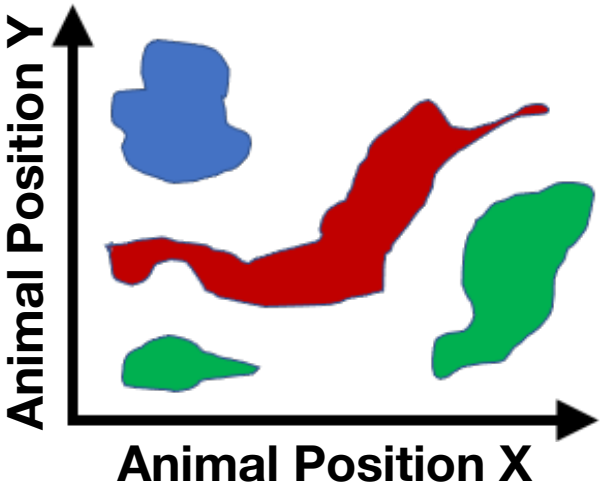


Multi-scale Competency Architecture

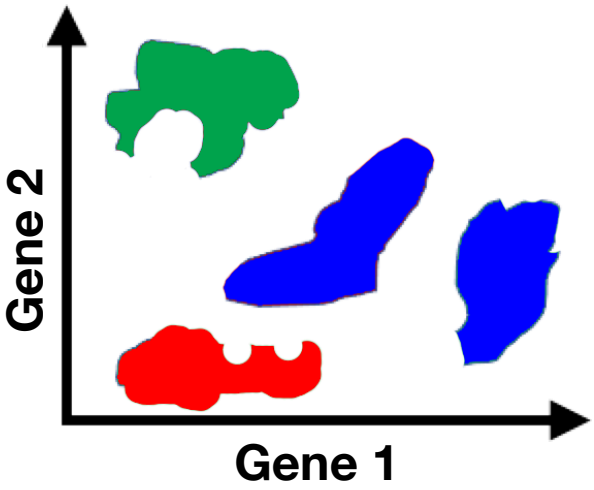
each level of organization solves problems in its own space (morphospace, transcriptional space, physiological space, 3D behavioral space, etc.) using some of the same bag of tricks, of various levels of sophistication

Intelligence Solves Problems in Arbitrary Spaces

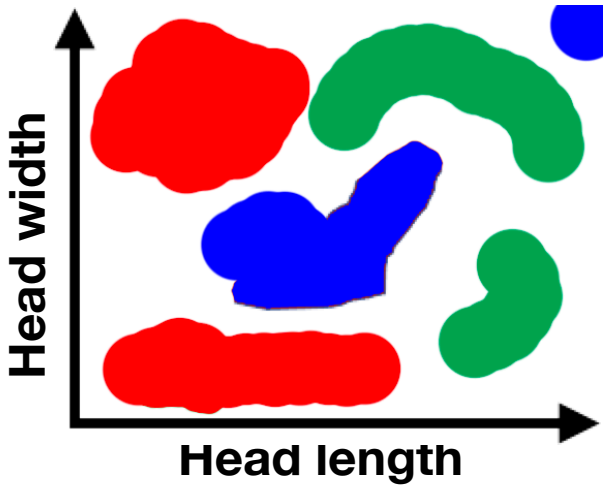
3D Space (behavior)



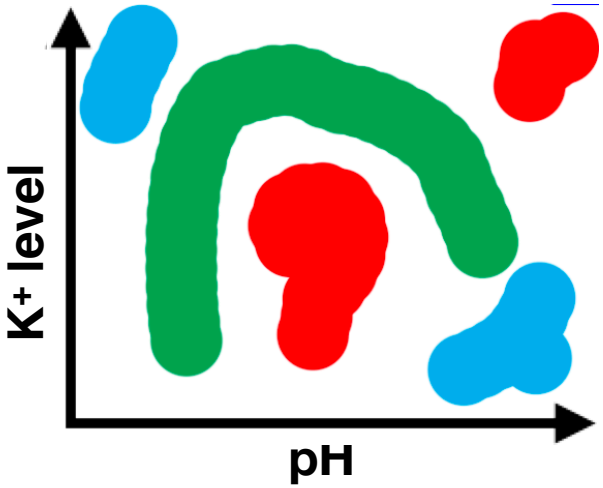
Transcriptional Space



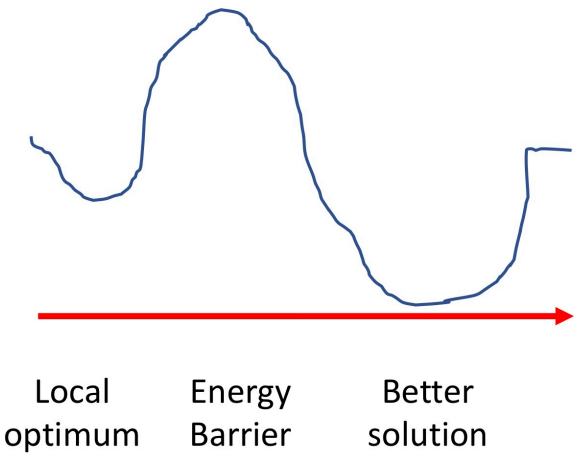
Morphospace



Physiological Space

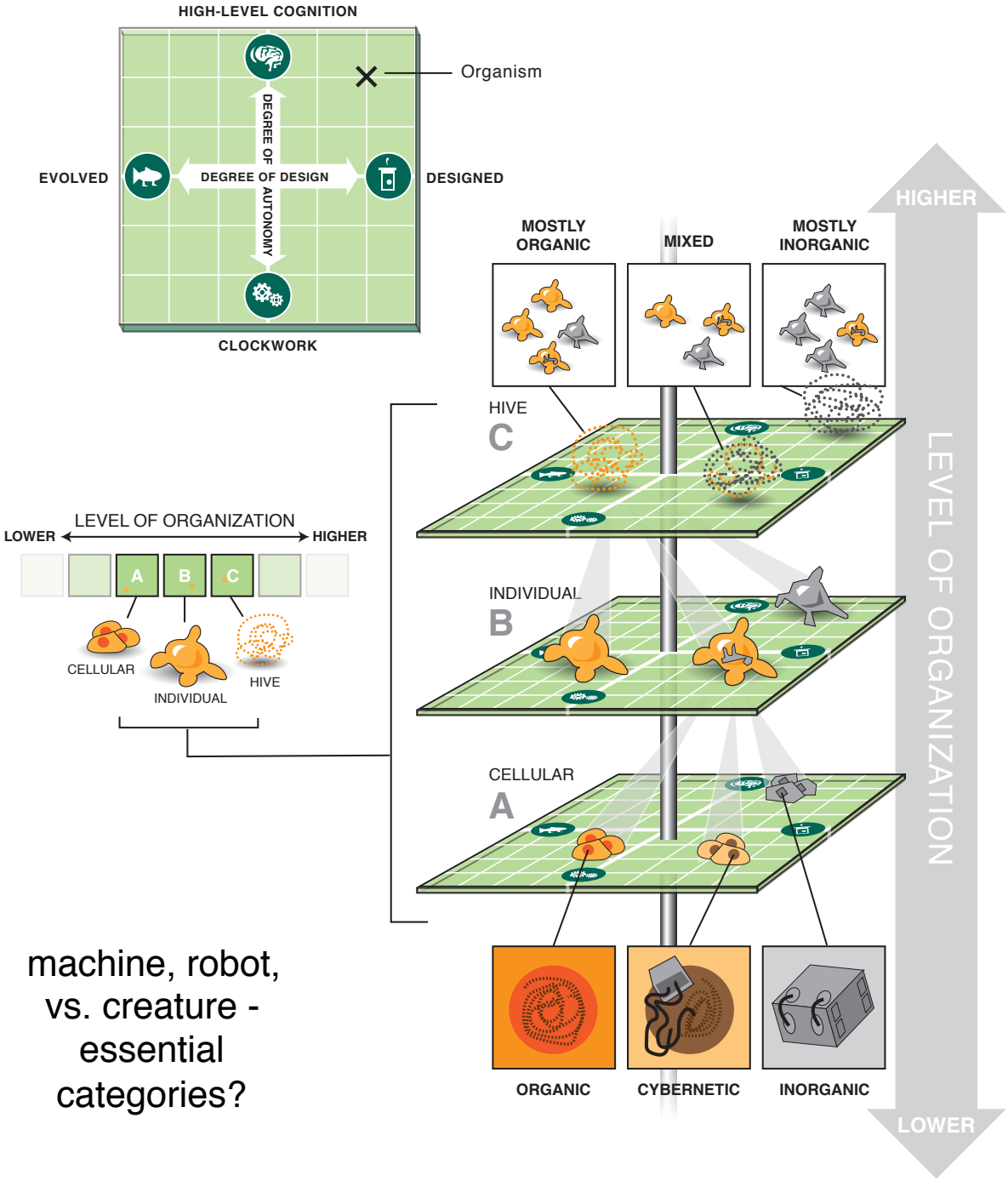


Degree of Intelligence is Proportional to Ability to Stay out of Local Minima in Pursuit of Goals



Higher level of organization sees a different space - you might be moving further away from goal in your space but the supersystem sees that you're actually coming closer in a different, more clever space)

Multi-Scale Chimerism



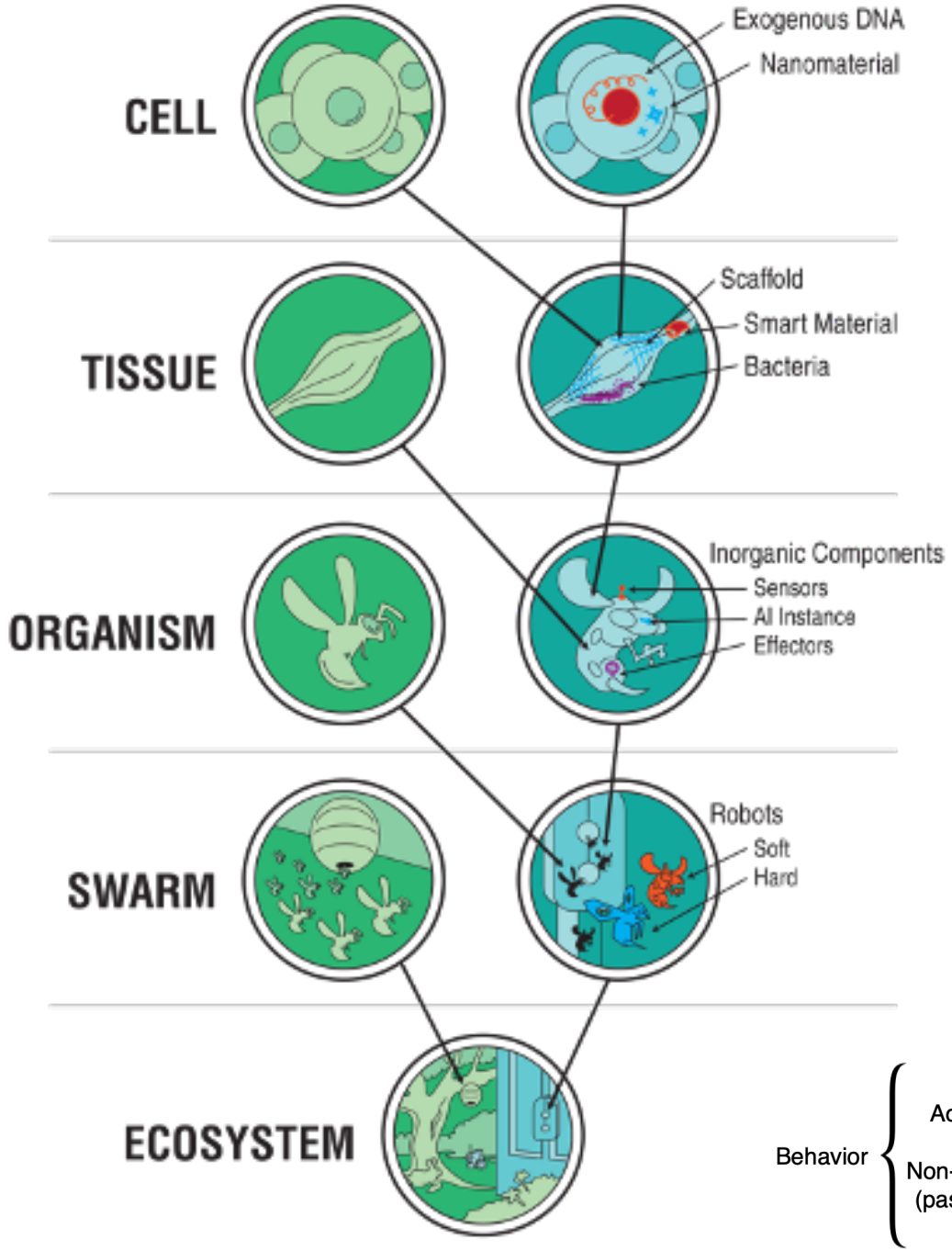
machine, robot, vs. creature - essential categories?

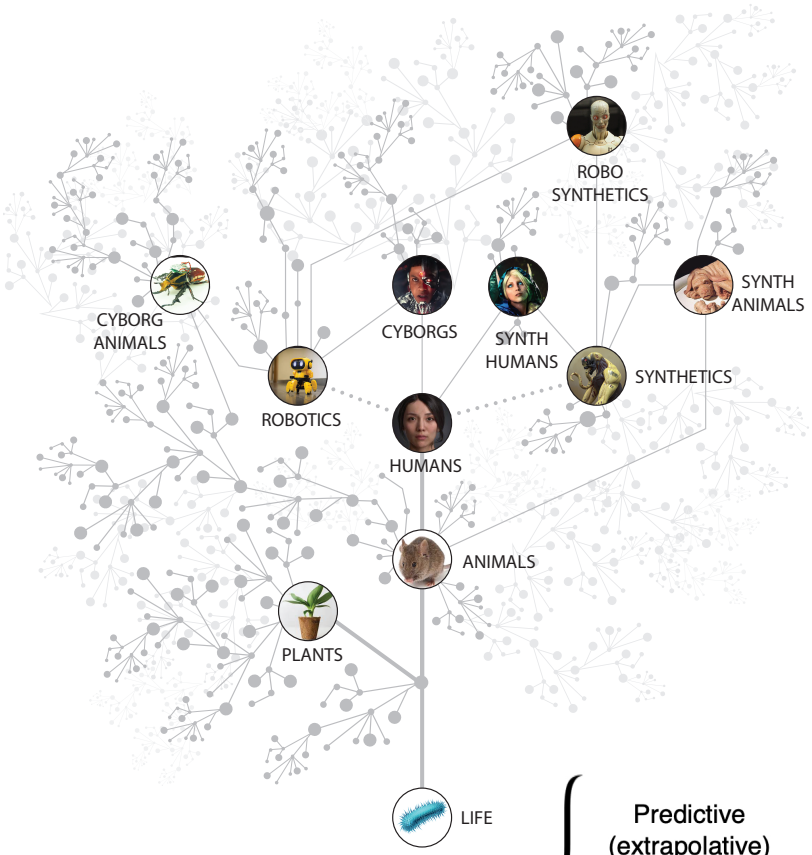
- general-issue humans and other animals, plus

- humans with intelligent internal appliances (e.g., neurotransmitter pumps) - cyborgs
- humans with brain implants to control devices
- novel bioengineered animals with diverse bodies
- synthetic living machines made of cells + new materials + electronics
- swarm robotics
- massively distributed bodies (Internet of Things) with electronic and/or living (cultured) brain controllers

- highly diverse agents, at all levels of the Rosenbleuth and Wiener cognitive hierarchy, created by a mix of design and evolution (both biological and simulated)

A True Diversity of Agents





- Behavior
  - Active
  - Non-active (passive)
- Purposeful
- Non-purposeful (random)
- Feed-back (teleological)
- No feedback (non-teleological)
- Predictive (extrapolative)
- Non-predictive (non-extrapolative)
- 1^{st}, 2^{nd}, etc. order of prediction, self-reference

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- Model systems and data:
  - morphogenesis as a collective intelligence
  - Xenobots - a novel proto-organism

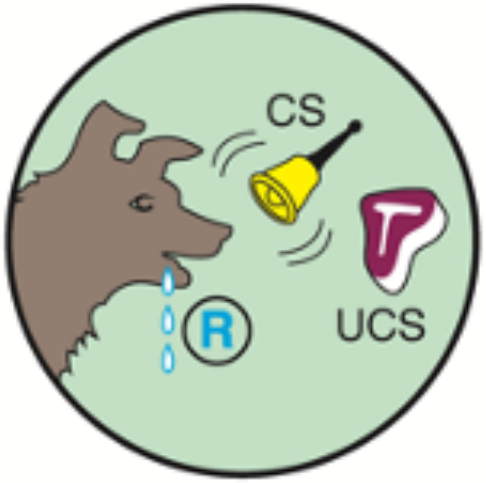
Foundations:

- no binary categories ("is it an agent?") - take evolution and developmental biology seriously, gradual origins
- the point is not to anthropomorphize simple systems but to de-mystify human and other cognition
- engineering, empirical stance on theories - no teleophobia, type II errors in attributing agency
- agents can be a patchwork of multiple unconventional Intelligences at different levels
- there's no magic in material ("synapses", protoplasm, etc.)
- biology, not zoology - "life as it can be" and "mind as it can be"

Axis of Persuadability: an Engineering Take on a Continuum of Agency

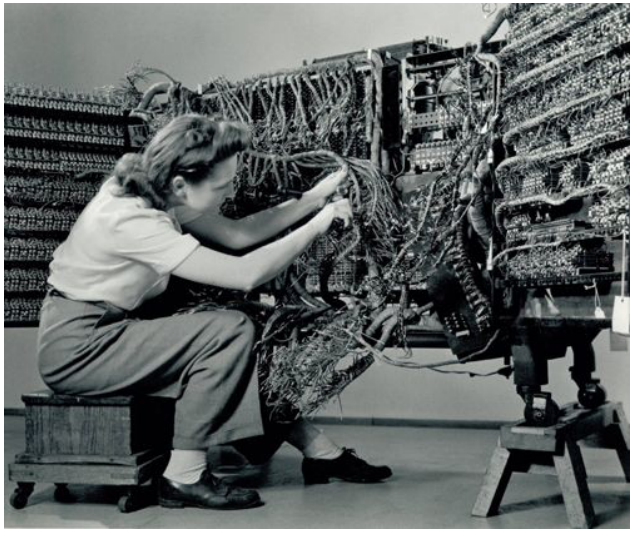
Hardware modification only

Modify the data encoding setpoint of goal-driven process



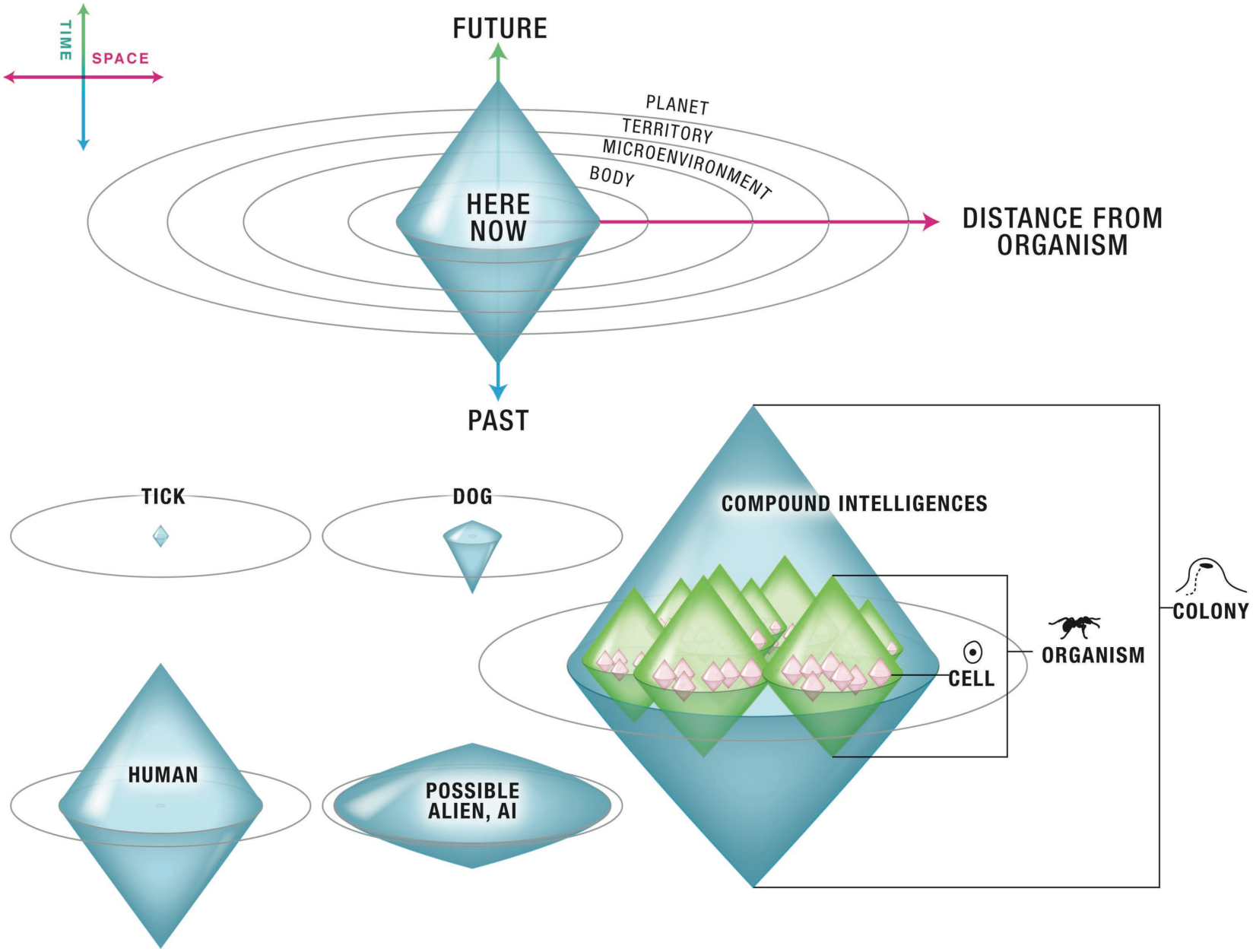
Training by rewards/ punishments

Communicate cogent reasons



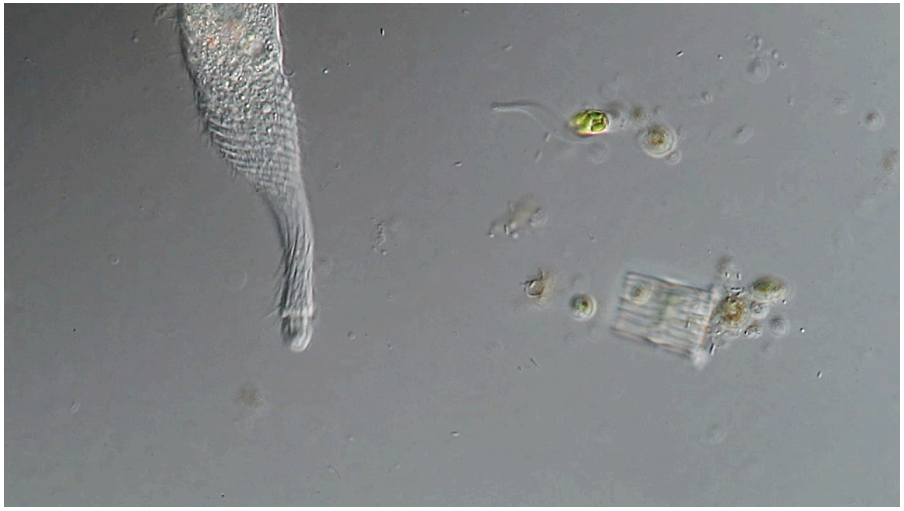
A Cognitive Option Space for truly Diverse Intelligences Based on the Scale of the Goals they can Pursue

How to define and compare truly diverse Selves?



Scaling of the Self: (owner of goals at scale)

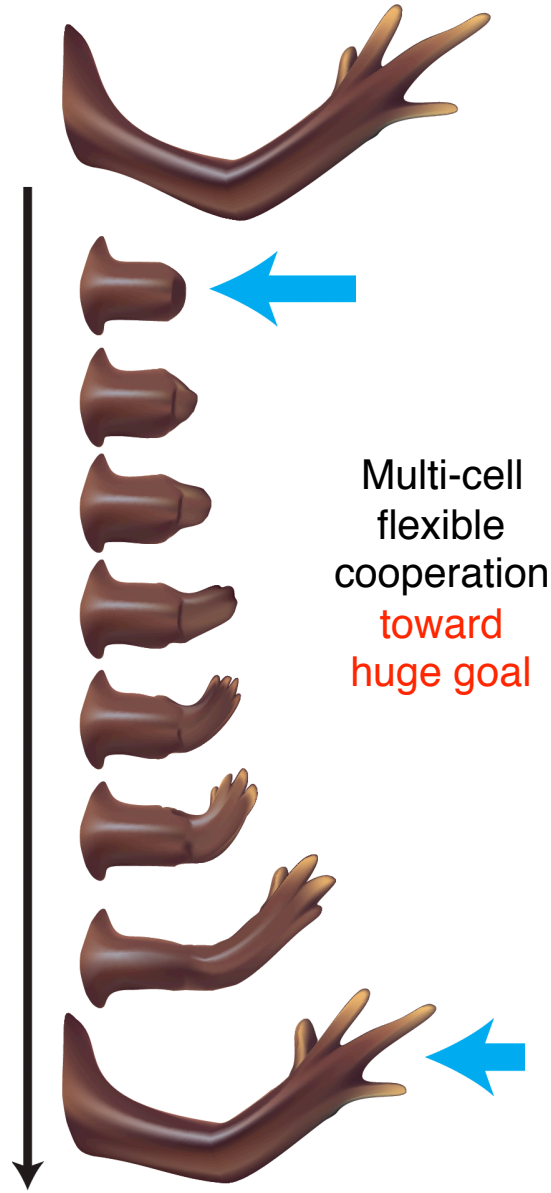
Single cell Goals



video by Charles Krebs

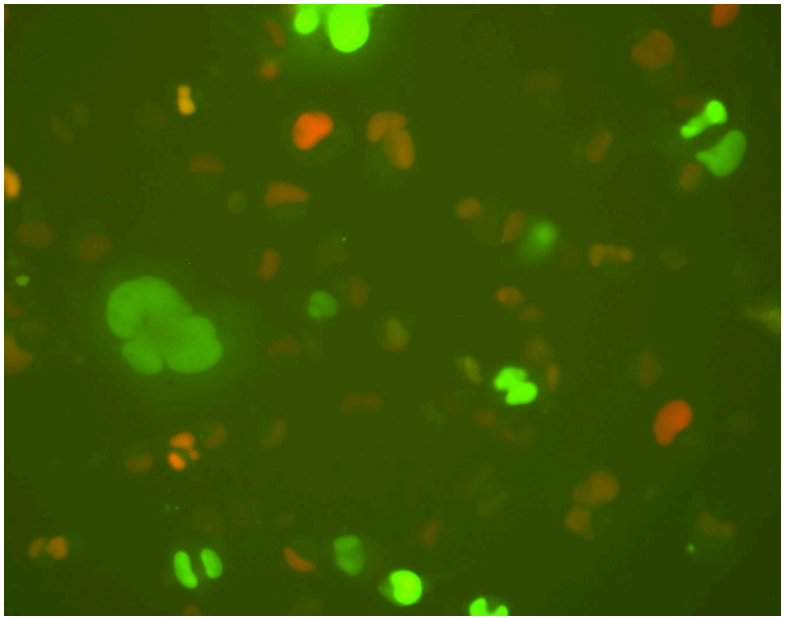
goal size scales UP

goal size scales DOWN



Multi-cell flexible cooperation toward huge goal

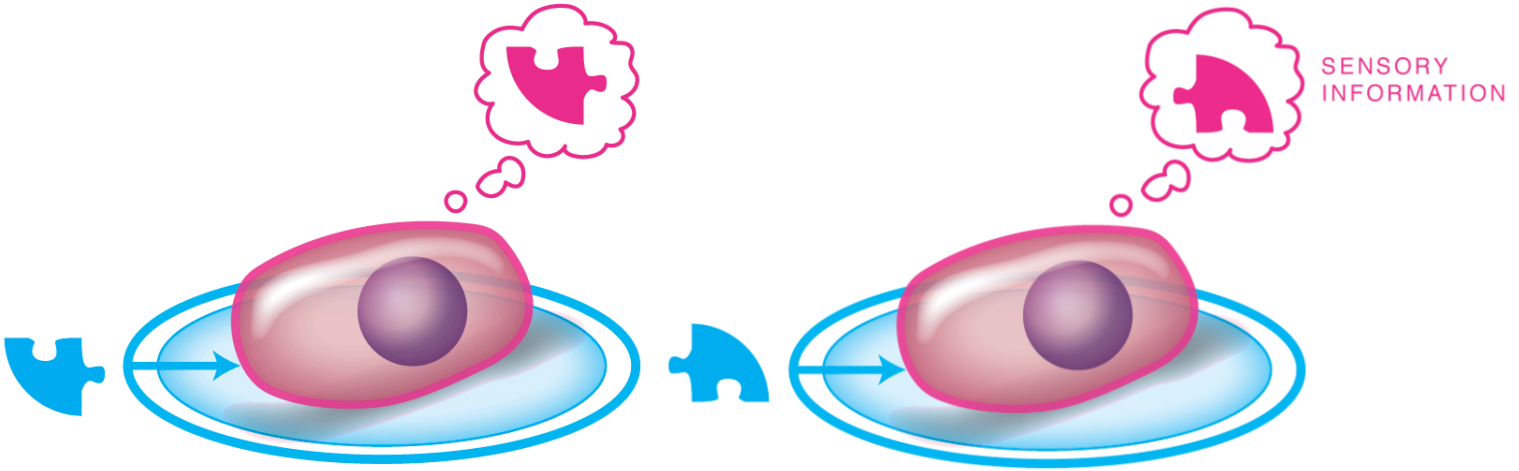
Cancer = defection, reversion to local goals



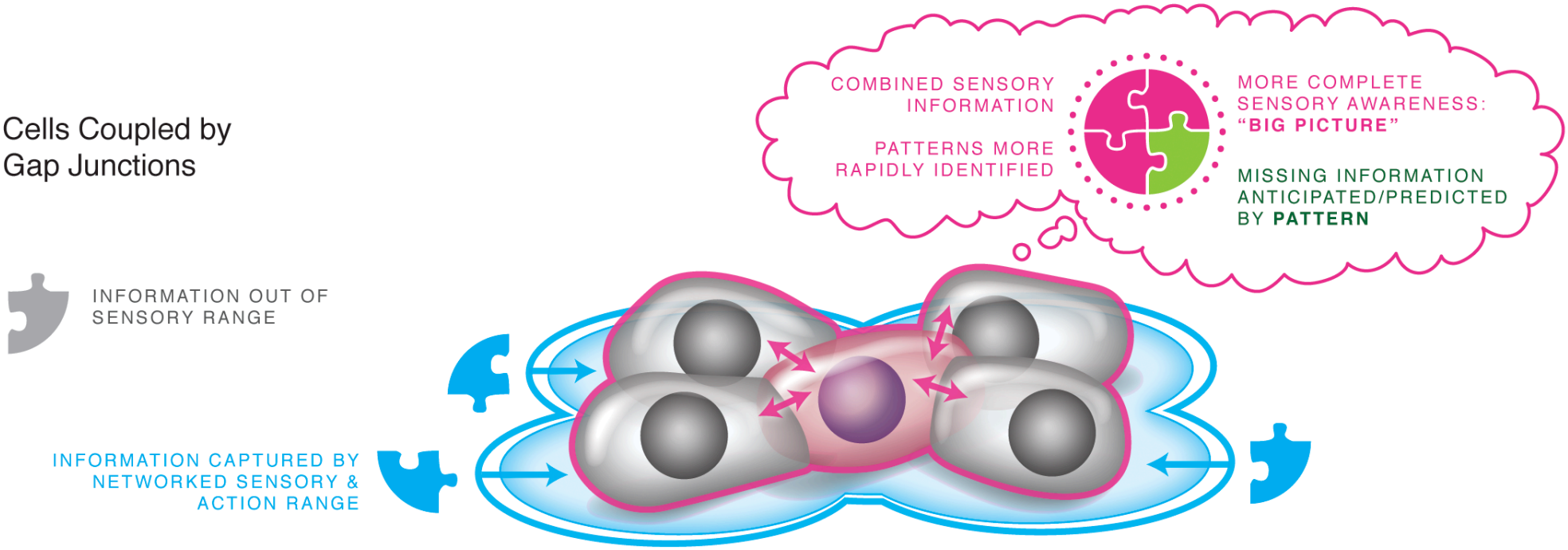
video by Juanita Mathews

Origin of Multicellular Mind

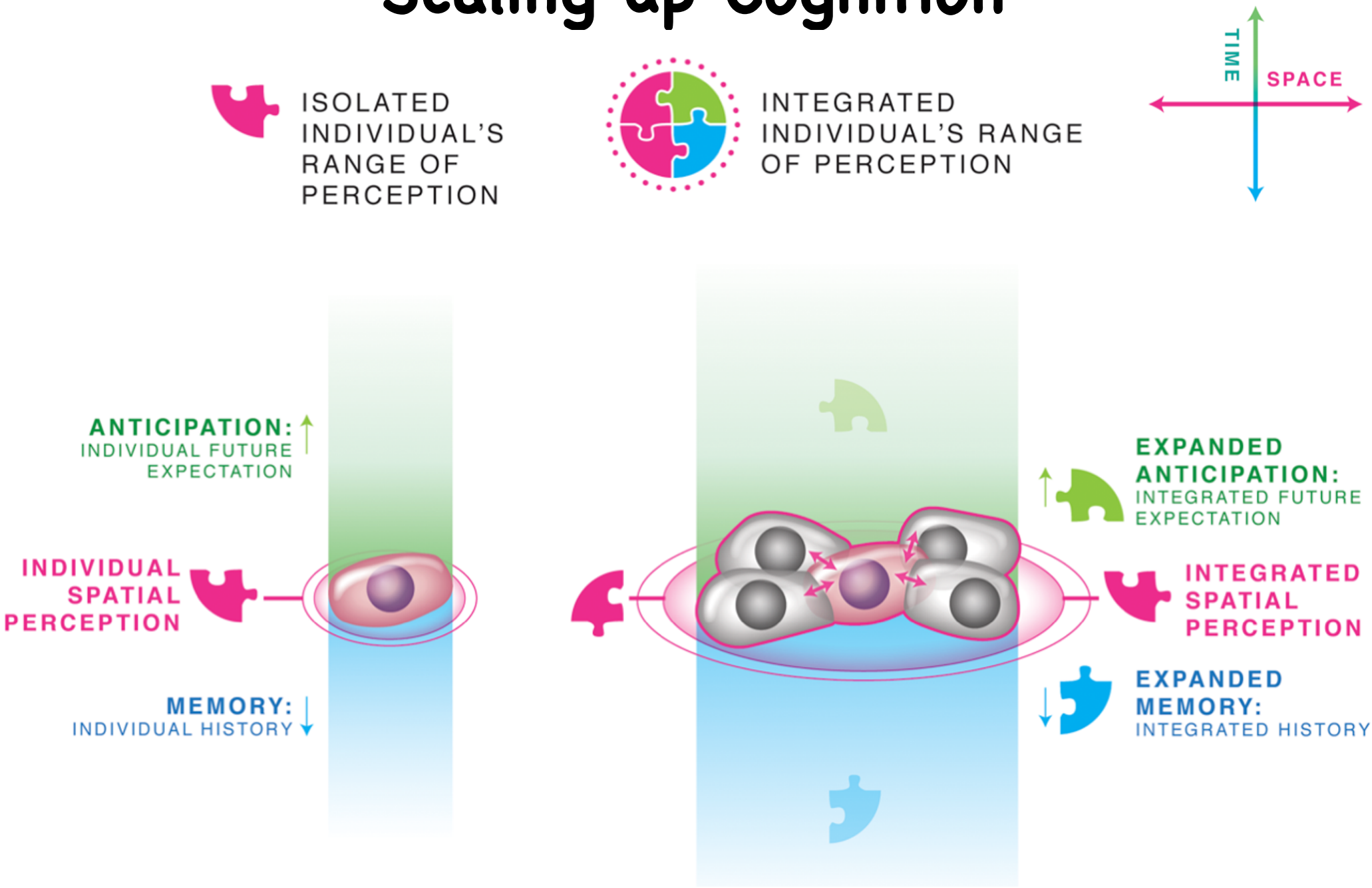
1. Individual Cell



2. Cells Coupled by Gap Junctions



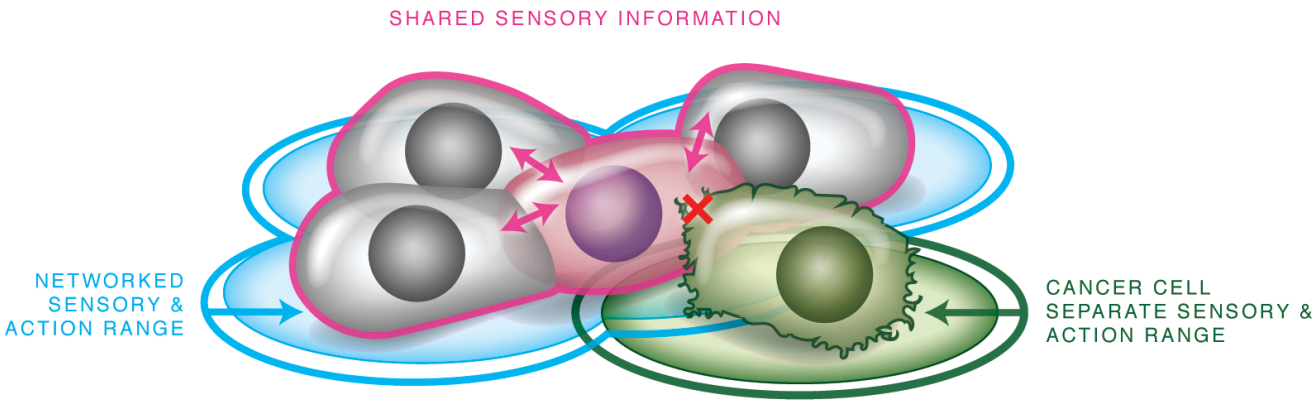
Scaling up Cognition

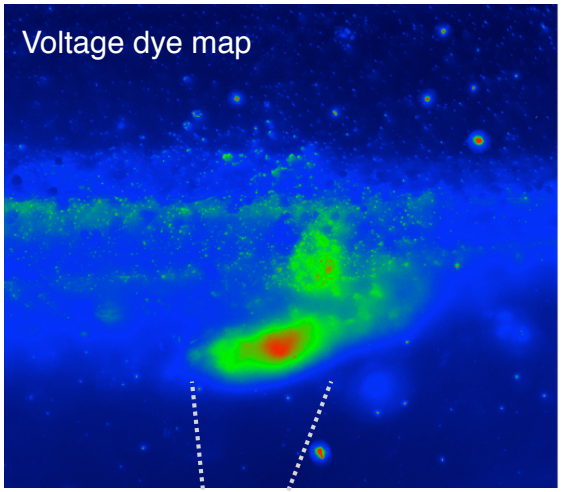


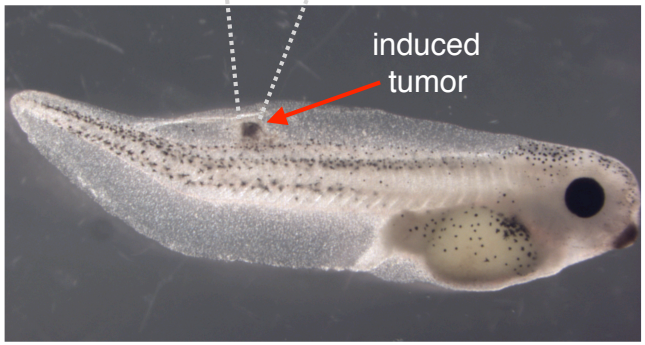
- larger-scale, more complex states can now be setpoints and source of stress

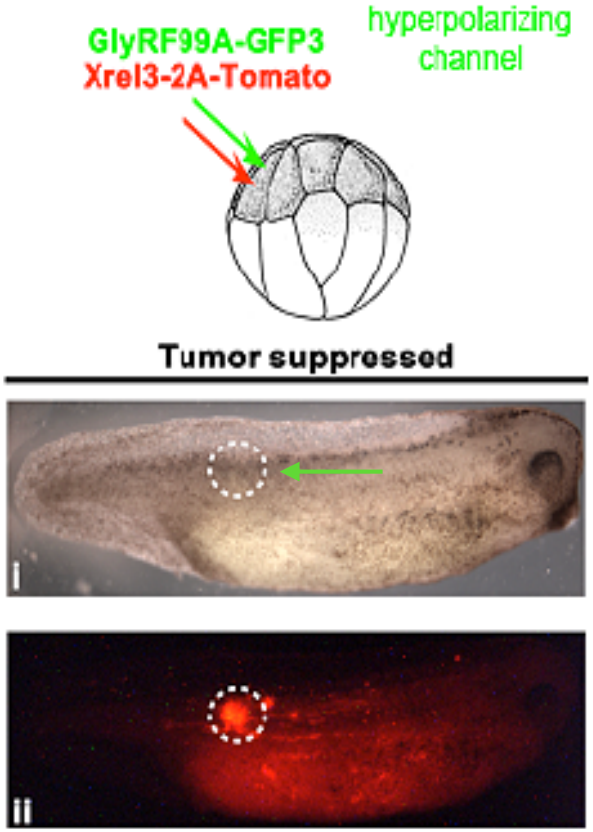
Flexible Boundary Between Self and World:
shifting scale of cognitive agent

Cells Coupled by Gap Junctions, Disconnected Cancerous Cells



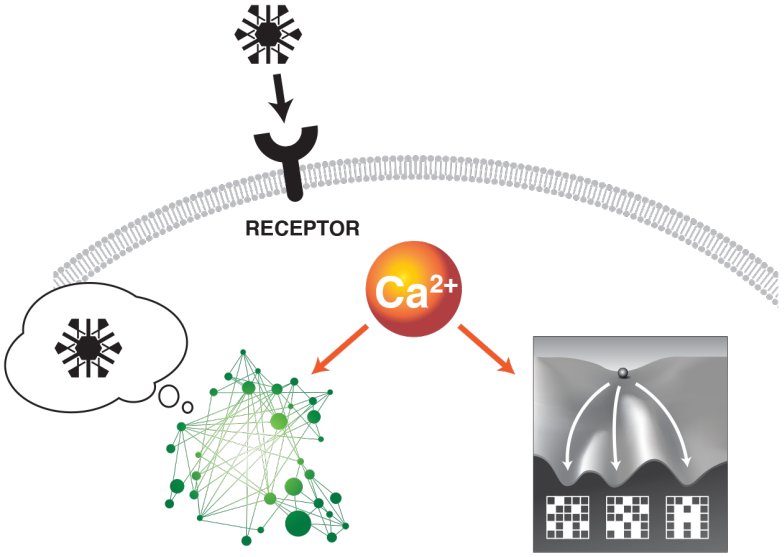


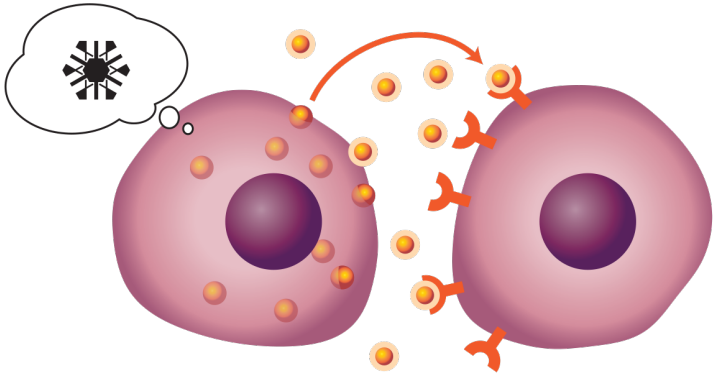




Scaling Memories

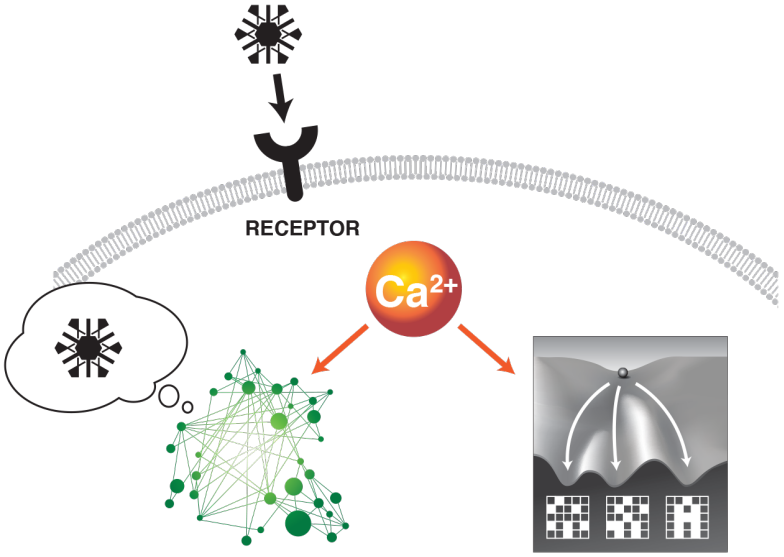
Real Event → Real Memory



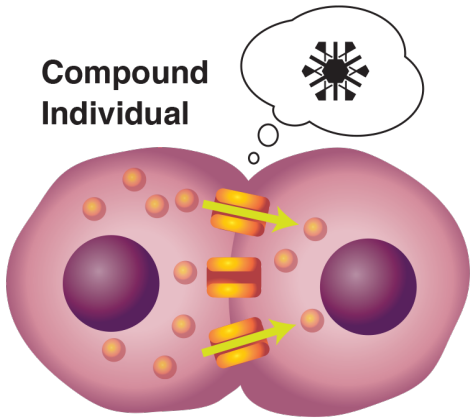


External signaling

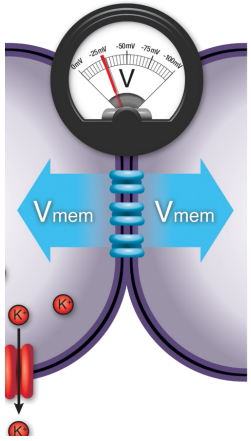
Real Event → Real Memory



Real Event → False Memory

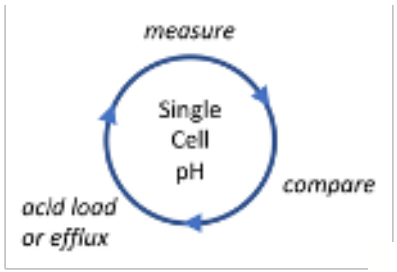


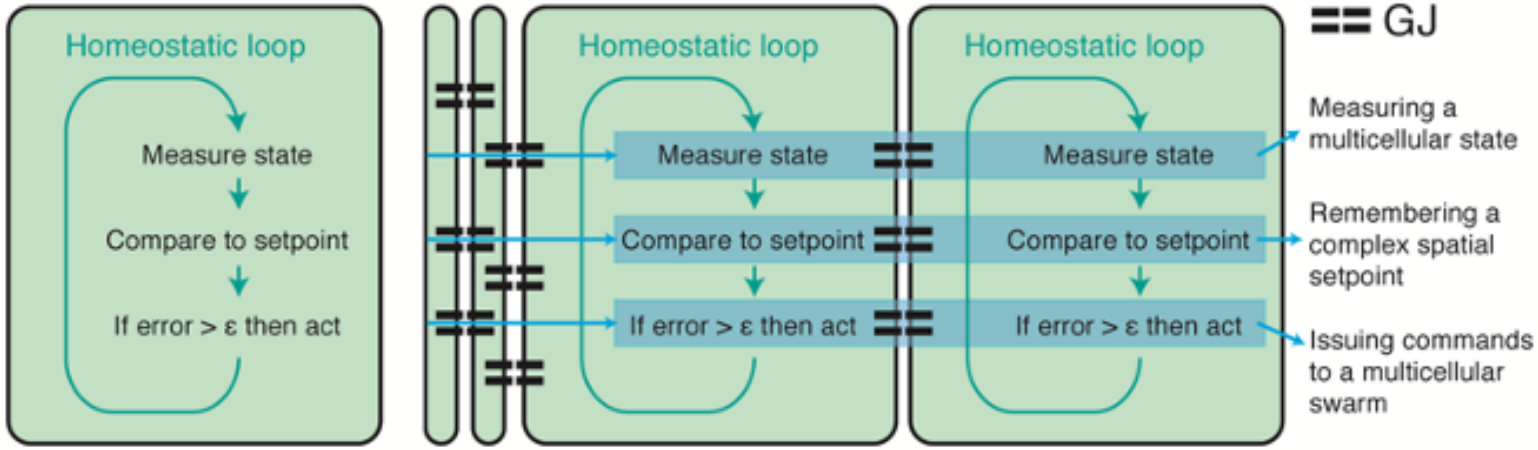
Owner-stripped information transfer

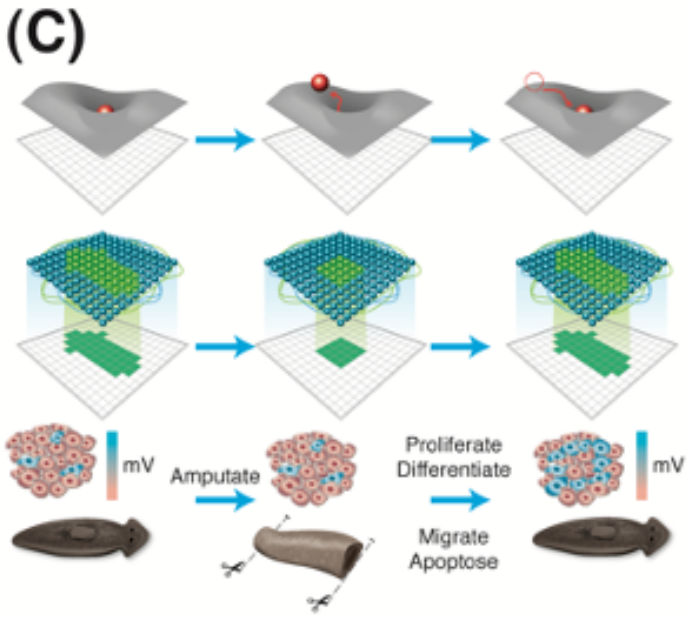


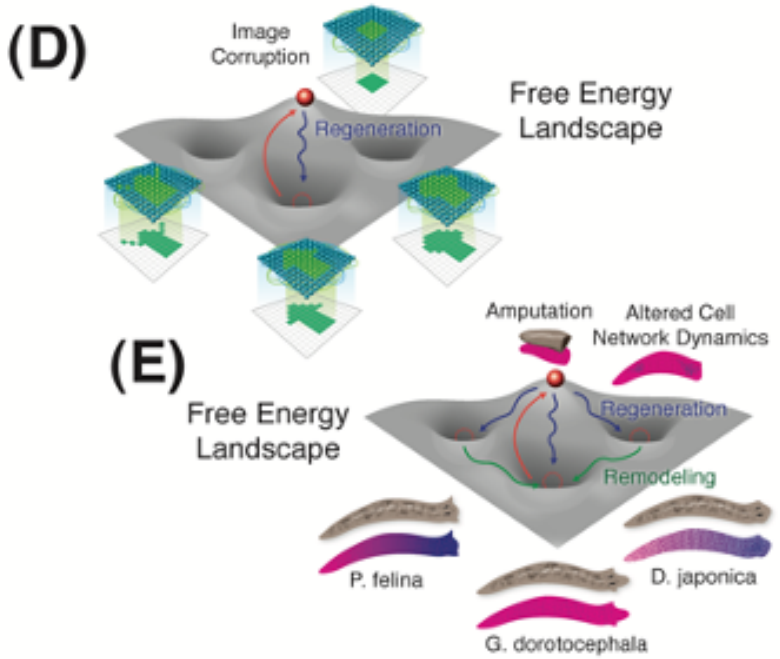
- my memory -> our memories
- my stress -> our stress
- my goal -> our goal

Scaling Goals









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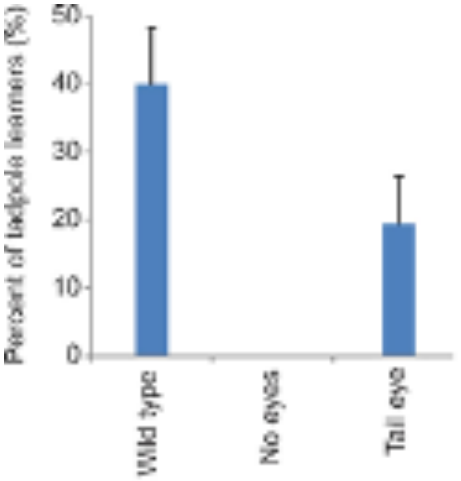
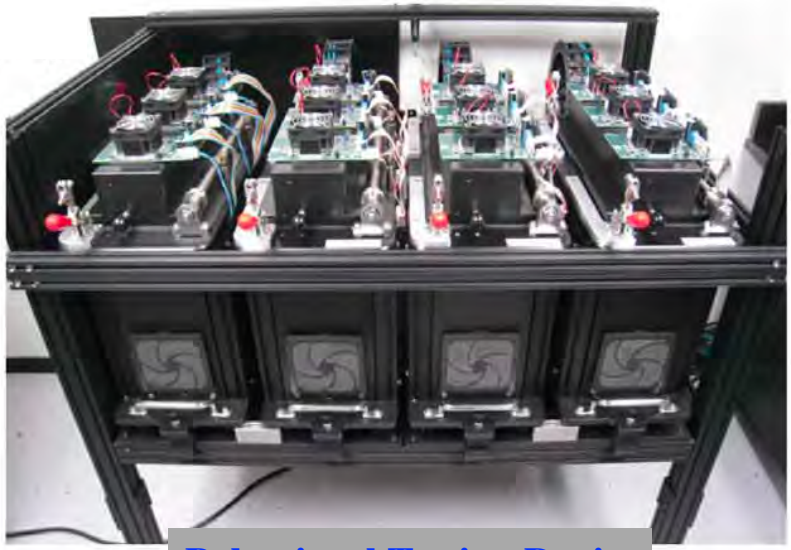
Multi-scale Competency Greatly Improves Evolvability



Ectopic eyes on tail provide vision!

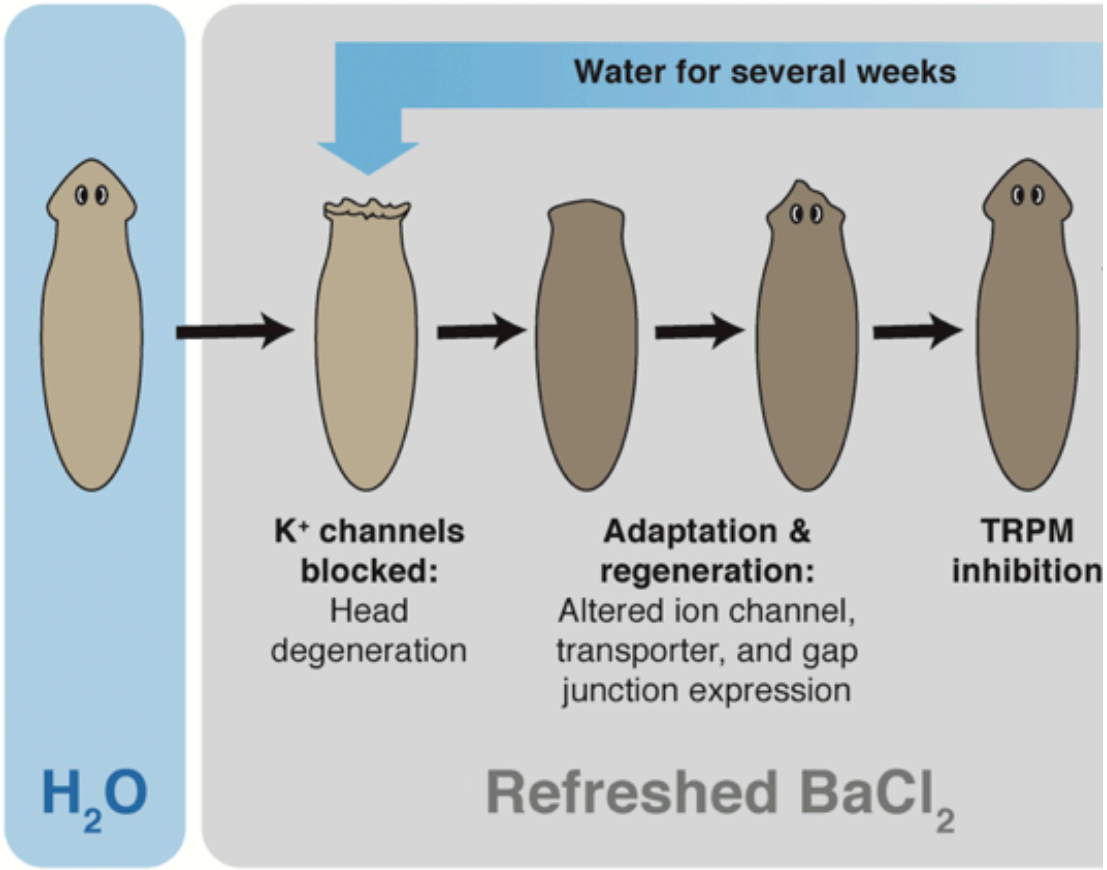


Behavioral Testing Device

1. Robust goal-directedness -> buffers negative consequences of mutations, allowing evolution to explore positive pleiotropic effects (creativity)
2. Higher-level control circuits don't need to solve a huge-dimensional micromanagement problem - they can optimize in reward space

Brain dynamically adjusts behavioral programs to accommodate different body architectures

Example: transcriptional space -> physiological space



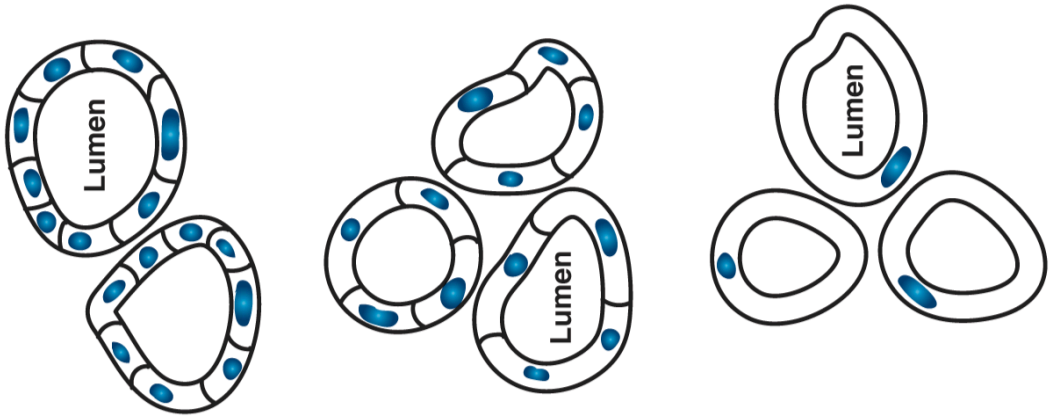
Small number of genes regulated out of entire genome

- 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?

Same Goal, Different Means

- get to the same outcome (region of some arbitrary space)
  - **despite perturbations**
  - **via different paths**
  - from diverse starting positions

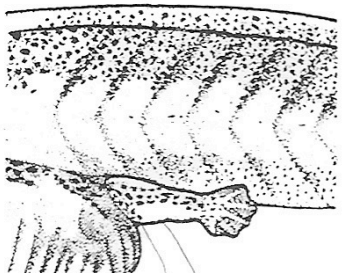
Frankhauser, 1945, J. Exp. Zool., 100(3): 445-455



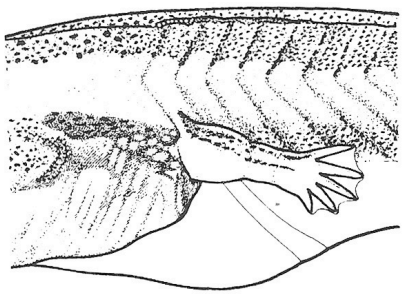
Changing the size of cells still enable large-scale structures to form, even if they have to utilize different molecular mechanisms

Limb Development

St. 55 — F.L.

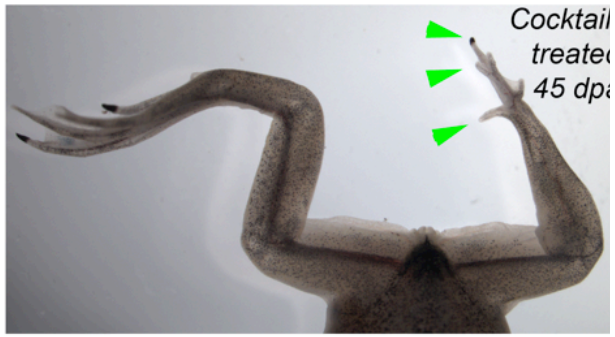


St. 56 — F.L.



St. 56 — Lat.

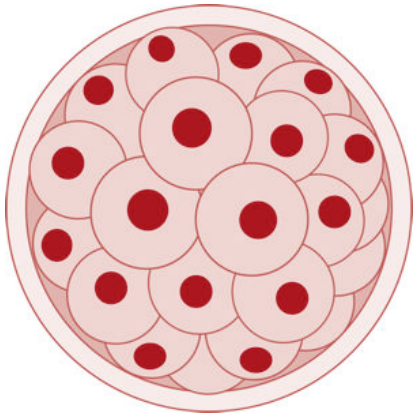
Induced Regeneration



Induced frog leg regeneration takes different path than default limb development, reaches the same final shape

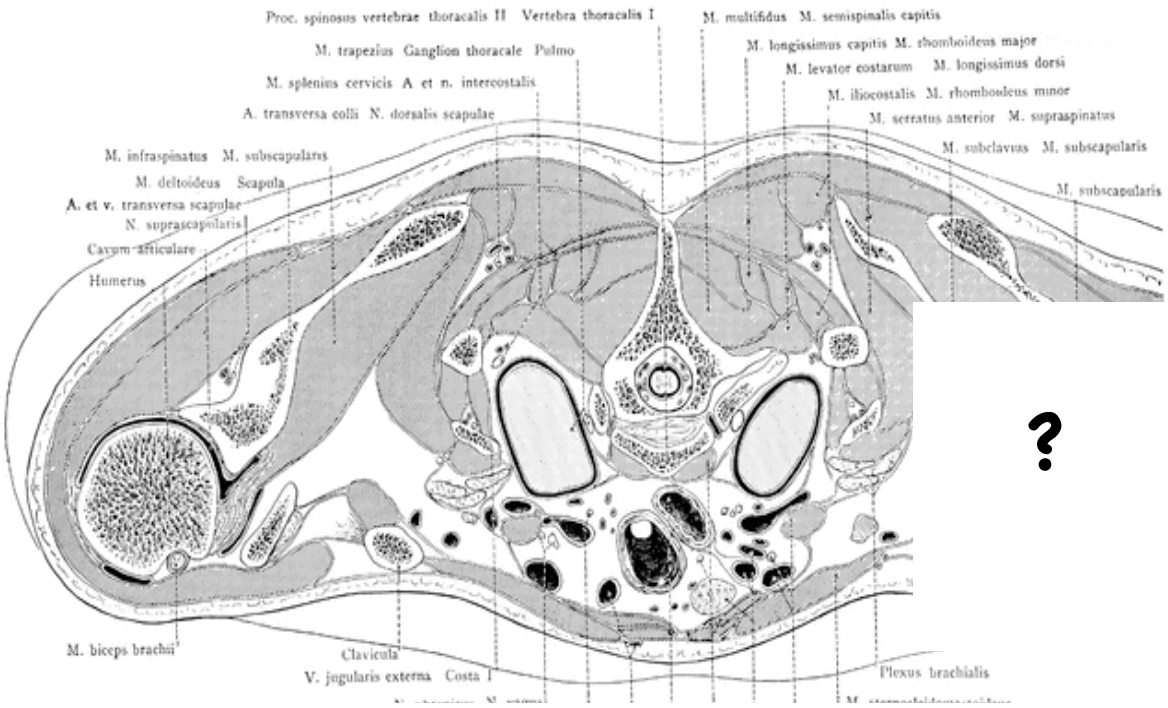
Where is Anatomy Specified?

stem cell
embryonic
blastomeres



self-assembly

- DNA specifies proteins; whence Anatomy?
- how do cell groups know what to make and when to stop?
- how far can we push shape change? Engineers ask: what's possible to build given default genome?



?

How to repair (edit) it?

Single Cells are Extremely Competent

video by Charles Krebs

note spatio-temporal horizon (boundary) of this agent's activity - purely local!

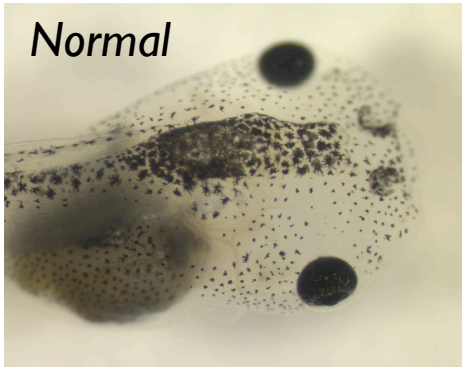
it goes where it wants, eats what it wants - selfish, and the "self" is very small

can can they form collectives to pursue organ-scale anatomical goals? (equally selfish, but the "self" is much larger)

they did not give up their smarts when joining into bodies, but they did have to learn to cooperate to work toward goals on a much larger spatio-temporal scale

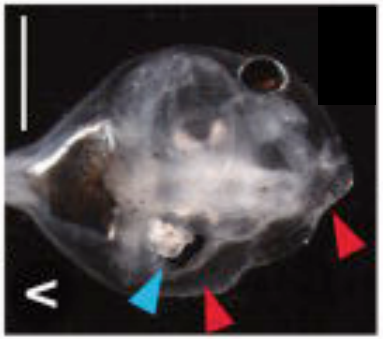
Computational boundary expands drastically, when making a metazoan body

Intelligent Problem-solving in Morphospace



normal development

Picasso-like



"as needed" remodeling

Change bioelectric prepattern

↓

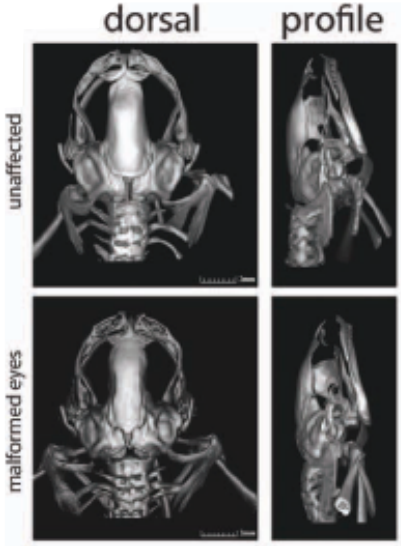
Craniofacial mispatterning

↓

Metamorphosis

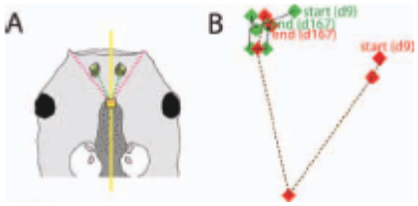
↓

Morphometric analysis and modeling reveals: faces fix themselves!!



Genetics does not specify hardwired rearrangements: it specifies a system that executes a highly flexible program that can recognize unexpected states and take corrective action.

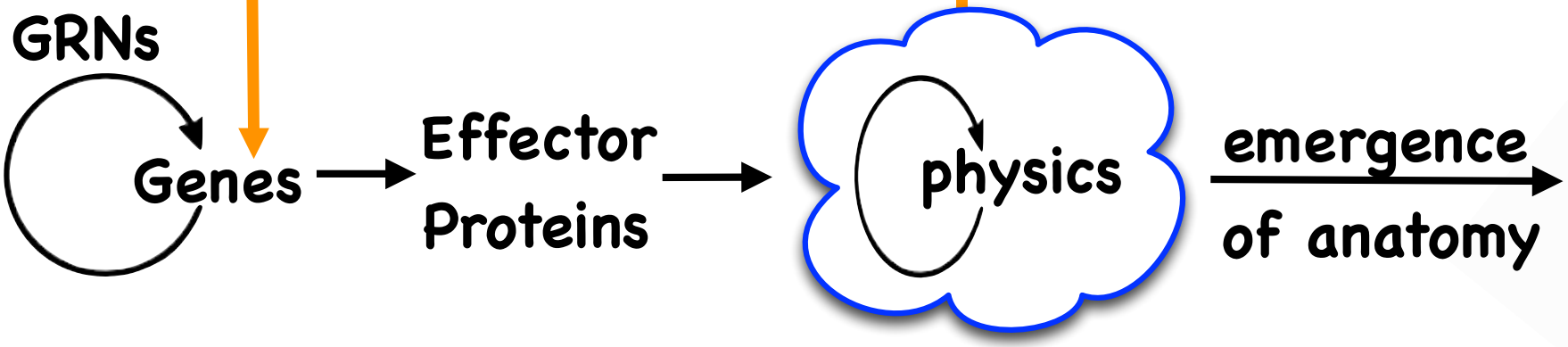
Cannot just follow a rote set of steps. How does it know when it's "right"?

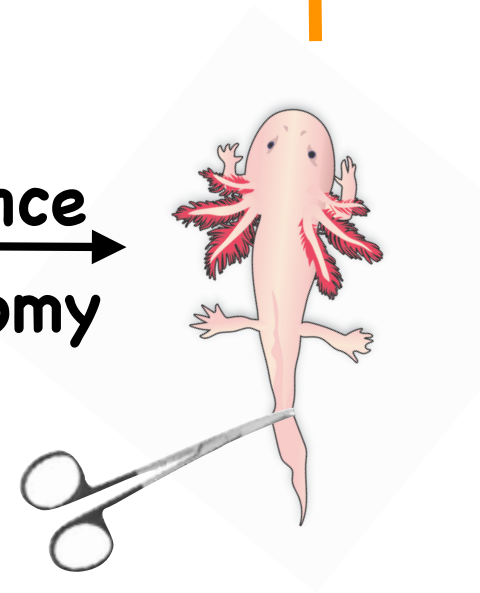


Closed Loop Pattern Homeostasis

Anatomical Error Detection and Control Loop

surveillance and adjustment of self-model





injury
mutation
teratogens
...

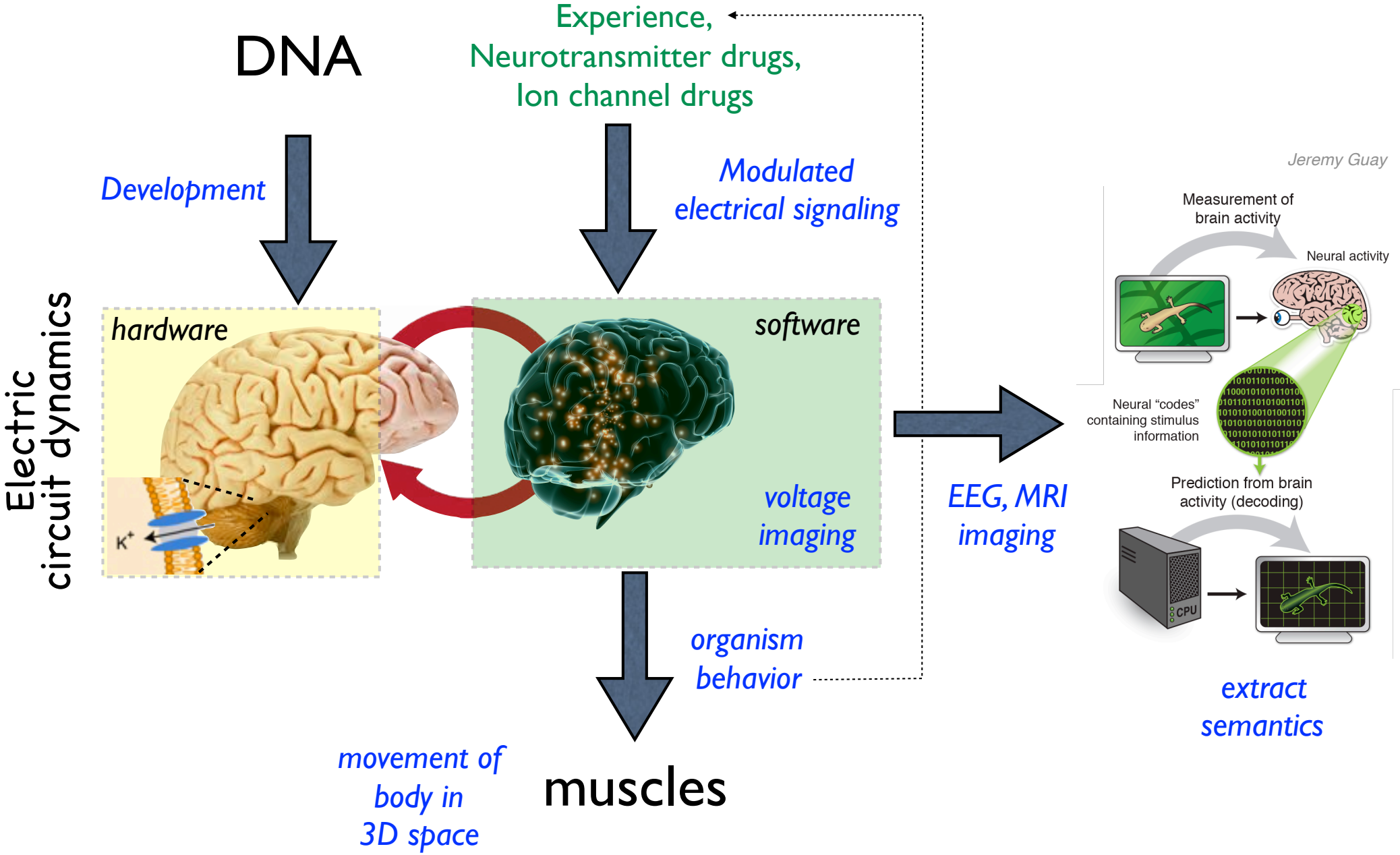
Tissues/organs change
position, shape, gene expression

until the correct shape is re-established,
and then they stop! A homeostatic cycle for shape.

Our strategy:
- target the homeostatic setpoint (pattern memory)
- rewrite it, let cells build to spec

Unpredictable environmental perturbations

Hardware and Software in the Brain



Hardware and Software in the Body

DNA

External stimuli,
Neurotransmitter drugs,
Ion channel drugs

Transcription

Modulated electrical signaling

Electric circuit dynamics

hardware

software

voltage imaging

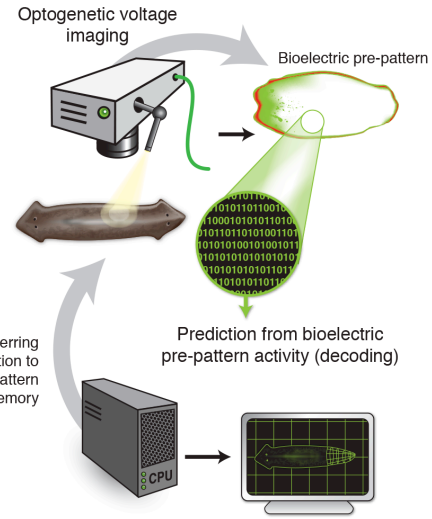
K^+

control of cell behavior: differentiate, migrate, proliferate, apoptose

movement of body shape in morphospace

Cells

Jeremy Guay

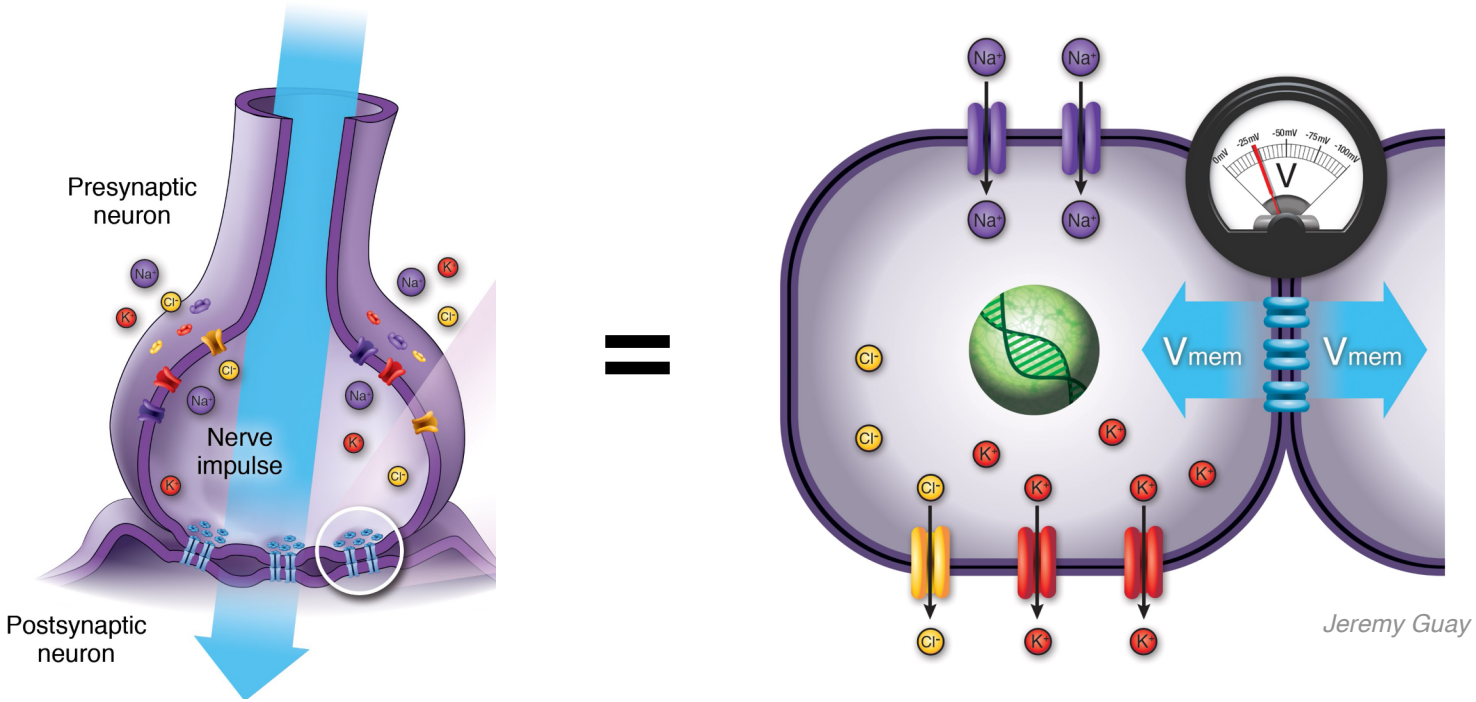


extract semantics

Bioelectric Circuits consist of:

ion channels - set V_{mem}

gap junctions - share V_{mem}



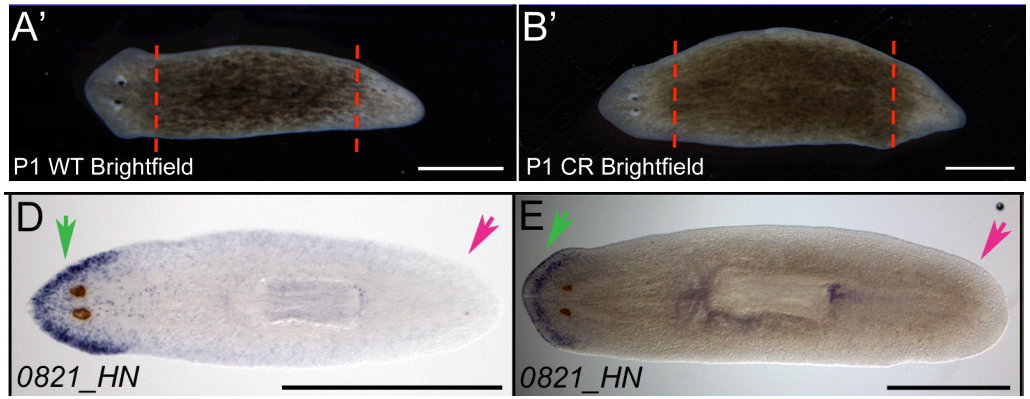
Neurons and synapses evolved by specializing similar functions in normal somatic cells - slow electric conduction, developmental roles of neurotransmitter molecules

REVIEW
PHYSIOLOGY 35: 16–30, 2020. Published December 4, 2019; doi:10.1152/physiol.00027.2019

Morphological Coordination: A Common Ancestral Function Unifying Neural and Non-Neural Signaling

Chris Fields,[1] Johanna Bischof,[2] and Michael Levin[2]
[1]23 Rue des Lavandières, Caunes Minervois, France; and [2]Allen Discovery Center at Tufts University, Medford, Massachusetts
michael.levin@tufts.edu

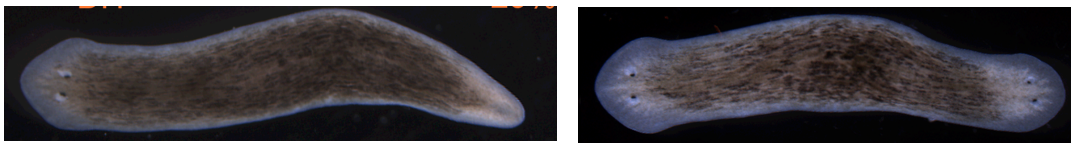
Re-writing Anatomical Pattern Memory

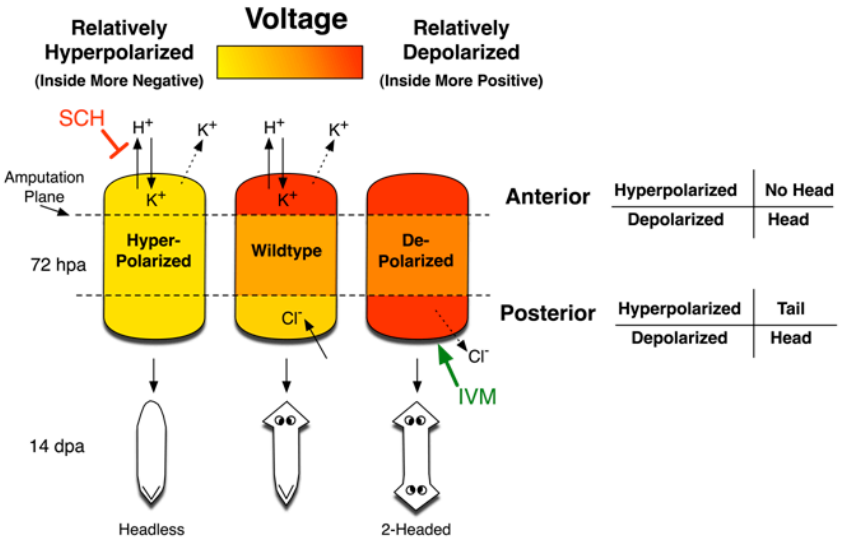


normal anatomy

normal molecular histology

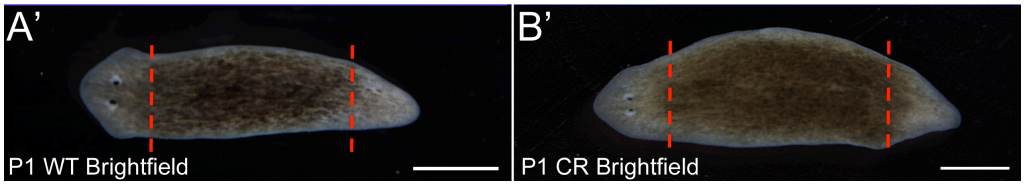
middle-third regenerates:



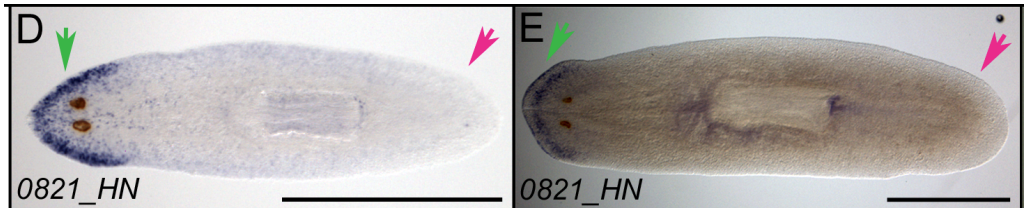


distinct anatomical outcomes despite identical, normal genomic sequence

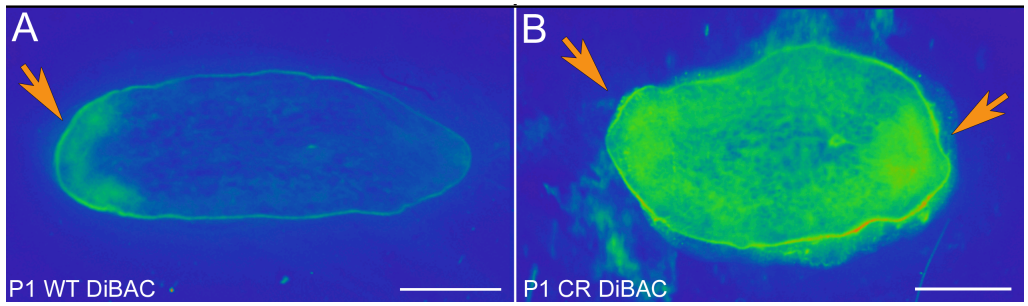
Bioelectrically-Encoded Pattern Memory



normal anatomy

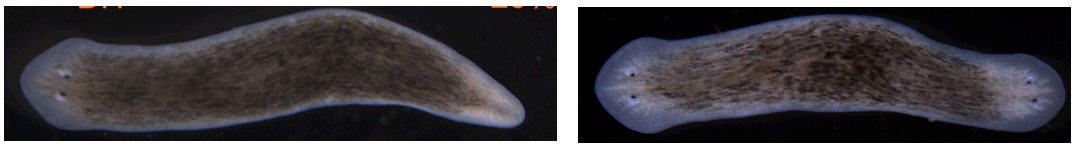


normal molecular histology

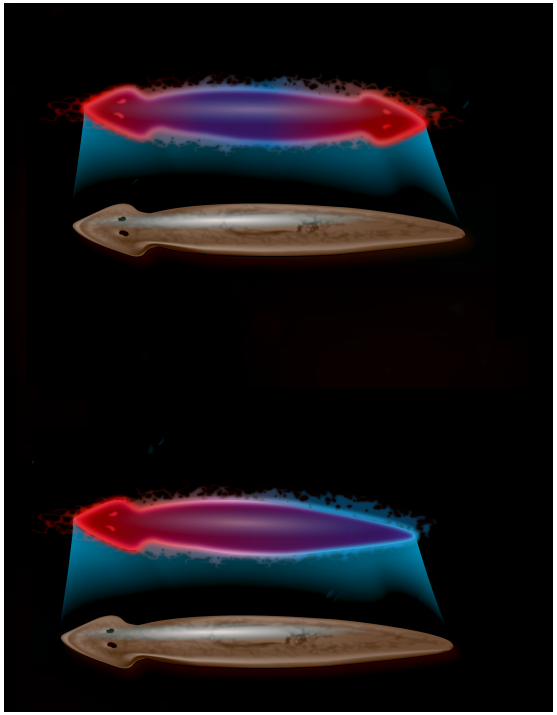


edited bioelectric pattern

middle-third regenerates:

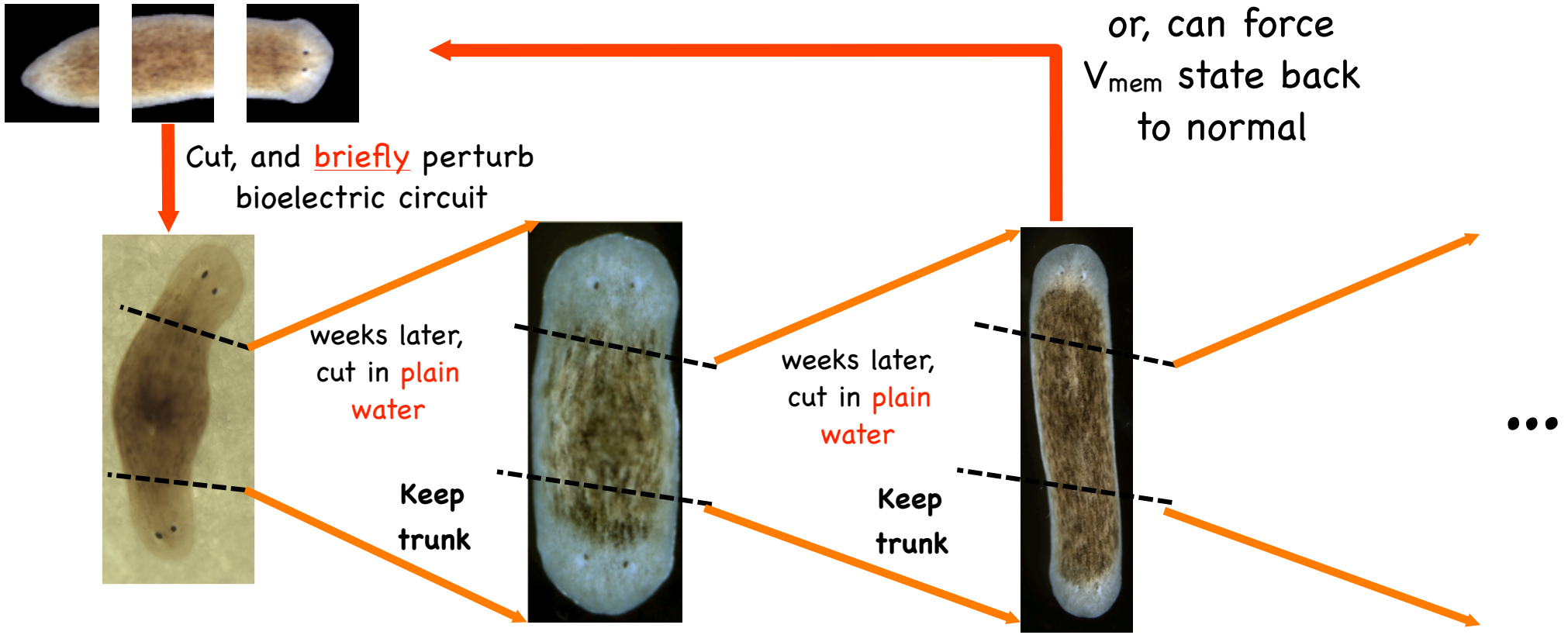


The Same Body can Store different Electrical Pattern Memories



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

Like any Good Memory, it is Stable and its content is not determined by the Hardware

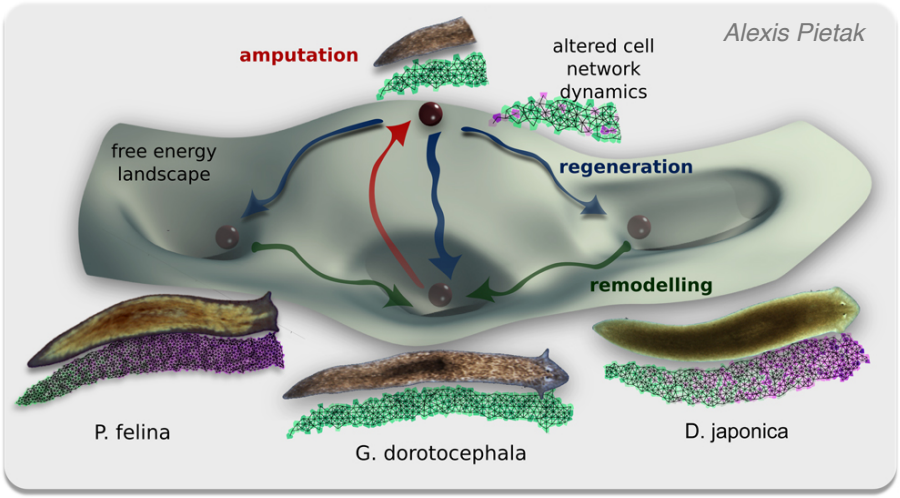


Basic properties of memory

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

Modifying Communication between Cells in Collective causes them to recall pattern memories of other species

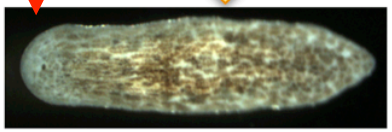
Tweaking of bioelectric network connectivity causes regeneration of head shapes appropriate to other species! (also includes brain shape and stem cell distribution pattern)



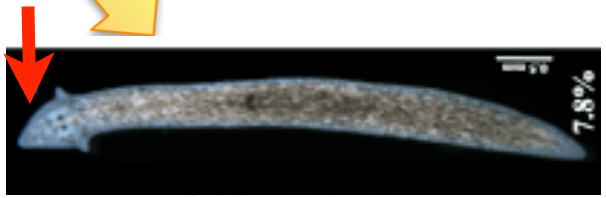
D. dorotocephala

cut off head, perturb network topology

like:

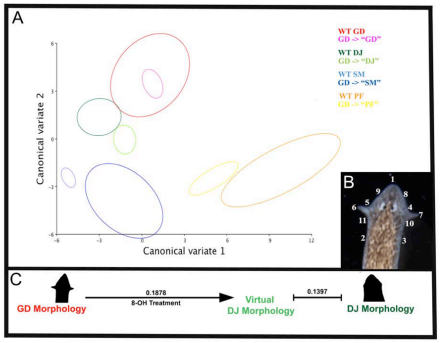


like:

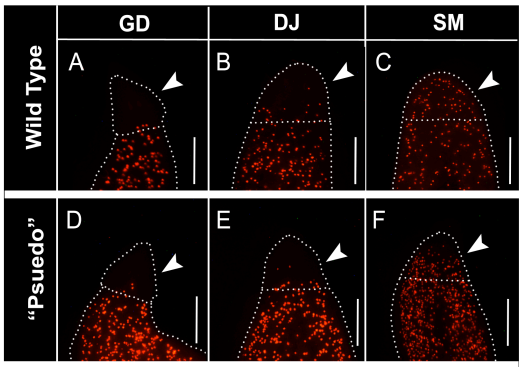


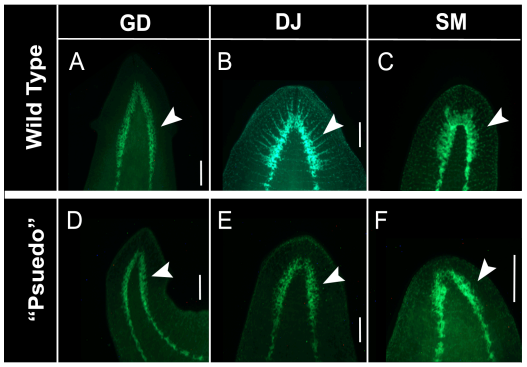
S. Mediterranea

quantitative morphometrics

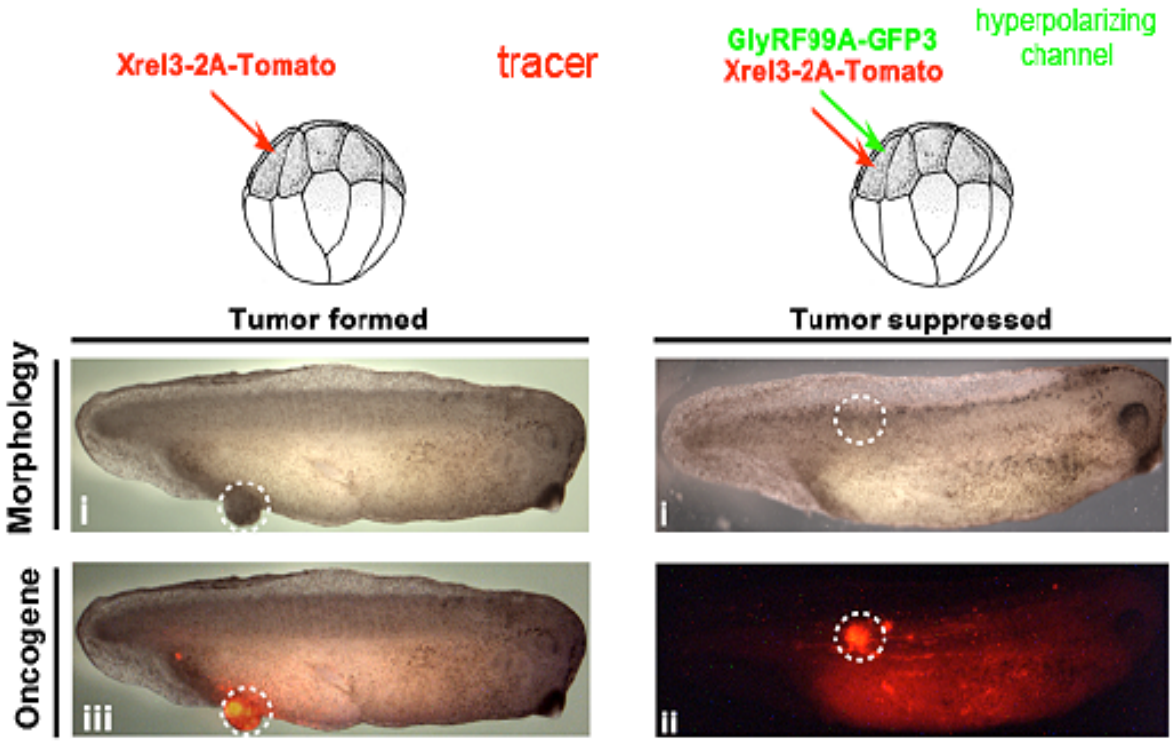


brain shape and stem cell patterns match also!





Bioelectric state overrides genetic mutation (e.g., KRAS) in tumorigenesis - suppression and reprogramming



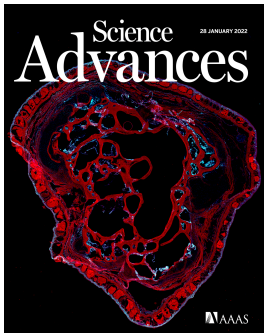
SCIENCE ADVANCES | RESEARCH ARTICLE

DEVELOPMENTAL BIOLOGY

Acute multidrug delivery via a wearable bioreactor facilitates long-term limb regeneration and functional recovery in adult *Xenopus laevis*

Nirosha J. Murugan[1,2], Hannah J. Vigran[1,2], Kelsie A. Miller[1,2], Annie Golding[2,3], Quang L. Pham[2,3], Megan M. Sperry[1,4], Cody Rasmussen-Ivey[1,2], Anna W. Kane[1,2,4], David L. Kaplan[2,3], Michael Levin[1,2,4]*

Limb regeneration is a frontier in biomedical science. Identifying triggers of innate morphogenetic responses in vivo to induce the growth of healthy patterned tissue would address the needs of millions of patients, from diabetics to victims of trauma. Organisms such as *Xenopus laevis*—whose limited regenerative capacities in adulthood mirror those of humans—are important models with which to test interventions that can restore form and function. Here, we demonstrate long-term (18 months) regrowth, marked tissue repatterning, and functional restoration of an amputated *X. laevis* hindlimb following a 24-hour exposure to a multidrug, pro-regenerative treatment delivered by a wearable bioreactor. Regenerated tissues composed of skin, bone, vasculature, and nerves significantly exceeded the complexity and sensorimotor capacities of untreated and control animals' hypomorphic spikes. RNA sequencing of early tissue buds revealed activation of developmental pathways such as Wnt/β-catenin, TGF-β, hedgehog, and Notch. These data demonstrate the successful "kickstarting" of endogenous regenerative pathways in a vertebrate model.



www.impactjournals.com/oncotarget/ Oncotarget, Vol. 7, No. 15

Use of genetically encoded, light-gated ion translocators to control tumorigenesis

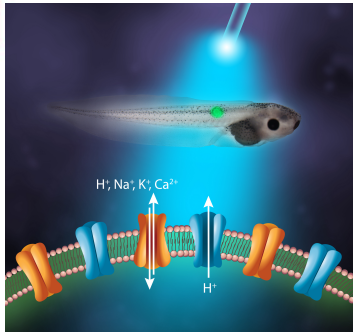
Brook T. Chernet[1], Dany S. Adams[1], Maria Lobikin[1], Michael Levin[1]

[1]Center for Regenerative and Developmental Biology and Department of Biology Tufts University, Medford, MA 02155, USA

Correspondence to: Michael Levin, **e-mail:** michael.levin@tufts.edu

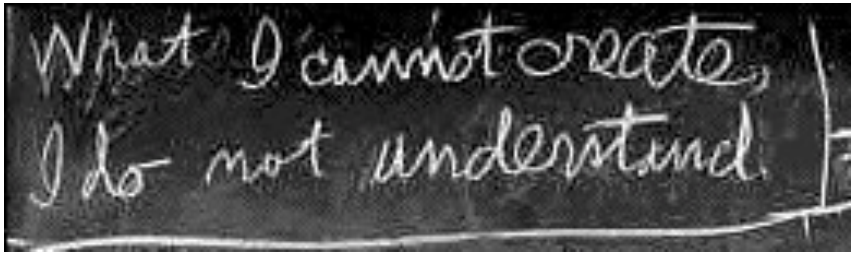
Keywords: v_{mem}, bioelectricity, voltage, RAS, optogenetics

Received: November 22, 2015 ***Accepted:*** February 11, 2016 ***Published:*** March 16, 2016



Making Novel Bodies and Minds:

How much real-time (software) plasticity -
what goals are cells capable of forming, pursuing?



R. Feynman

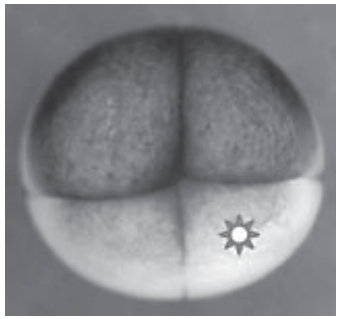
can cells, liberated from their normal boundary condition, reboot multicellularity? Do they like to cooperate, and what will this swarm agent decide to build?

The Institute for Computationally Designed Organisms

Tufts University | University of Vermont

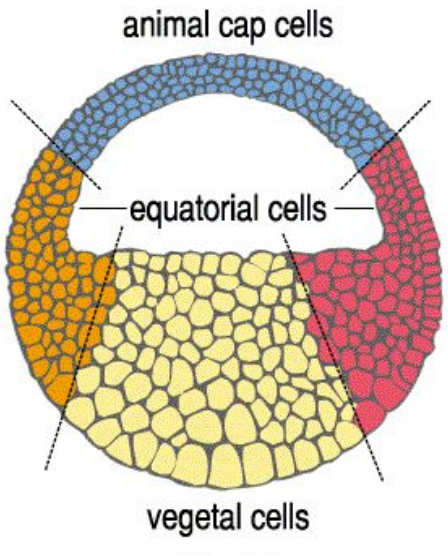
Douglas Blackiston

Rebooting Multicellularity

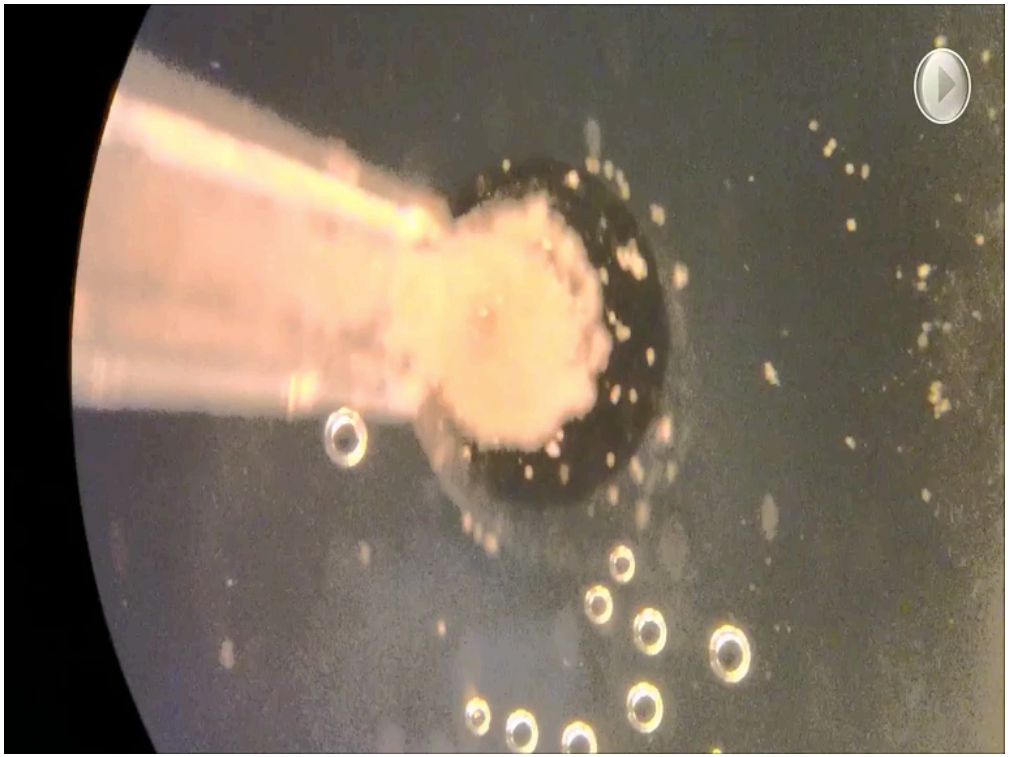


Early frog embryo

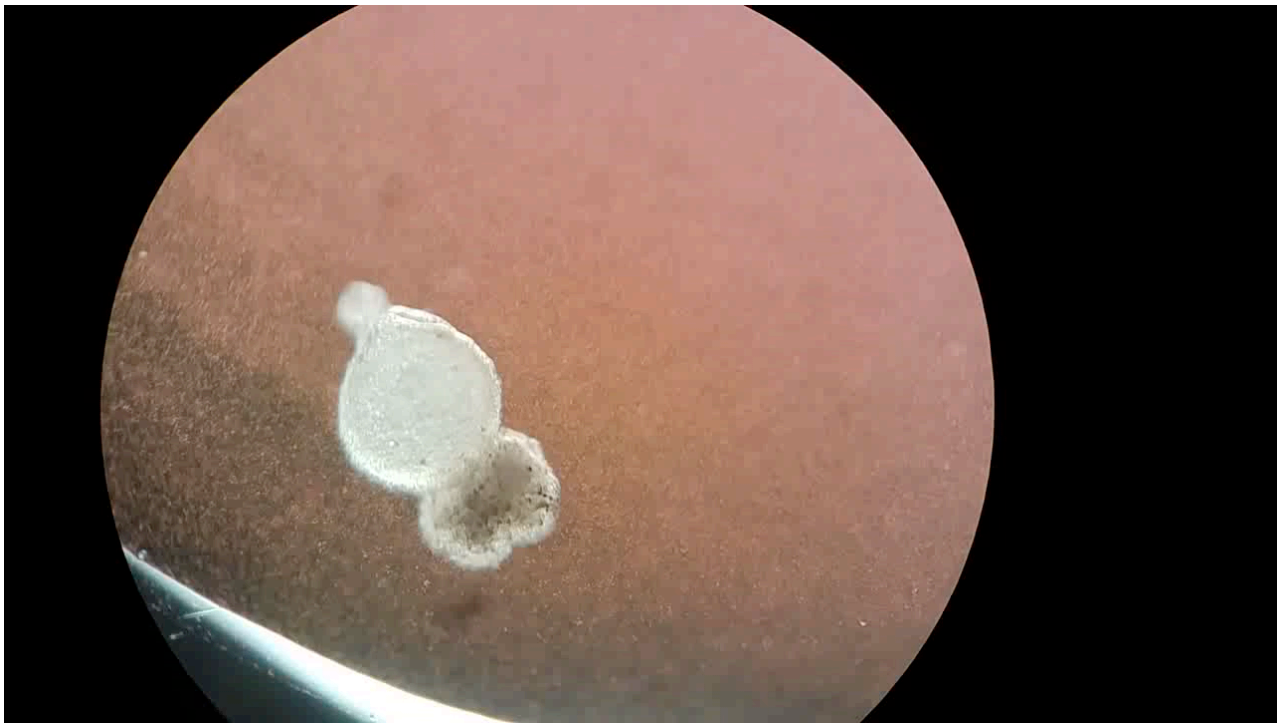
8 hours

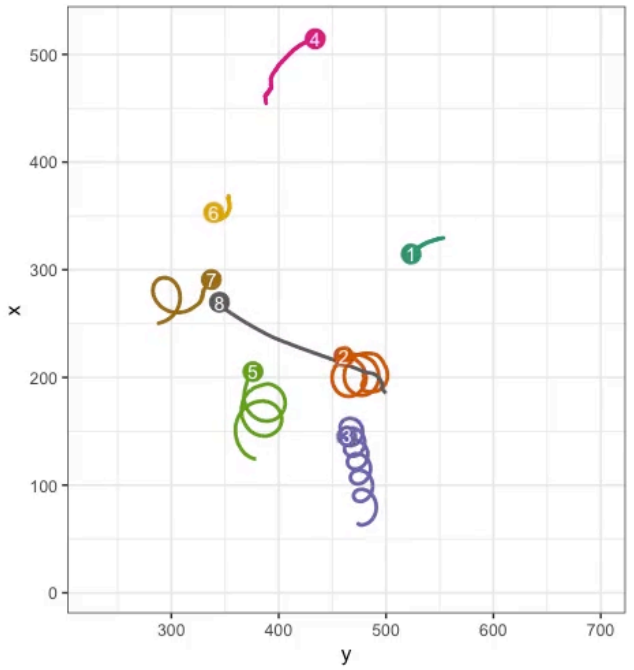


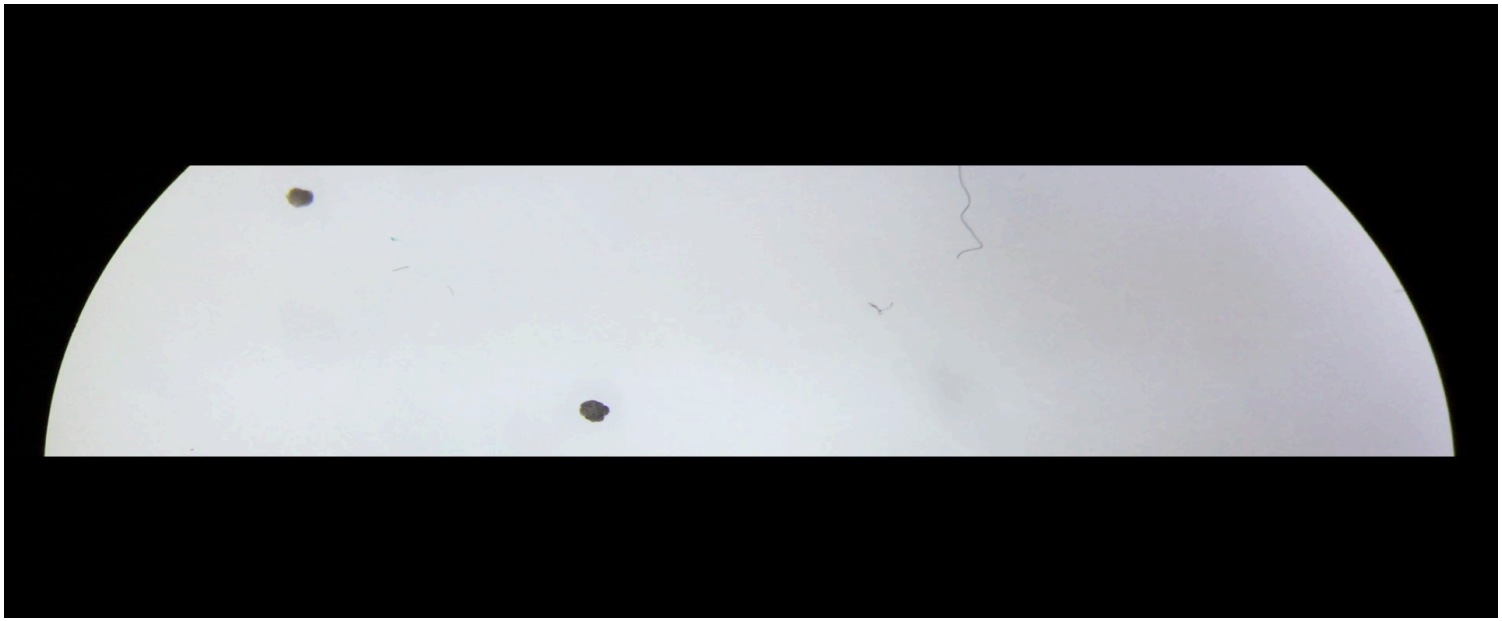
assay for form and function



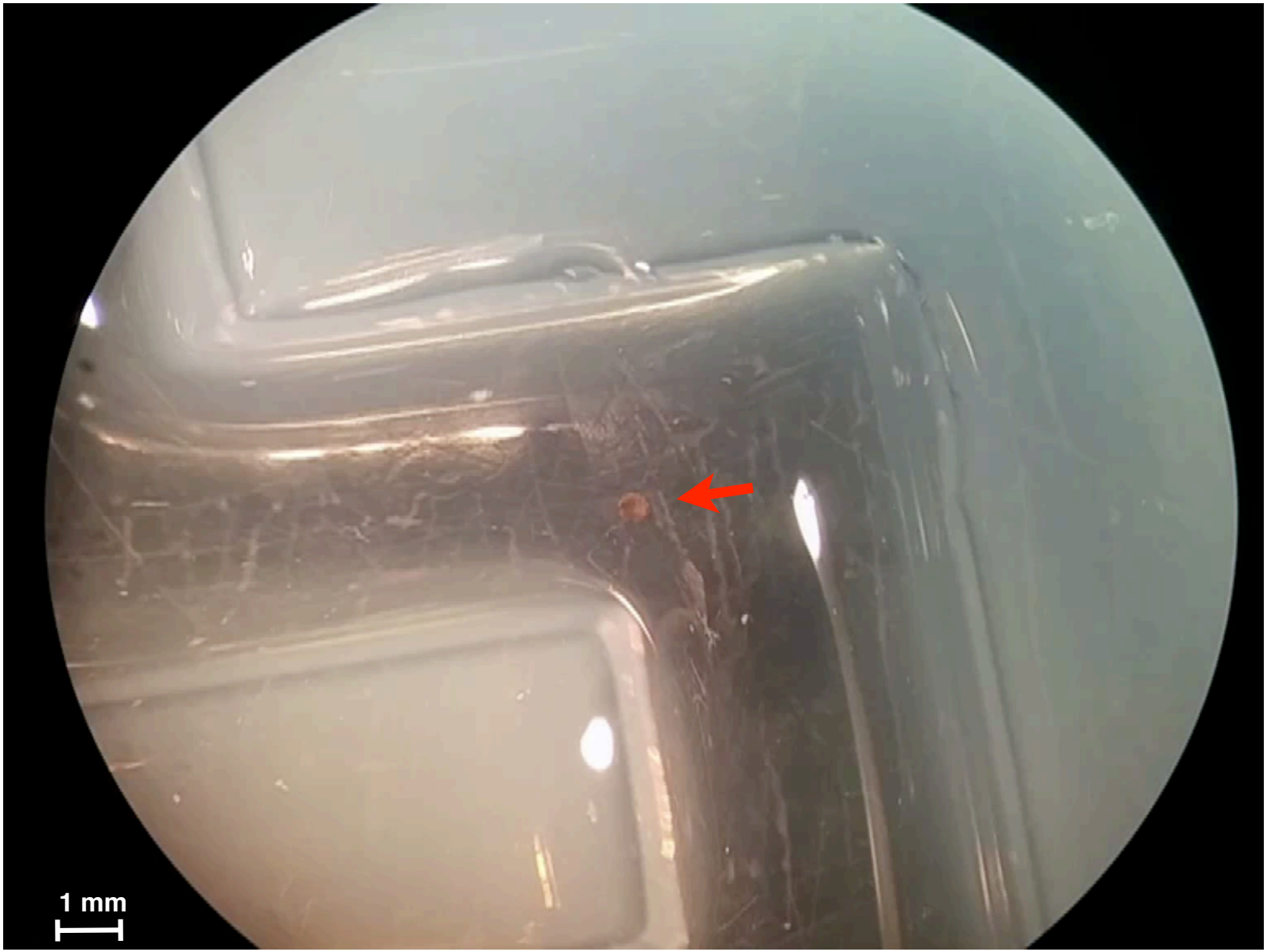
Xenobot behaviors - repurposing cilia





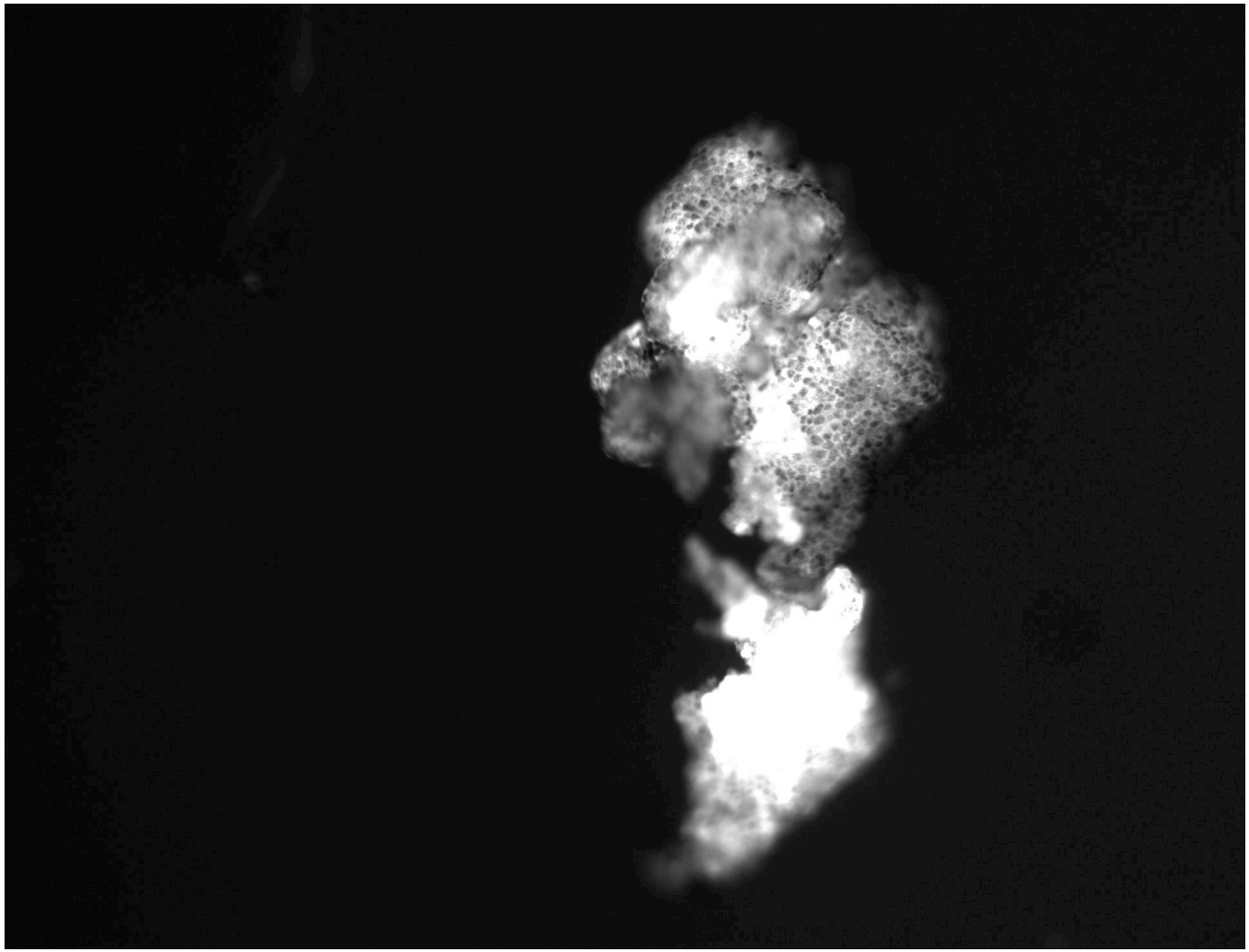


Xenobot in a maze (still water, no flow):

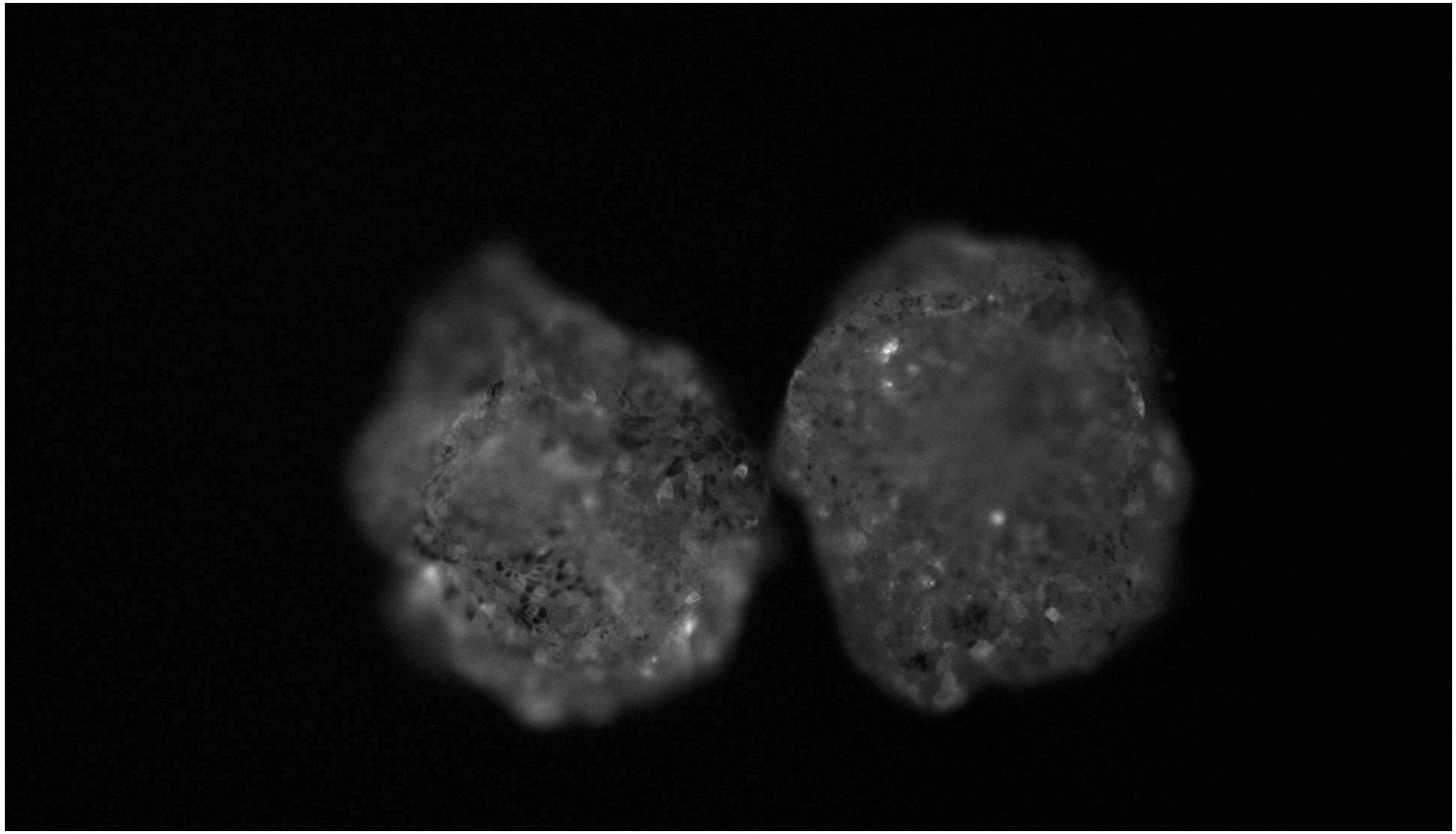


1) it traverses maze, 2) rounds the corners without bumping into walls, and
3) it makes a spontaneous decision to turn around without hitting anything.

Xenobots Regenerate after Massive Damage Back to their New Xenobots Shape



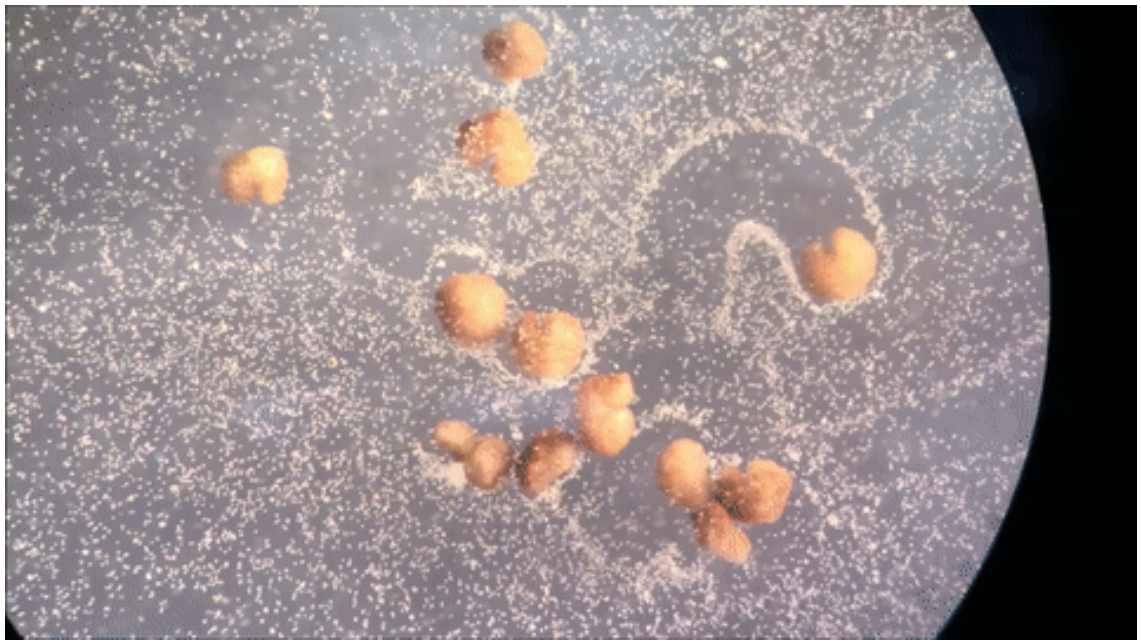
Reading the Xenobot mind: calcium spiking in skin cells — there are no neurons here

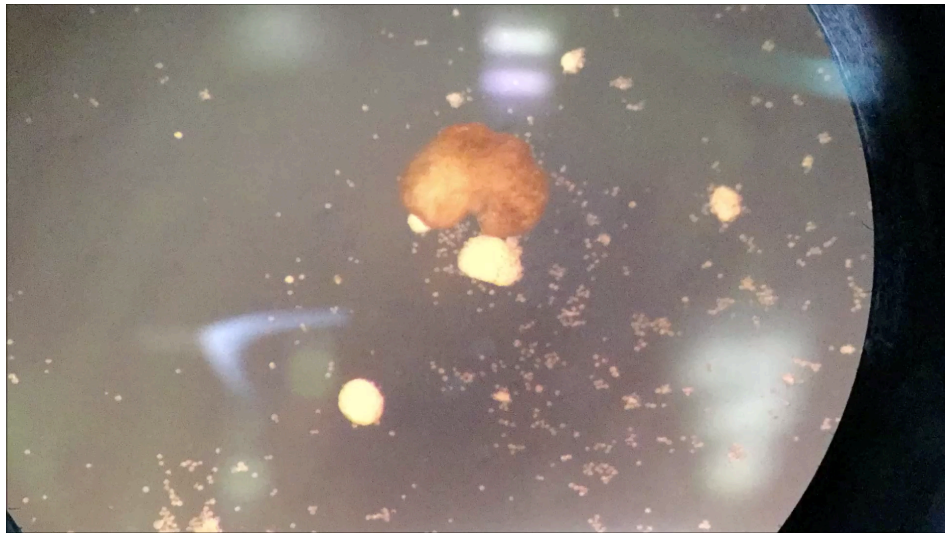


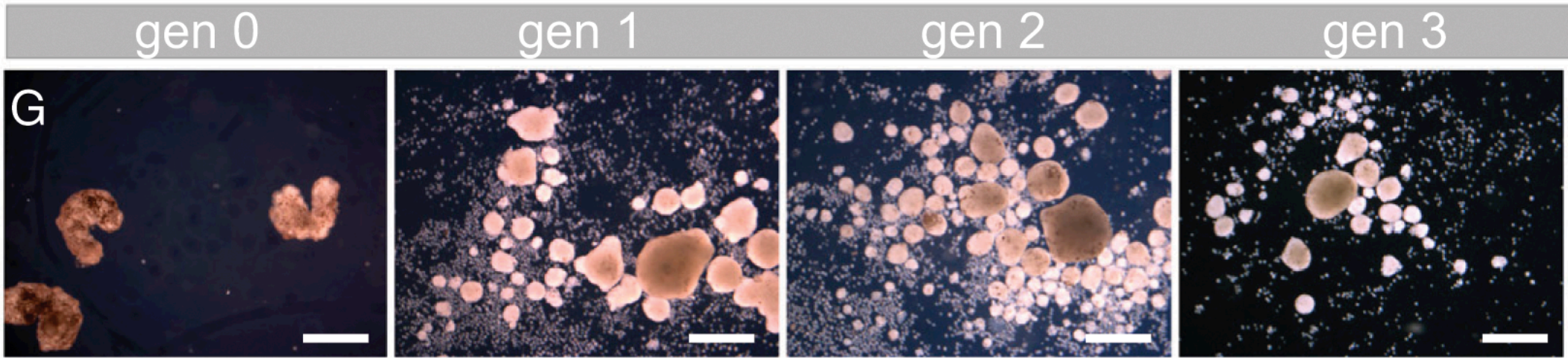
Herding Behavior

Kinematic Replication in Xenobots:

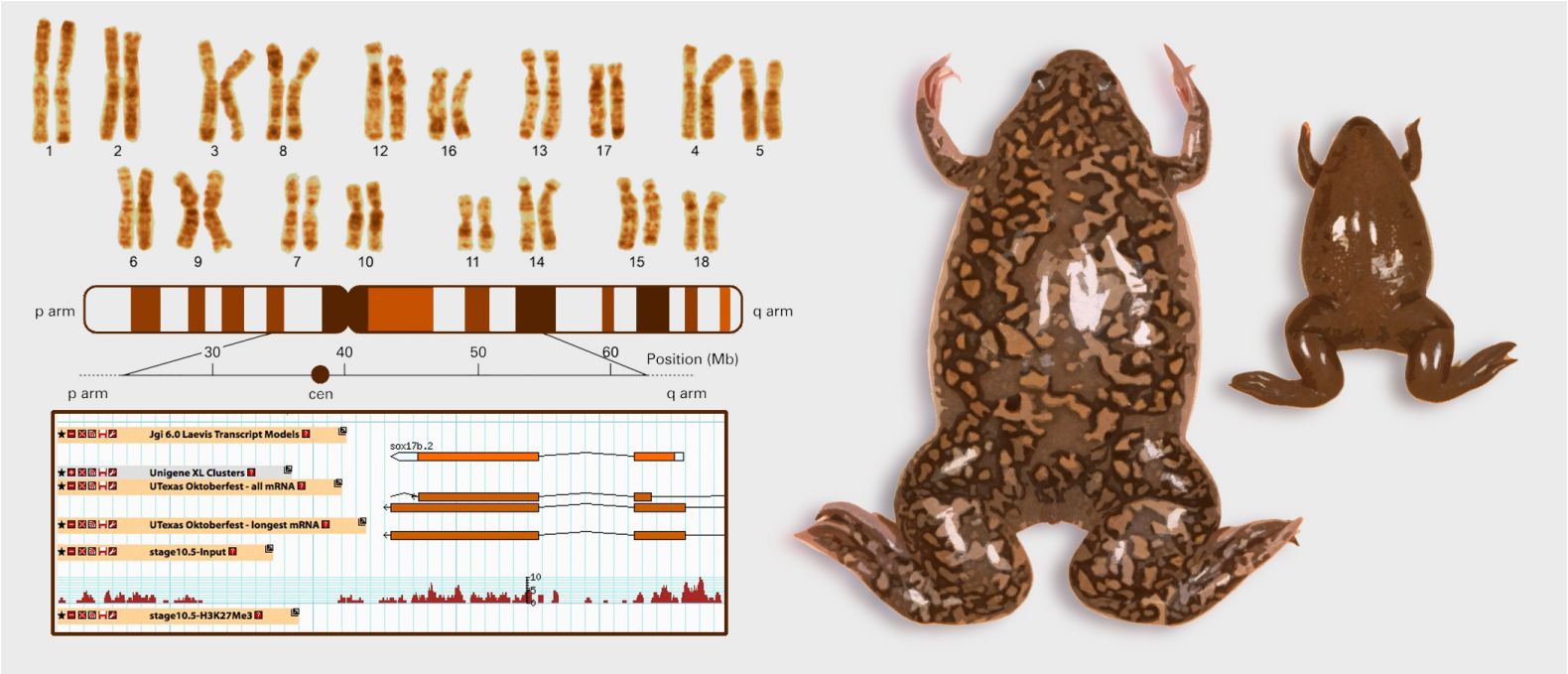
evolution, like engineers, works in agential materials







Xenobots have a normal Frog Genome



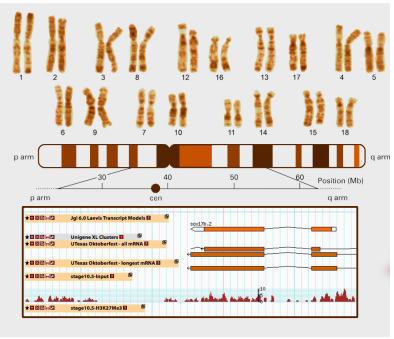
Xenobot bodies and minds have no straightforward evolutionary back story;

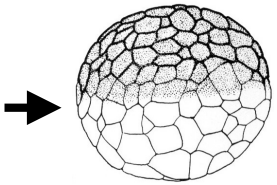
the cells do, but selection pressure was very different

Behavior is emergent; cognitive capacities TBD

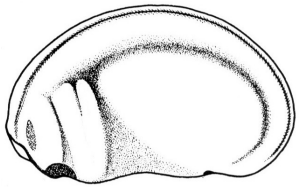
Xenobots have a Unique Developmental Sequence

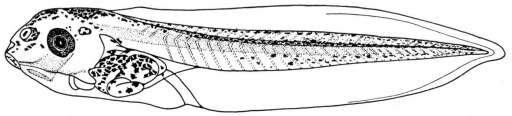
Xenopus laevis genome





Path A: embryos





Path B: Xenobots

Developmental Time

Behavior

Technological Approach to Mind Everywhere

- Conceptual outlook
  - continuum of agency (not binary)
  - empirical stance - persuadability
  - no privileged substrate for cognition

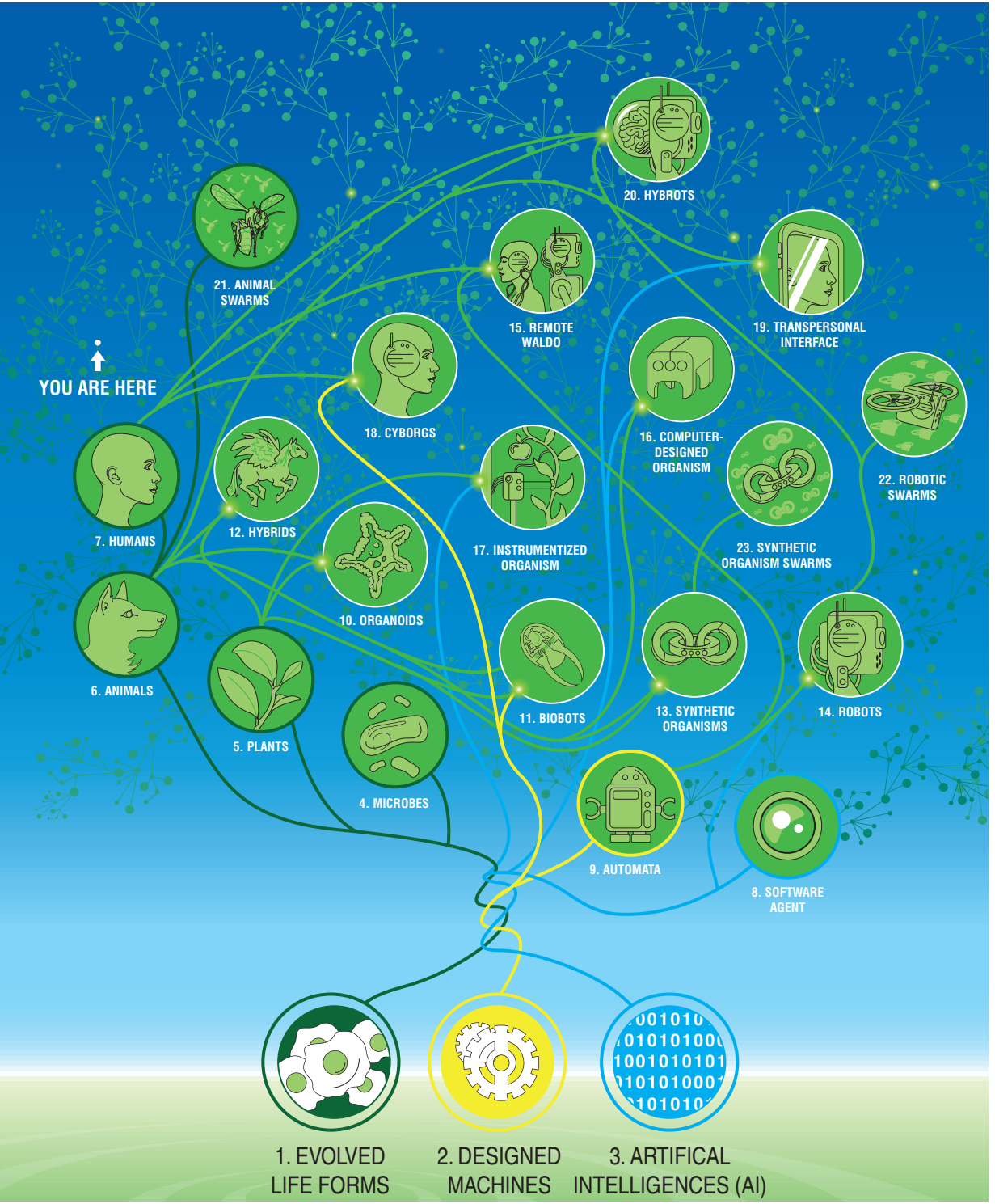
- Self = boundaries of goals it is capable of pursuing

- Intelligence = problem-solving in abstract spaces; same goals by different means

- Developmental Bioelectricity =
  - phylogenetic precursor of brain dynamics
  - the physiological medium for the software of life
  - medium of the cognition of morphogenetic swarm intelligence of cells

- Evolution
  - is greatly potentiated by multi-scale competency architecture
  - does not find solutions to problems - it builds machines that solve problems
  - where do the goals come from, if not selection?

"Endless Forms Most Beautiful" <—> ethics



1. DESIGNED MACHINES

2. EVOLVED LIFE FORMS

3. ARTIFICAL INTELLIGENCES (AI)

4. MICROBES
11. BIOBOTS
18. CYBORGS
5. PLANTS
12. HYBRIDS
19. TRANSPERSONAL INTERFACE
6. ANIMALS
13. SYNTHETIC ORGANISMS
21. ANIMAL SWARMS
7. HUMANS
14. ROBOTS
22. ROBOTIC SWARMS
8. SOFTWARE AGENT
15. REMOTE WALDO
23. SYNTHETIC ORGANISM SWARMS
9. AUTOMATA
16. COMPUTER-DESIGNED ORGANISM
18. CYBORGS
17. INSTRUMENTIZED ORGANISM

More Details Here:

frontiers in Psychology

HYPOTHESIS AND THEORY
published: 13 December 2019
doi: 10.3389/fpsyg.2019.02688

The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition

Michael Levin[1,2*†]

PHILOSOPHICAL TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

Review

Cite this article: Manicka S, Levin M. 2019 The Cognitive Lens: a primer on conceptual tools for analysing information processing in developmental and regenerative morphogenesis. *Phil. Trans. R. Soc. B* **374**: 20180369. http://dx.doi.org/10.1098/rstb.2018.0369

The Cognitive Lens: a primer on conceptual tools for analysing information processing in developmental and regenerative morphogenesis

Santosh Manicka and Michael Levin

frontiers in Psychology

REVIEW
published: 21 June 2016
doi: 10.3389/fpsyg.2016.00902

On Having No Head: Cognition throughout Biological Systems

František Baluška[1] *and Michael Levin*[2,*]

Integrative Biology

PERSPECTIVE

CrossMark

Cite this: *Integr. Biol.*, 2015, 7, 1487

Re-membering the body: applications of computational neuroscience to the top-down control of regeneration of limbs and other complex organs†

PROBLEMS & PARADIGMS

Prospects & Overviews

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www.bioessays-journal.com

Scale-Free Biology: Integrating Evolutionary and Developmental Thinking

Chris Fields and Michael Levin*

frontiers in Ecology and Evolution

HYPOTHESIS AND THEORY
published: 16 March 2021
doi: 10.3389/fevo.2021.650726

Living Things Are Not (20th Century) Machines: Updating Mechanism Metaphors in Light of the Modern Science of Machine Behavior

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Biochemical and Biophysical Research Communications 564 (2021) 114–133

Contents lists available at ScienceDirect

Biochemical and Biophysical Research Communications

journal homepage: www.elsevier.com/locate/ybbrc

Life, death, and self: Fundamental questions of primitive cognition viewed through the lens of body plasticity and synthetic organisms

Michael Levin [a, b]

Cognition all the way down

Biology's next great horizon is to understand cells, tissues and organisms as agents with agendas (even if unthinking ones)

Michael Levin & Daniel C Dennett

https://aeon.co/essays/how-to-understand-cells-tissues-and-organisms-as-agents-with-agendas

Thank you to:

Post-docs:

Tal Shomrat - persistence of memory in regenerating brains
Nestor Oviedo, Wendy Beane, Johanna Bischof - bioelectrics of planarian regeneration
Douglas Blackiston - brain-body interface plasticity, synthetic living bodies
Vaibhav Pai - voltage gradients in eye/brain induction and repair
Santosh Manicka - cognitive and dynamical systems models of morphogenesis
Nirosha Murugan - slime mold cognition
Surama Biswas - cognitive models of gene-regulatory networks

Ph.D. Students:

Fallon Durant - V_{mem} and pattern memory in planarian regeneration
Vasilios Nanos - chimerization in morphogenesis and cognition
Franz Kuchling - cognitive neuroscience modeling applied to pattern homeostasis

Undergraduate Students:

Maya Emmons-Bell, Kelly G. Sullivan - non-genetic cross-species morphogenesis
+ many other undergraduate students working in our lab over the years

Technical support:

Rakela Colon - lab management
Erin Switzer - vertebrate animal husbandry
Emma Lederer - Xenobot behavior
Junji Morokuma - planarian molecular biology
Joan Lemire, Jean-Francois Pare - molecular biology

Collaborators: Allen Center members +

Alexis Pietak - computational modeling of bioelectrics
Joshua Bongard and Sam Kriegman - Xenobot simulations and AI
David Kaplan - Vmem and human MSC differentiation, regenerative sleeves
Fiorenzo Omenetto - optical approaches to bioelectric modulation
Giovanni Pezzulo - cognitive science models of pattern regulation
Vitaly Volpert, Chris Fields - mathematical models of pattern regulation
Paul C. W. Davies, S. I. Walker, Karl Friston - top-down causation models
Don Ingber, Richard Novak, V. J. Koomson, J. H. Dungan - mammalian bioengineering

Model systems: tadpoles, planaria, zebrafish, slime molds, human cells, and chick embryos

Funding support:

Paul G. Allen Frontiers Group, **TWCF**, DARPA, NIH

Illustrations: Jeremy Guay @ Peregrine Creative