Evolution and Intelligence:
Inversion and a Positive Feedback Spiral

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https://drmichaellevin.org//
http://allencenter.tufts.edu/


Garden of Eden 2.0

ALLEN DISCOVERY CENTER at Tufts University

Computer-designed Organisms
TUFTS UNIVERSITY | UNIVERSITY OF VERMONT

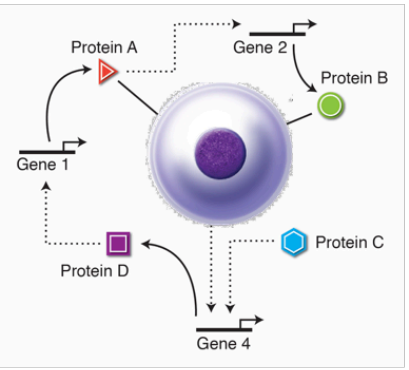
WYSS INSTITUTE

HARVARD

Preface:

- Intersection of biology, computer science, cognitive science: what are minds and how do embodied minds operate and scale in the physical world?

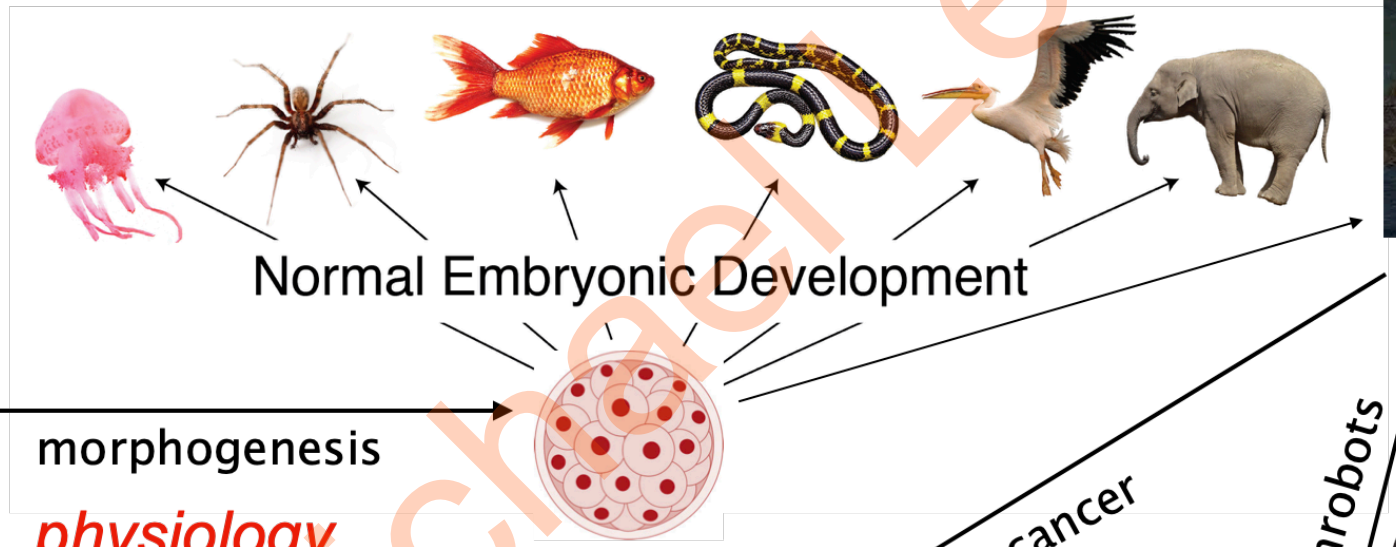
"just physics" - oocyte

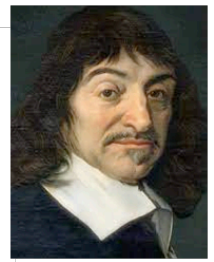


chemistry

behavioral science

psychology



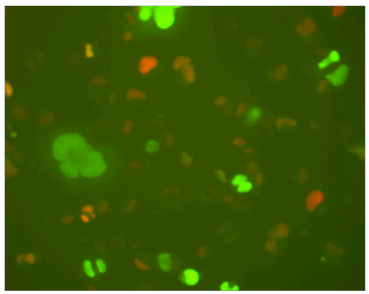


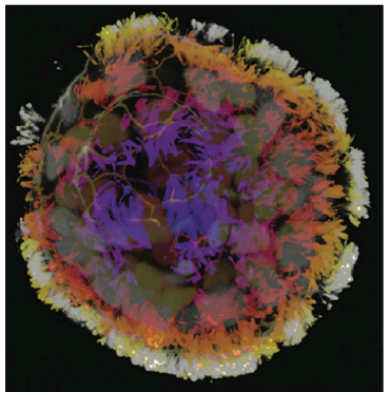
physiology

cancer

Anthrobots

oncology

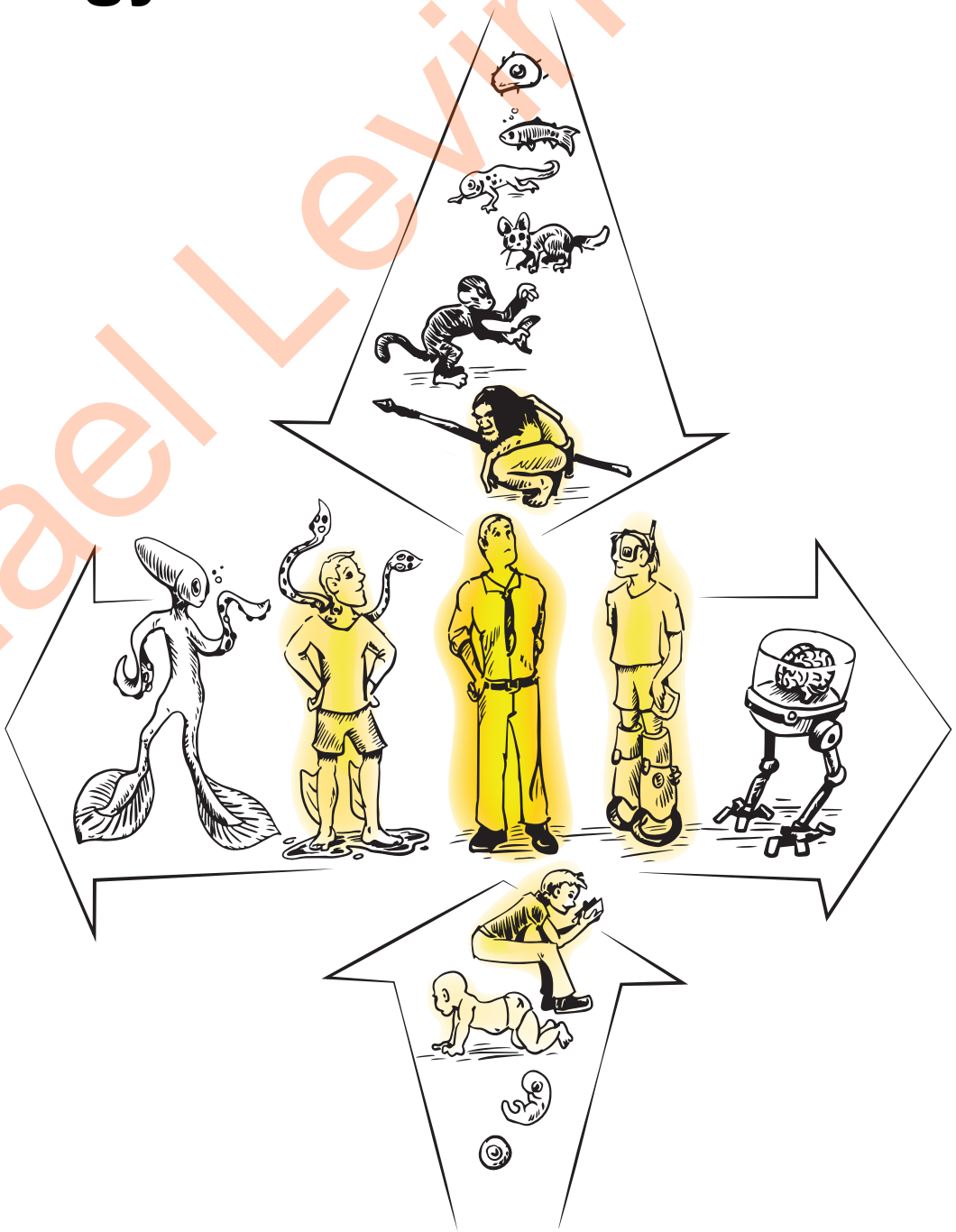




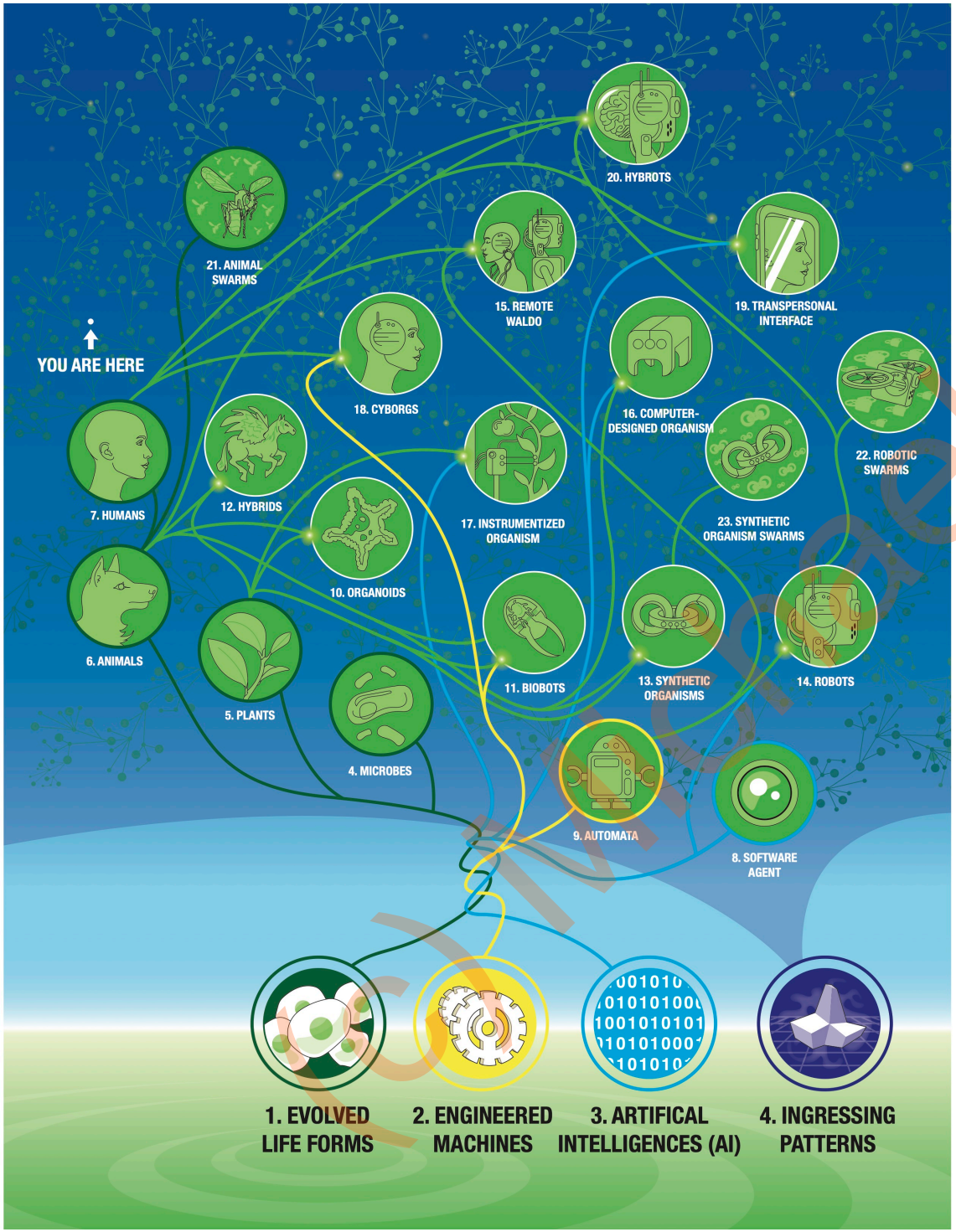
bioengineering

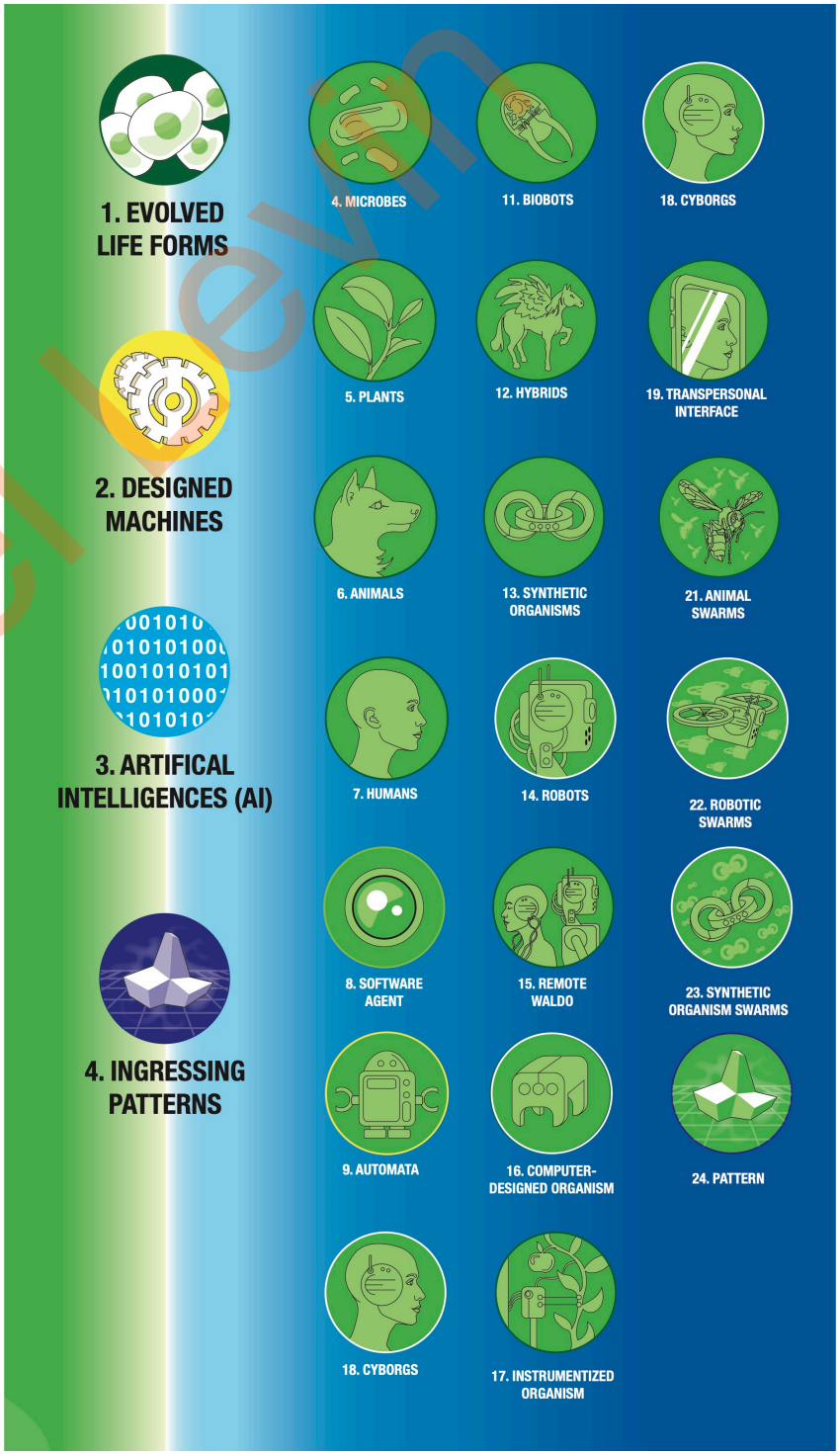
disciplines are distinct
the substrate is continuous

Beyond Bio-chauvinism and Anthropomorphism - A Radical Ecology of Minds



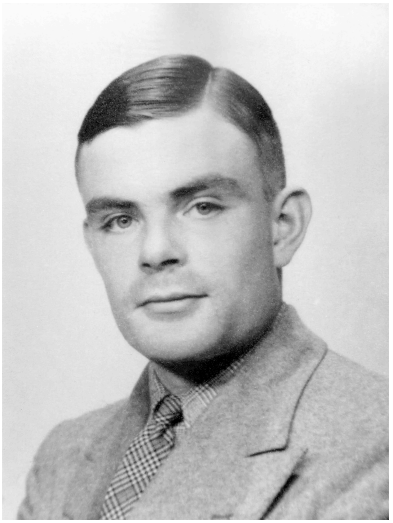
“Endless Forms Most Beautiful” <—> synthbiosis





Preface:

- *"Developmental biologists don't concern themselves with the mind-body problem."*
  — anonymous reviewer



COMPUTING MACHINERY AND INTELLIGENCE

By A. M. Turing

230 A. M. Turing [Nov. 12,

ON COMPUTABLE NUMBERS, WITH AN APPLICATION TO THE ENTSCHEIDUNGSPROBLEM

By A. M. Turing.

[Received 28 May, 1936.—Read 12 November, 1936.]

The "computable" numbers may be described briefly as the real numbers whose expressions as a decimal are calculable by finite means. Although the subject of this paper is ostensibly the computable *numbers*, it is almost equally easy to define and investigate computable functions

PHILOSOPHICAL TRANSACTIONS
OF THE
ROYAL SOCIETY OF LONDON

Series B. Biological Sciences
No. 641 Vol. 237 pp. 37–72 14 August 1952

THE CHEMICAL BASIS OF MORPHOGENESIS

By
A. M. Turing, F.R.S.

- I will not be talking about directed (non-random) mutations.

Main Points:

- Genotype -> Phenotype map is *intelligent*
  - a problem-solving, creative process.

Autonomy all the way down

- Evolving an *agential material* is different - major implications for evolution.

- Origins:

(same latent space that *e* comes from)

  - Where do the properties of novel beings come from?
  - What kickstarts the process before differential replication?

Functional Agency Ratchet (FAR)

- Conclusion and future

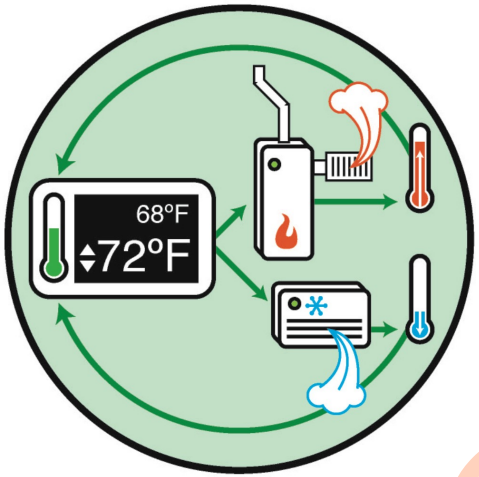
Outline:

- Genotype -> Phenotype map is *intelligent* - a problem-solving, creative process.
  - Diverse Intelligence = continuum
  - Morphogenesis as improvisation with genome as prompt

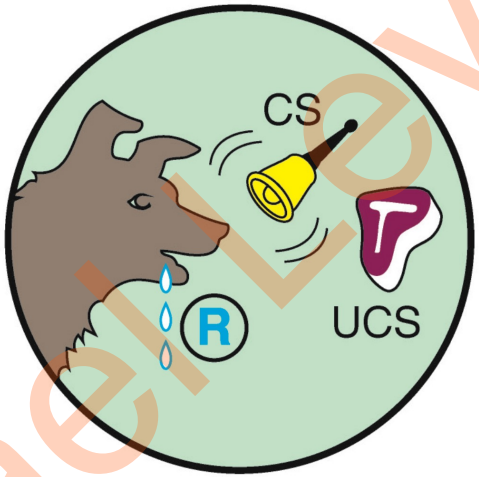
need to dissolve assumptions that intelligence, problem-solving, etc. are things that brainy animals do in 3D space

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

Hardware modification only

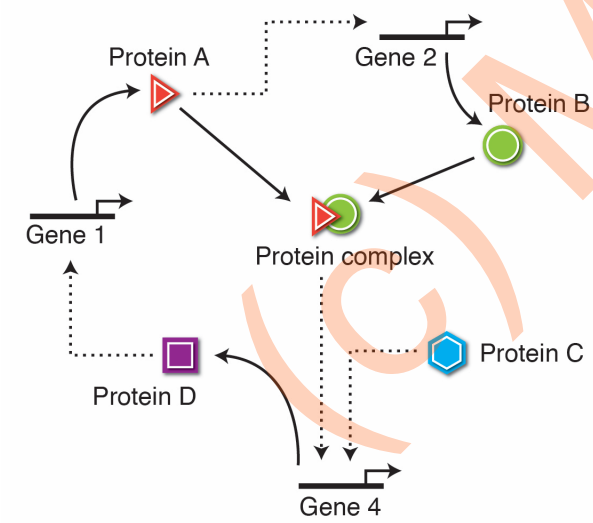


Modify the data encoding setpoint of goal-driven process



Training by rewards/ punishments

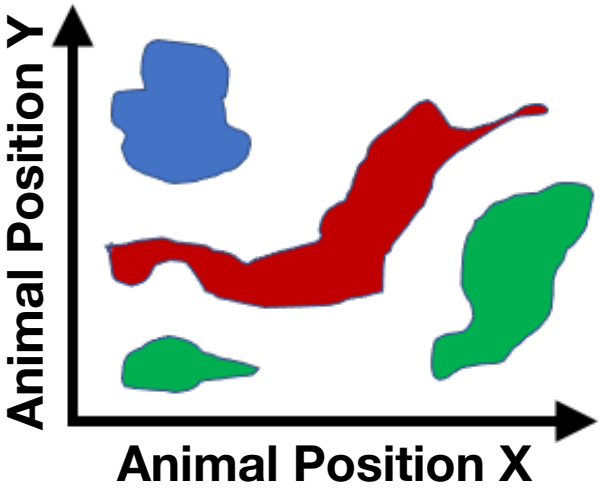
Communicate cogent reasons



?

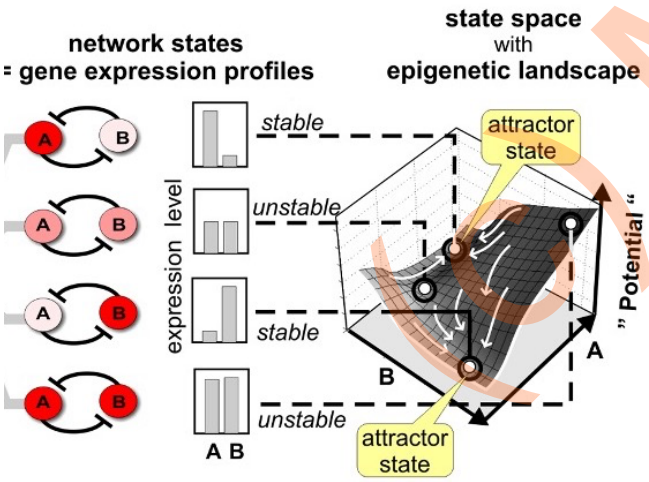
Collective Intelligence of Cells: Competency in Diverse Spaces

3D Space (behavior)



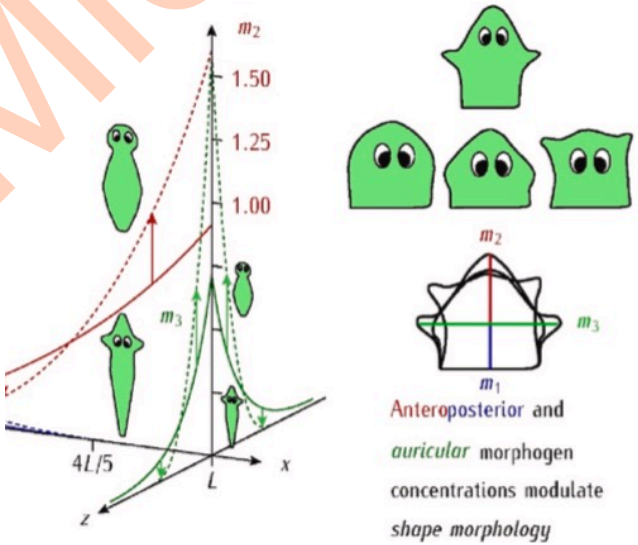
Transcriptional Space

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



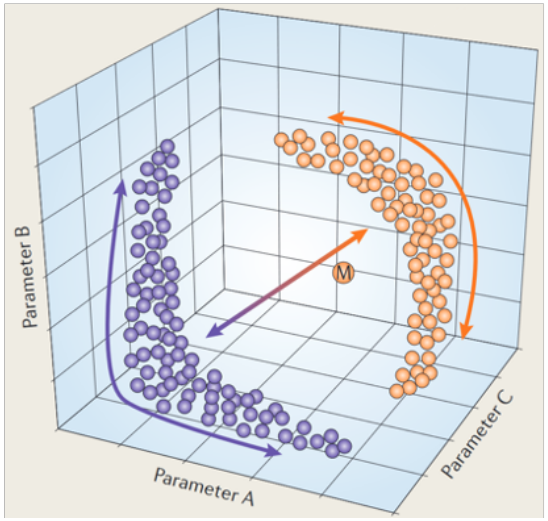
Morphospace

Cervera, J., Levin, M., and Mafe, S., (2021), BioSystems, 209:104511

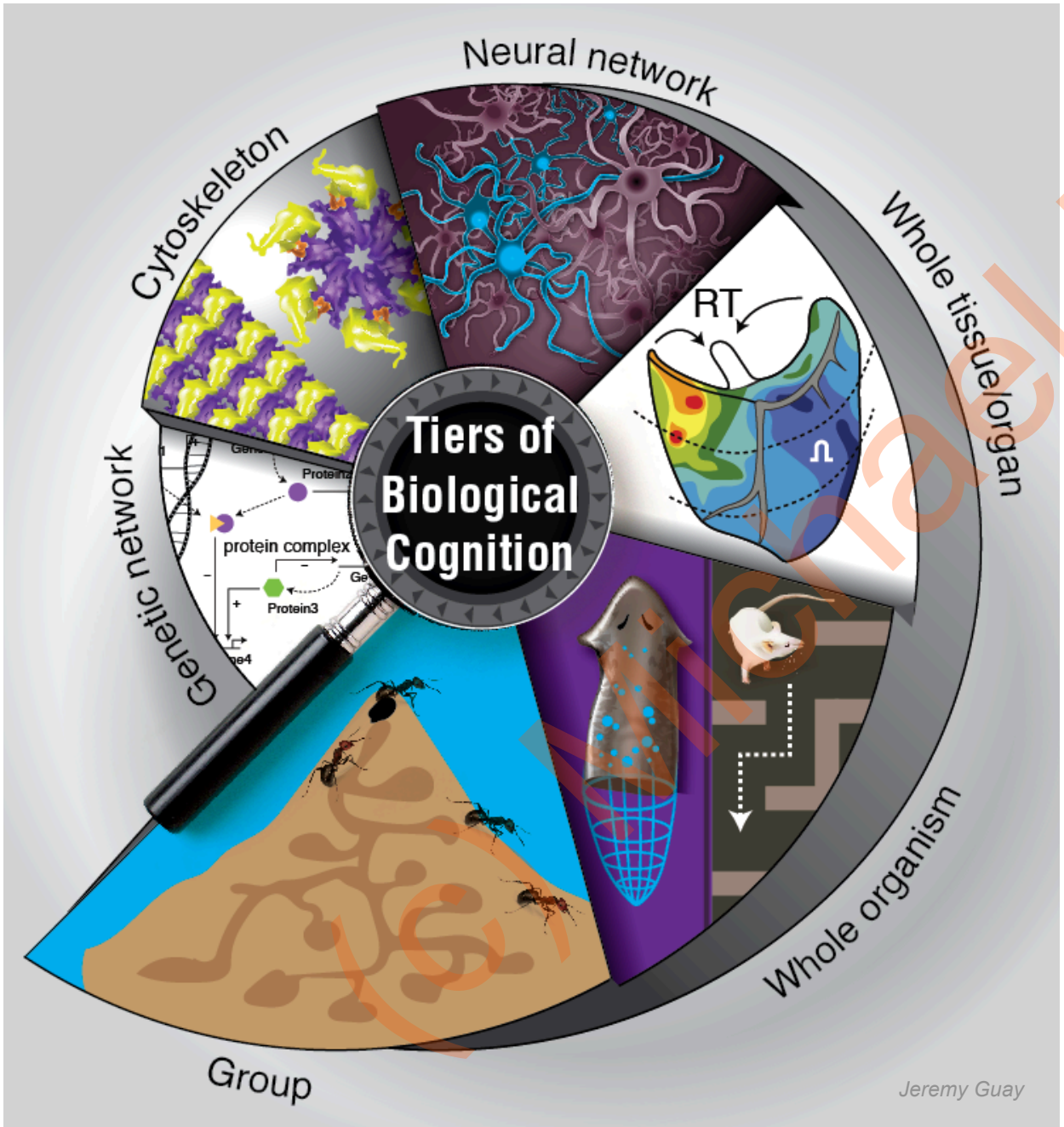


Physiological Space

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



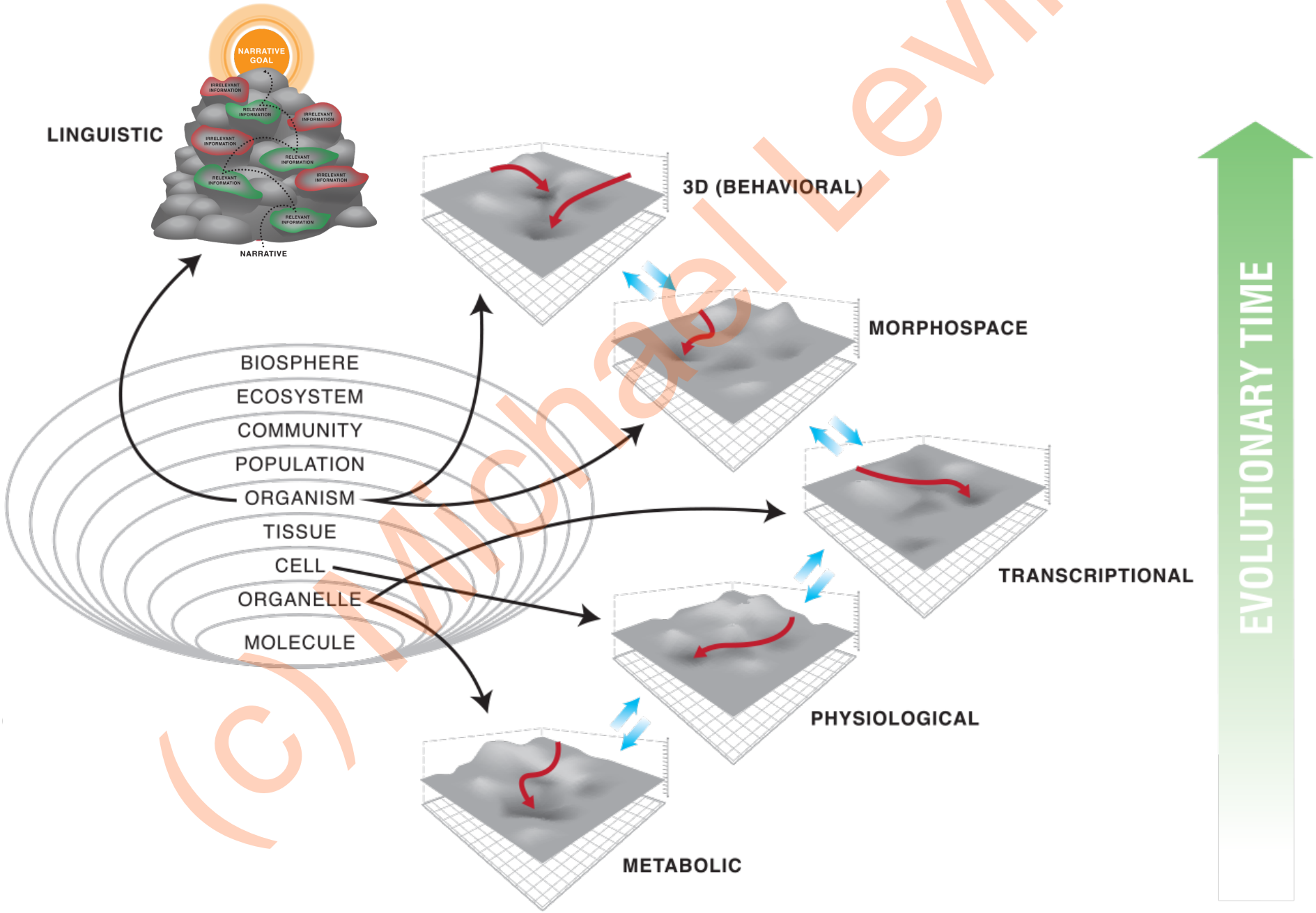
Nested Cognition in Biology



Multi-scale Competency Architecture

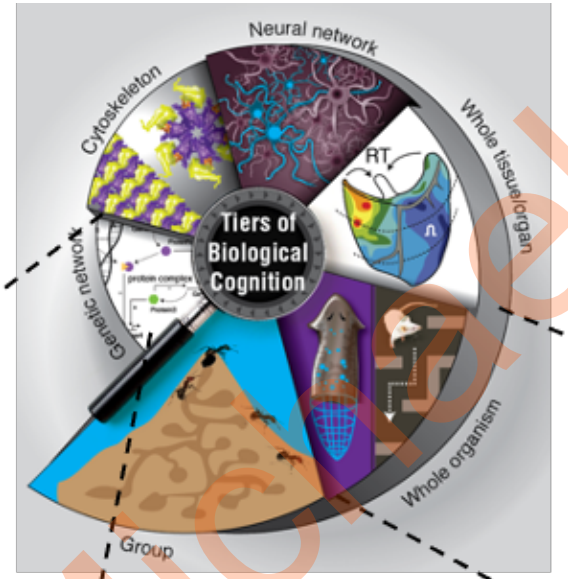
each level of organization solves problems in its own space (morphospace, transcriptional space, physiological space, 3D behavioral space, etc.) using some of the same bag of tricks, of various levels of sophistication

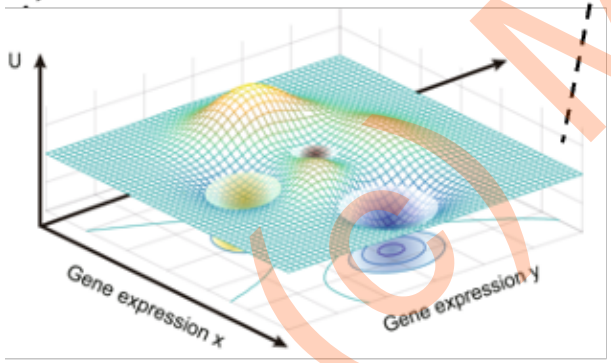
Evolution Pivots Its Navigational Competencies into new Spaces

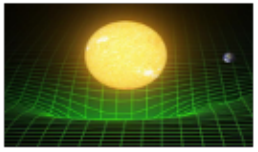


Evolutionary Implications

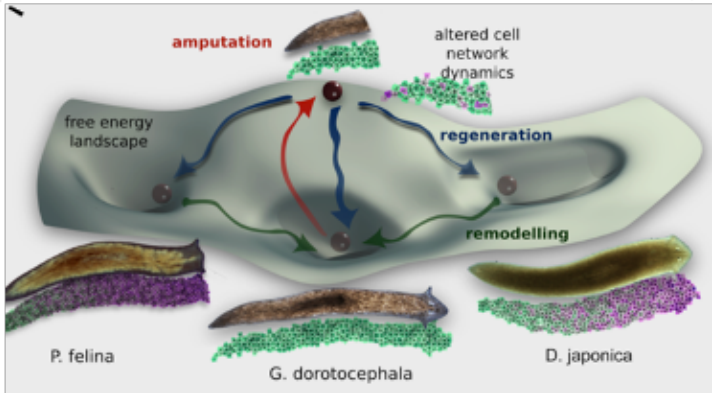
- Hierarchical control = search the nicer space of behavior-shaping inducements, rewards, signals, incentives, inputs, etc. not the chaotic, rugged space of microstates







deforms



Outline:

- Genotype -> Phenotype map is *intelligent* - a problem-solving, creative process.
  - Diverse Intelligence = continuum
  - Morphogenesis as improvisation with genome as prompt

Enormous distance and divergence between genotype and form/function but NOT just complexity, polygenicity, or degeneracy!

Deep parallel between cognitive science and developmental biology

"Intelligence = ability to reach the same goal by different means."

- William James

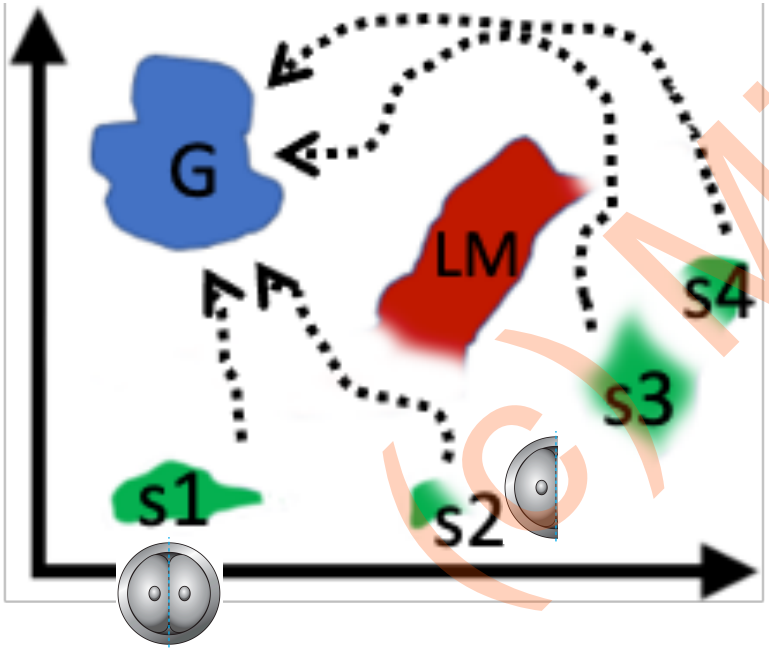
Hypothesis: morphogenesis is a collective intelligence, exerting its behavioral competencies in anatomical morphospace

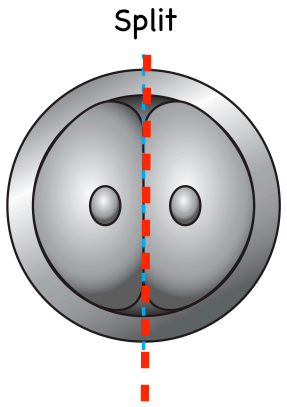
- Homeostasis: goal-directed activity
- Homeostasis^2: same ends by different means - context sensitivity
- Hierarchical, non-local control
- Hackability (software, not just hardware)
- Learning
- Creative problem-solving toward default goals
- Novel beings, novel goals: never give up

Same anatomy, from different starting states

- get to the same outcome
  - despite perturbations
  - **from diverse starting positions**
  - via different paths
  - stop when goal is achieved

(regulative) development = regeneration from 1 cell

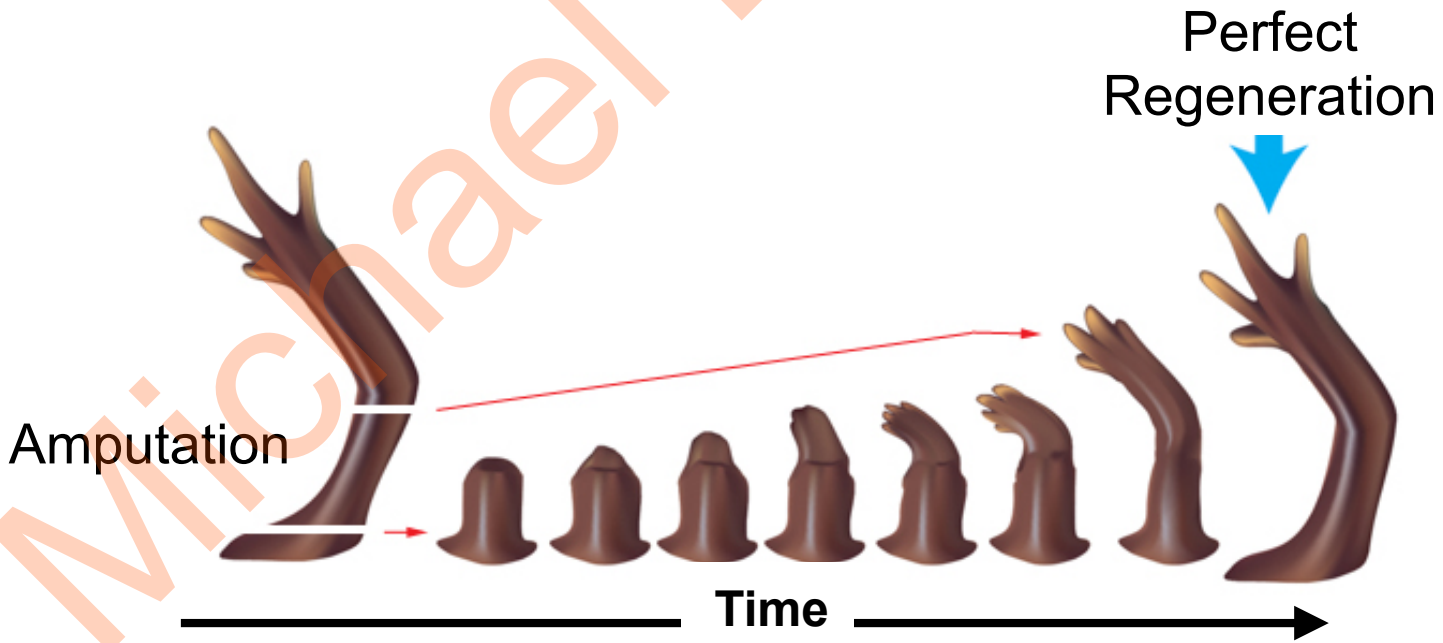




Splitting an embryo in half makes 2 normal embryos

Anatomical Homeostasis:

- get to the same outcome (maintain set point)
  - despite perturbations
  - from diverse starting positions
  - via different paths
  - **stop when goal is achieved**

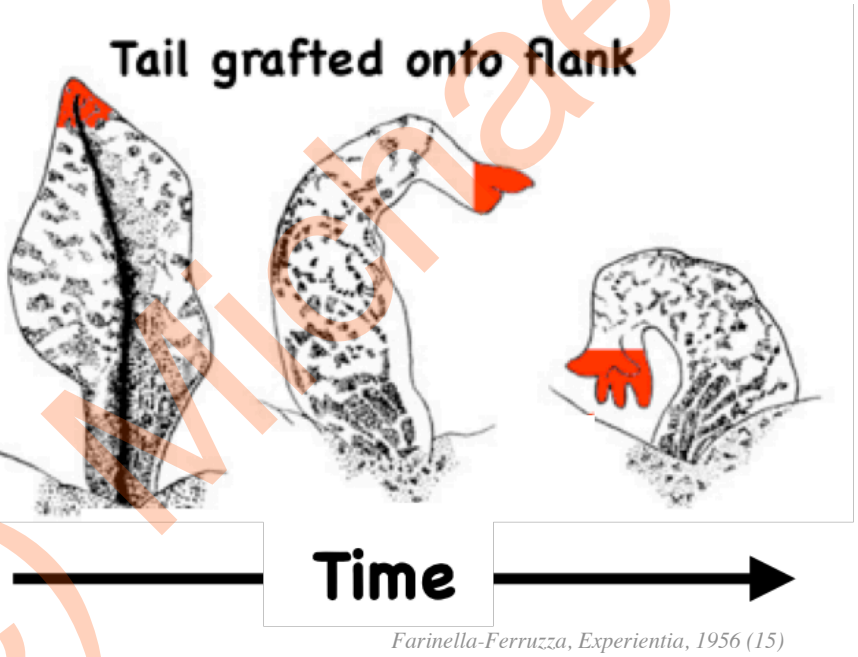


Anatomical homeostasis:

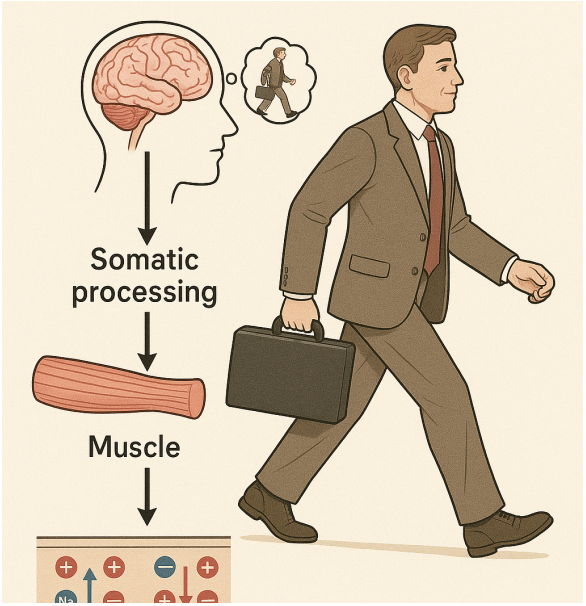
it stops when the correct large-scale setpoint (target morphology) has been reached

It's not Just about Damage: Holistic Order

- get to the same outcome (maintain set point)
  - despite **non-local, large-scale** perturbations
  - top-down control of parts: align toward abstract goals



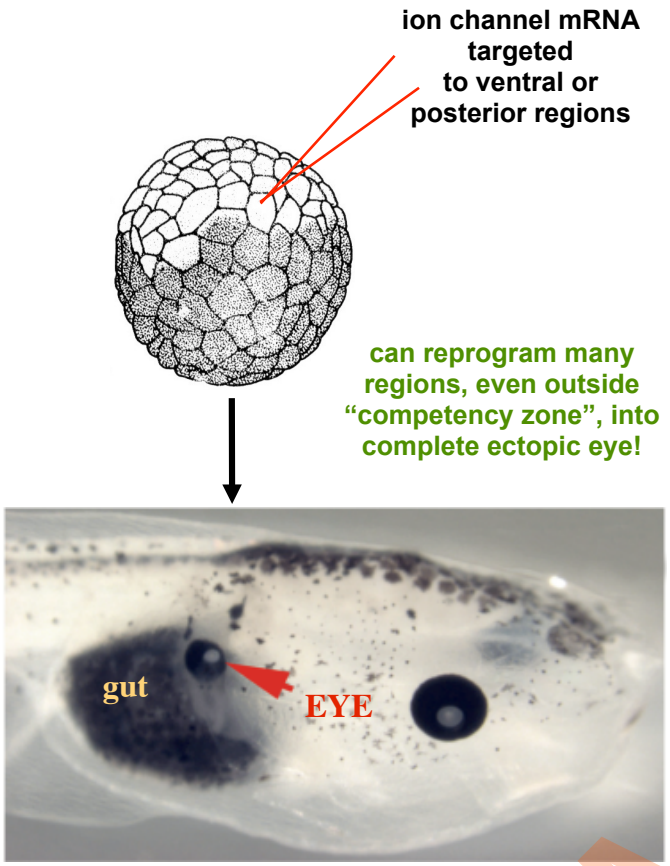
Farinella-Ferruzza, Experientia, 1956 (15)

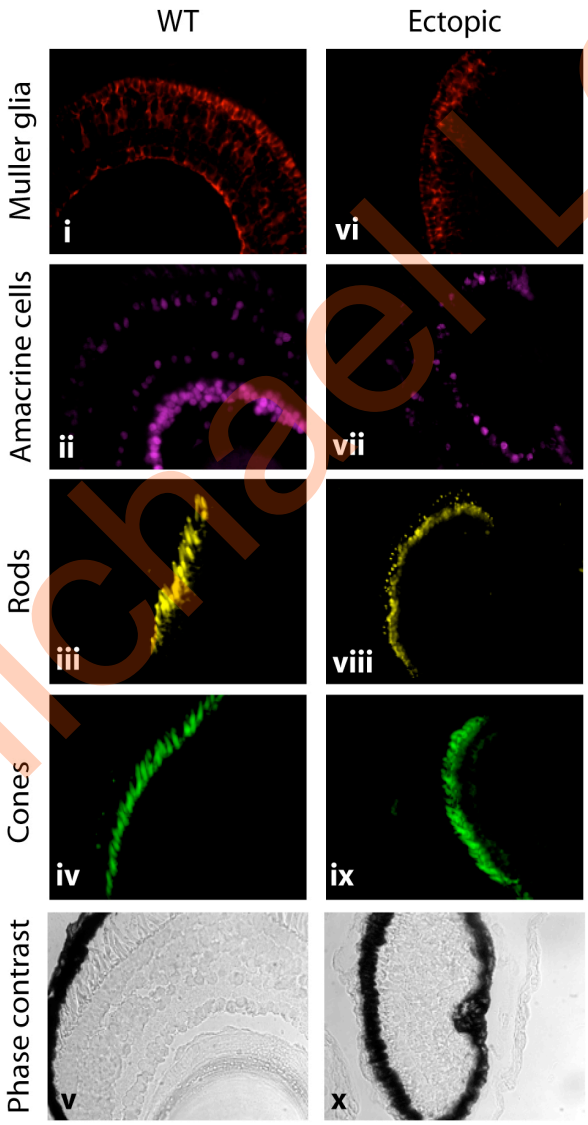


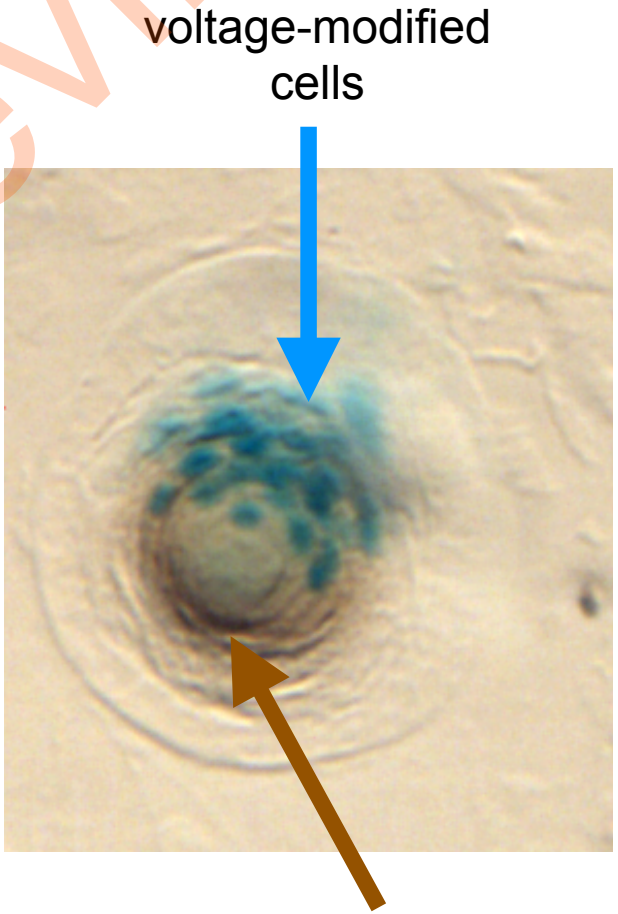
Anatomical homeostasis:

local order obeys global plan

Complex Morphogenetic Behaviors Triggered by Short Prompts





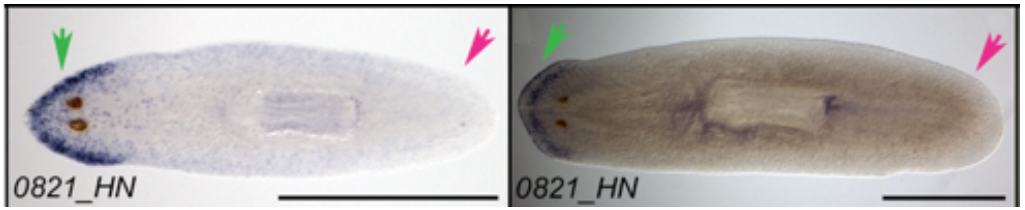


1. BIOE is instructive
2. modularity - not cell level, organ-level subroutine call
3. higher-level prompt reveals higher tissue competency than Pax6 prompt
4. self-scaling of system to task

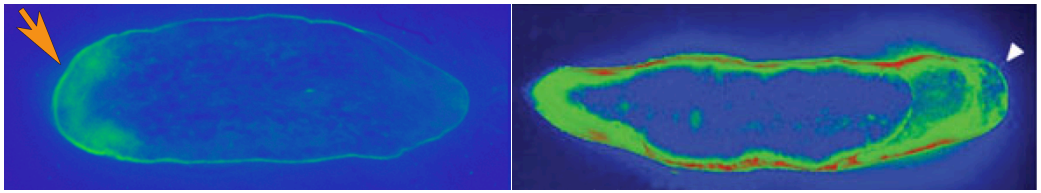
Getty Images

Re-writing Anatomical Pattern Memory

control worms | bioelectrically edited



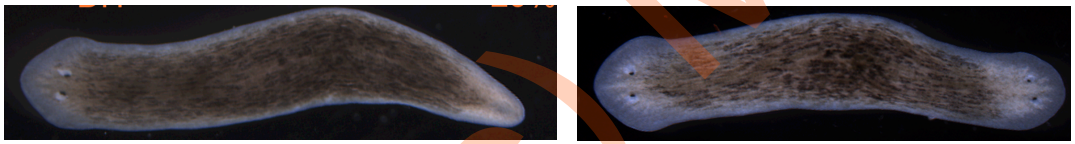
normal axial identity gene expression



bioelectric pattern

normal anatomy

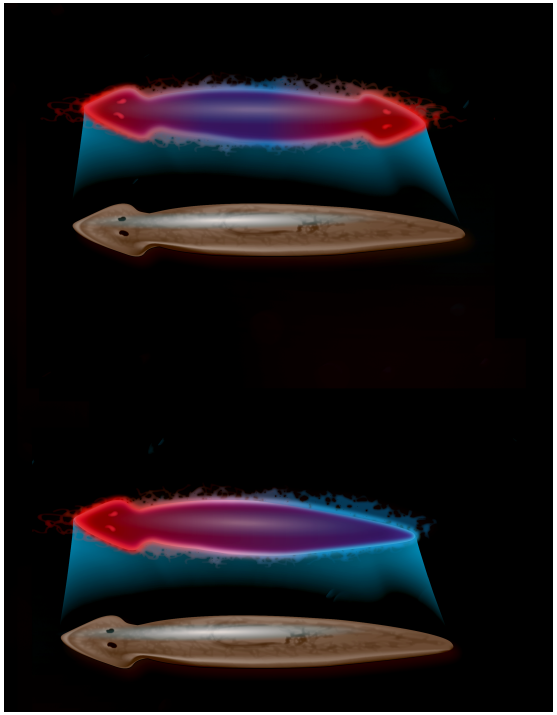
middle-third regenerates:



built anatomy after cutting

Fallon Durant

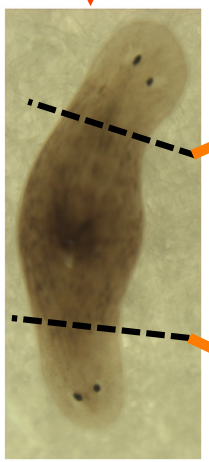
The Same Body can Store different Electrical Pattern Memories



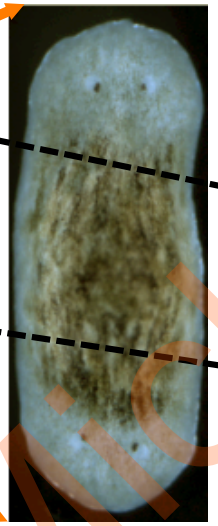
The bioelectric pattern doesn't indicate what the anatomy is now, it encodes the latent pattern memory that will guide anatomy **if** it is cut at a future time = counterfactual

Re-writing Pattern Memory to Create New, Permanent Bodyplan without Genetic Change

Cut, and briefly perturb bioelectric circuit

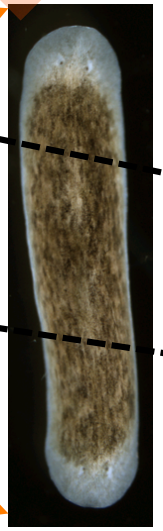


weeks later, cut in plain water



Keep trunk

weeks later, cut in plain water



Keep trunk

or, can force V_{mem} state back to normal

Nestor Oviedo
Junji Morokuma

. . .

Basic properties of memory

- Long-term stability
- Lability (rewritable)
- Latency (conditional recall)
- Discrete possible behaviors (1H v. 2H)
- Not genetic (and the only “mutant line”!)

Hardwired Development, Genotype -> Phenotype?

White Oak Leaf - Photo by Chris Evans, River to River CWMA, Bugwood.org

This is what the oak genome does?

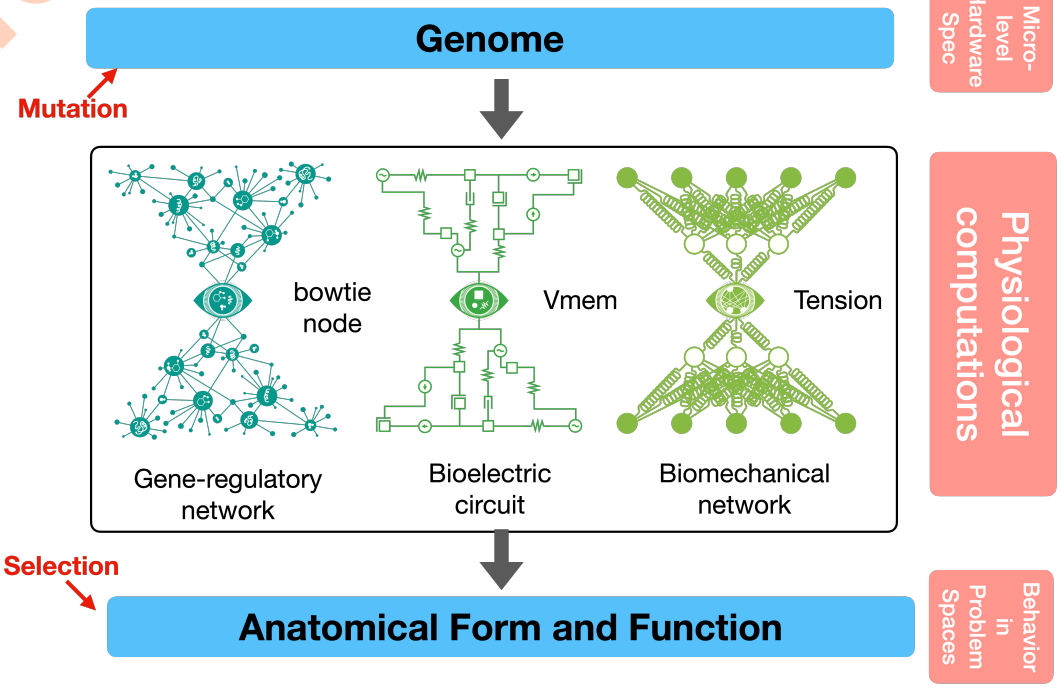
Cellular and Molecular Life Sciences (2023) 80:142
https://doi.org/10.1007/s00018-023-04790-z

Cellular and Molecular Life Sciences

REVIEW

Darwin's agential materials: evolutionary implications of multiscale competency in developmental biology

Michael Levin[1,2]



Intelligent Materials can be Hacked:

Photo Credit: Andrew Deans

Hedgehog Gall

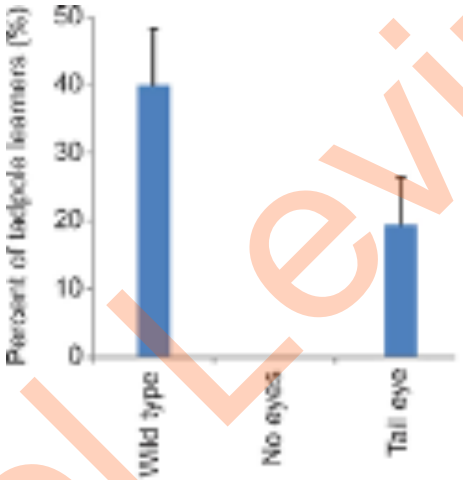
Acraspis erinacei

August - November

Bio-prompting by wasp parasite

Biology exploits reprogrammable hardware

Eye on Tail? No problem.



Ectopic eyes on tail provide vision!

The Journal of Experimental Biology 216, 1031-1040
© 2013. Published by The Company of Biologists Ltd
doi:10.1242/jeb.074963

RESEARCH ARTICLE

Ectopic eyes outside the head in *Xenopus* tadpoles provide sensory data for light-mediated learning

Douglas J. Blackiston and Michael Levin*

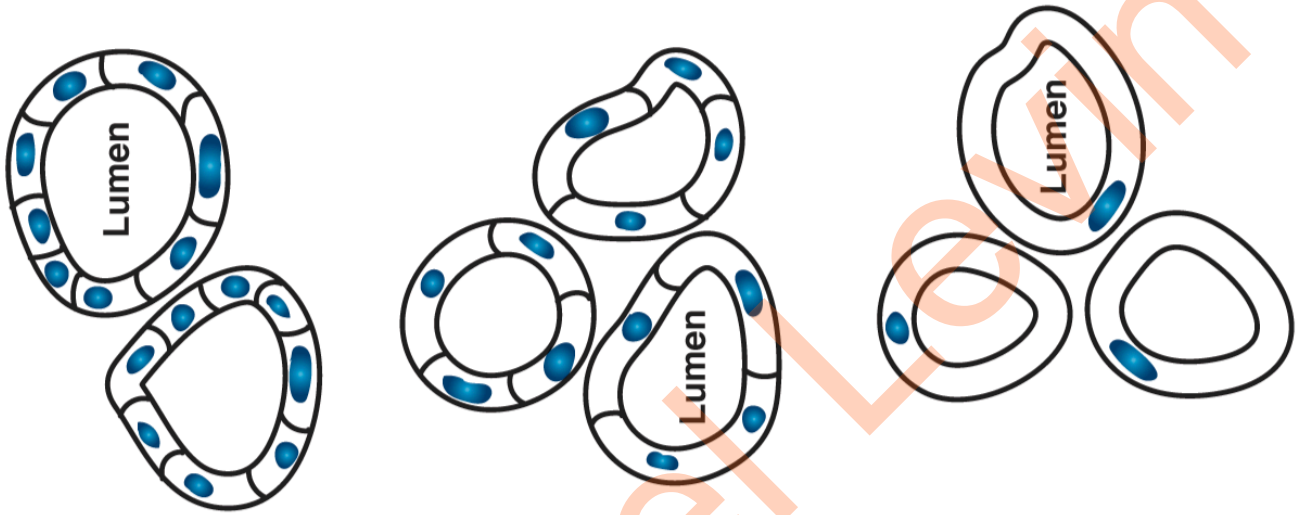
Behavioral Testing Device

Brain dynamically adjusts behavioral programs to accommodate different body architectures, no lengthy adaptation needed!

Douglas Blackiston

Creative Problem-solving in Morphospace

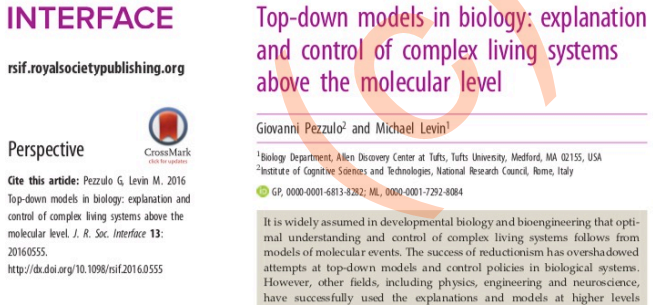
newt kidney tubule cross-section



Fankhauser, 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 = top-down causation

- Beginner's Mind approach to survival - can't even count on your own parts, but you can count on change
- Creative, intelligent problem-solving - repurpose available tools to new circumstances
- Tail-eye tadpoles and galls (and V_{mem}-induced ectopic eyes) work because *every* instance of development is creative problem-solving


INTERFACE

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Perspective

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Top-down models in biology: explanation and control of complex living systems above the molecular level

Giovanni Pezzulo[2] and Michael Levin[1]

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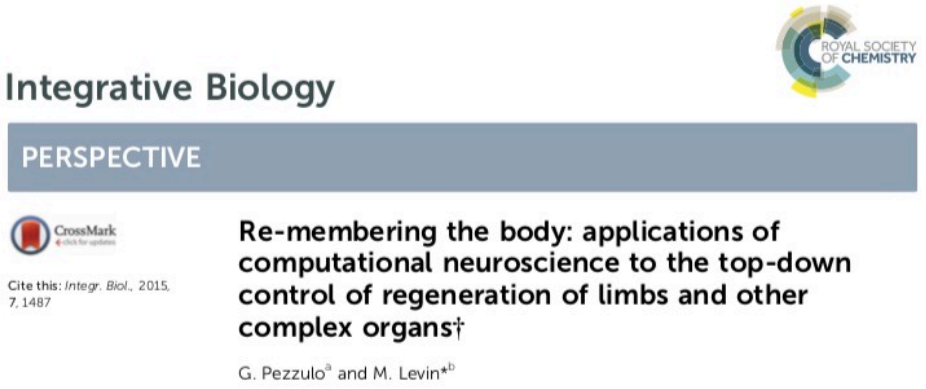
[2]Institute of Cognitive Sciences and Technologies, National Research Council, Rome, Italy

GP, 0000-0001-6813-8282; ML, 0000-0001-7292-8084

It is widely assumed in developmental biology and bioengineering that optimal understanding and control of complex living systems follows from models of molecular events. The success of reductionism has overshadowed attempts at top-down models and control policies in biological systems. However, other fields, including physics, engineering and neuroscience, have successfully used the explanations and models at higher levels


Integrative Biology

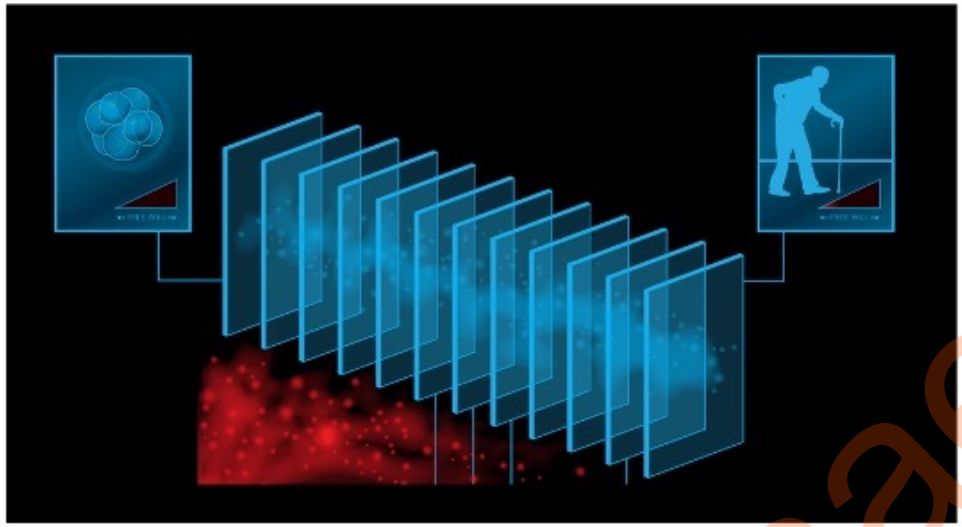
PERSPECTIVE

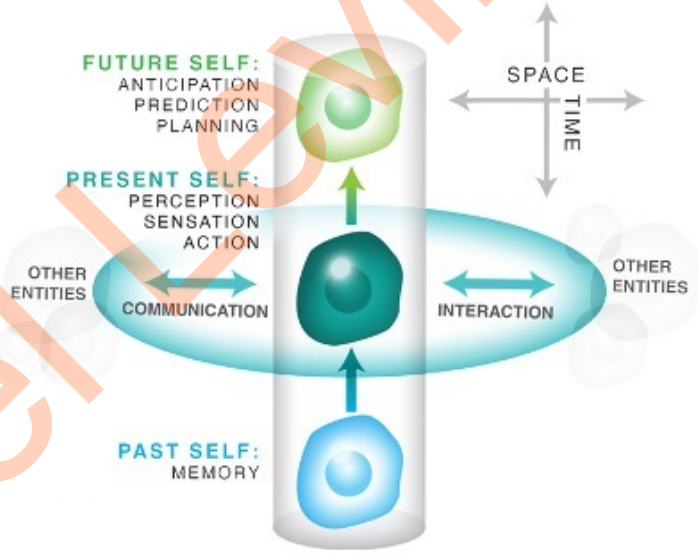
Cite this: *Integr. Biol.*, 2015, 7, 1487

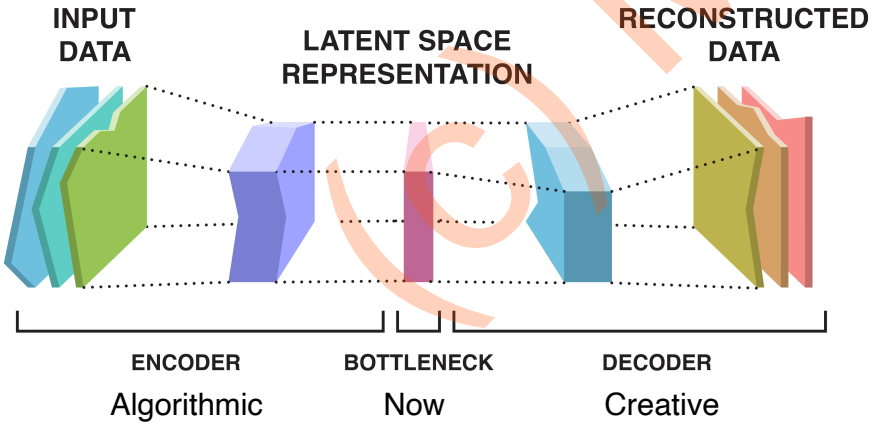
Re-membering the body: applications of computational neuroscience to the top-down control of regeneration of limbs and other complex organs†

G. Pezzulo[a] and M. Levin*[b]

Memory and the Paradox of Change:







entropy

Perspective

Self-Improvising Memory: A Perspective on Memories as Agential, Dynamically Reinterpreting Cognitive Glue

Michael Levin

Morphogenesis and Beginner's Mind:

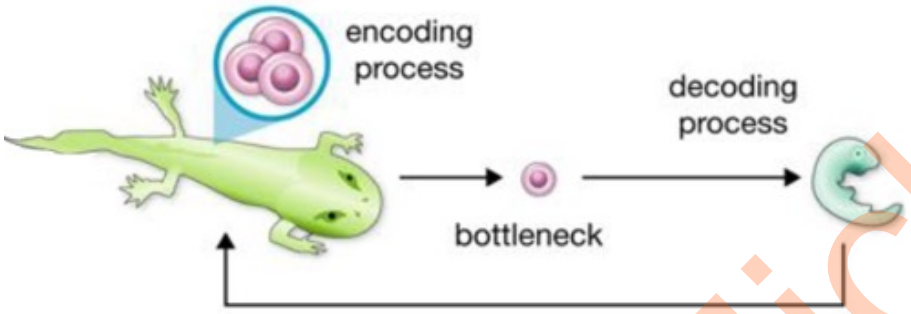
CellPress

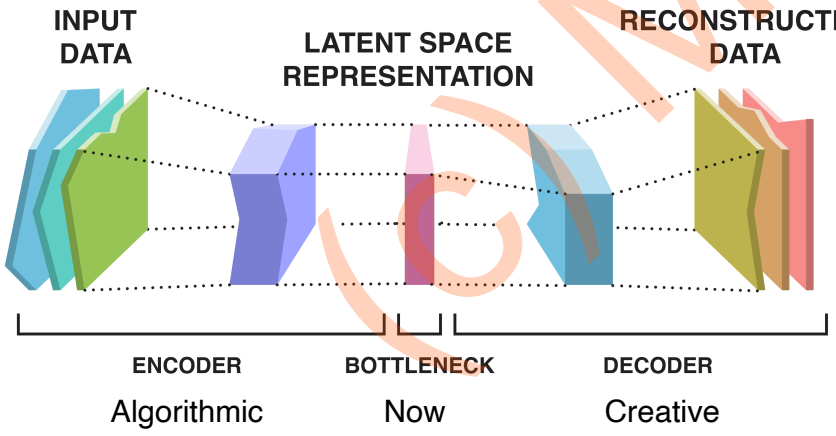
Trends in Genetics

Opinion

What does evolution make? Learning in living lineages and machines

Benedikt Hartl [1,2,4] and Michael Levin [1,3,4,*]





Biology assumes the hardware is unreliable
Environment *and your own parts* will change, **don't over-train**
Little allegiance to past Self's meaning of engrams
Re-interpret on-the-fly - present/future is all that matters
Engram is highly compressed - creative remembering, not deduction
Unreliable hardware and improvisation are a feature, not a bug

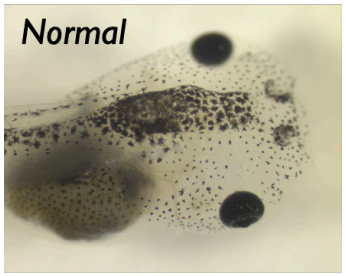
Main Points:

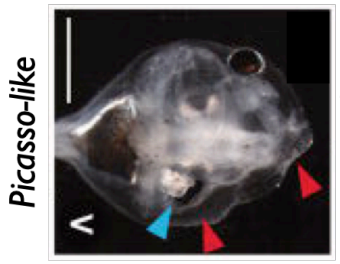
Evolutionary Implications

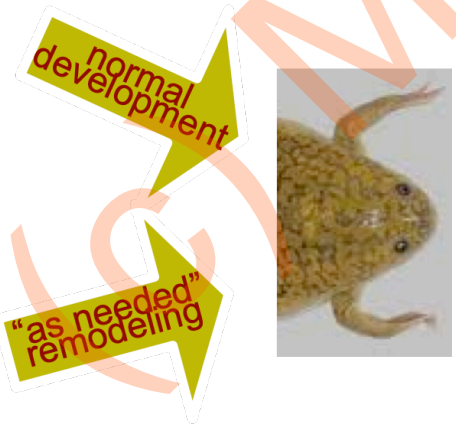
- Hierarchical control = search the nicer space of inducements, rewards, signals, incentives, etc. not the chaotic space of microstates

- Competencies of modules smooths the evolutionary landscape and buffers negative effects of mutation, giving the process patience (improves evolvability)

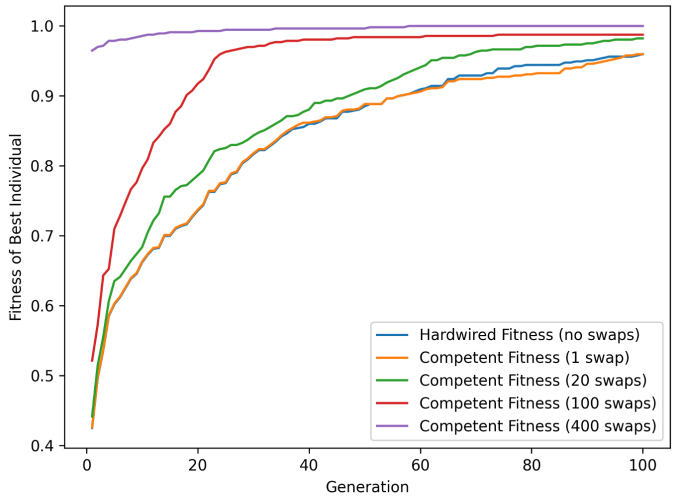
- Competency hides genetic information from selection, resulting in intelligence ratchet: might all the work now be done by improving the IQ of the material, vs. micromanaging the hardware (genome)?





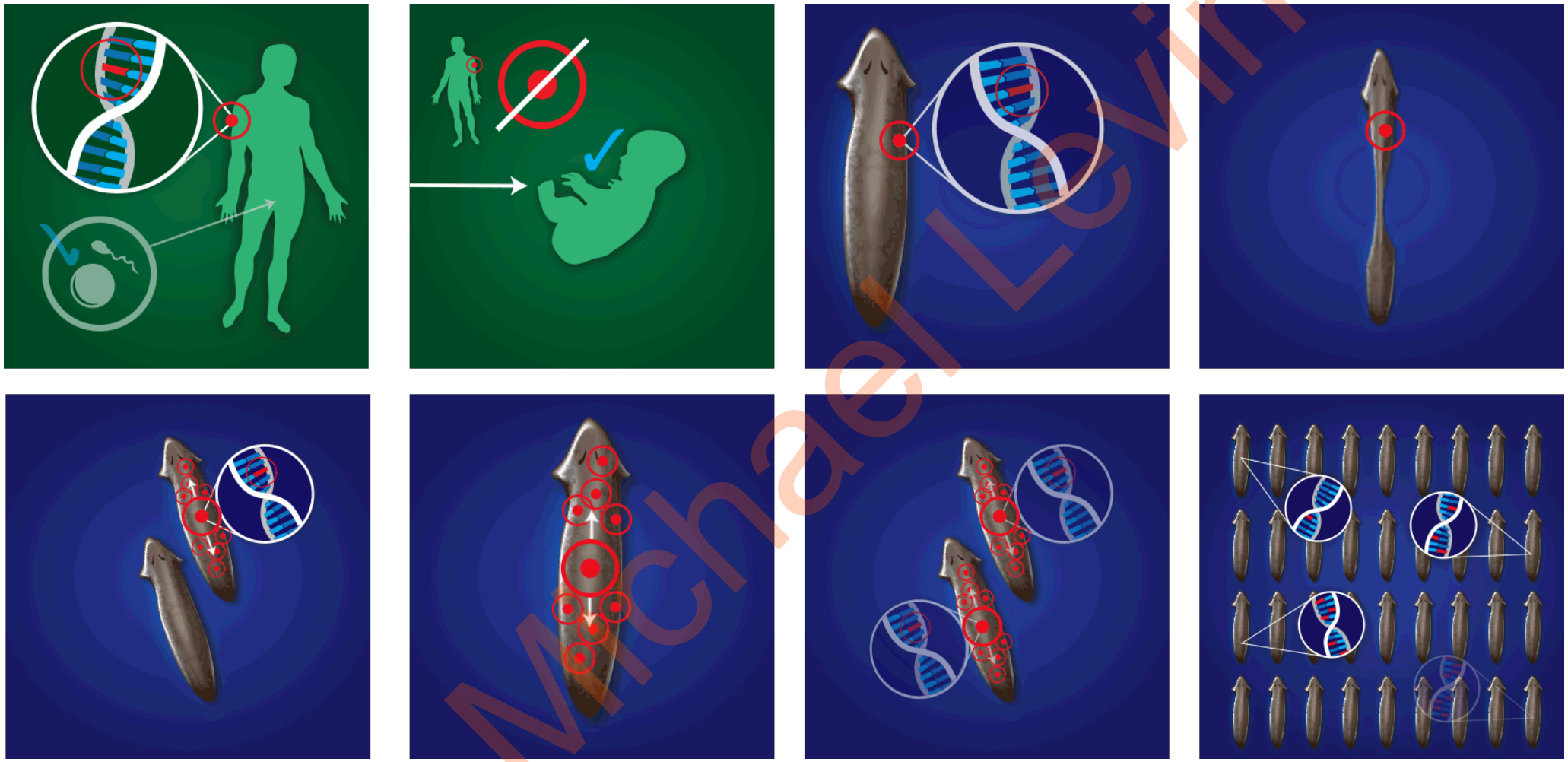


Laura Vandenberg



"Chance favors the prepared mind" - how evolution makes use of random mutations in an agential medium!

Maxing out the Unreliability of the Substrate



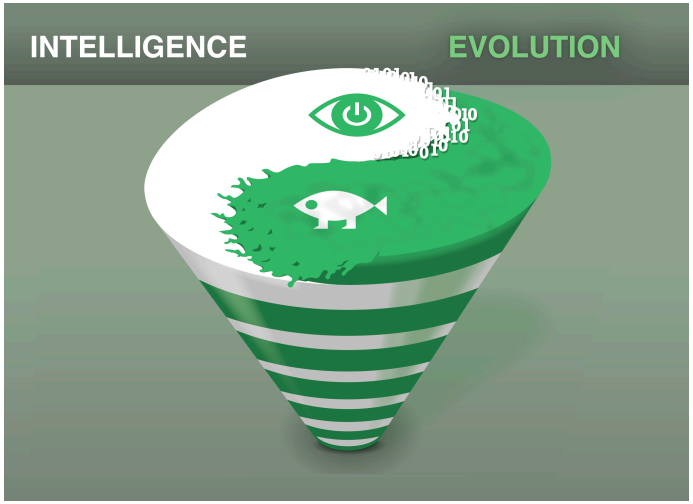
- Planaria that reproduce by fission+regeneration:
- Body mutations propagate to next generation
- Despite hundreds of millions of years of somatic inheritance,
- Regenerative pattern correct with 100% fidelity!

Resistant to:

cancer
memory loss (tails regenerate memories)
decomposition (no cell lines)
aging (immortal!)
mutations (no genetic or transgenic lines)

~~**in spite of**~~
because of

very noisy genome



Evolutionary Implications

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- Competencies of modules smooths the evolutionary landscape and buffers negative effects of mutation, giving the process patience (improves evolvability)

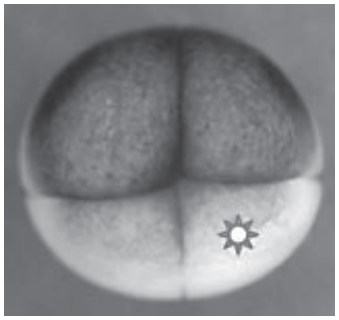
- Competency hides genetic information from selection, resulting in intelligence ratchet: might all the work now be done by improving the IQ of the material, vs. micromanaging the hardware (genome)?

- Evolution doesn't just create solutions for specific environments (problems) - it creates problem-solving systems (because each multicellular Self has to identify borders, salient inputs, causally-potent outputs, etc. on the fly) - normal development, even without perturbations, is already a problem-solving process.

The need to interpret anew makes evolution be faster and much more powerful

Main Points:

Rebooting Multicellularity: Xenobots

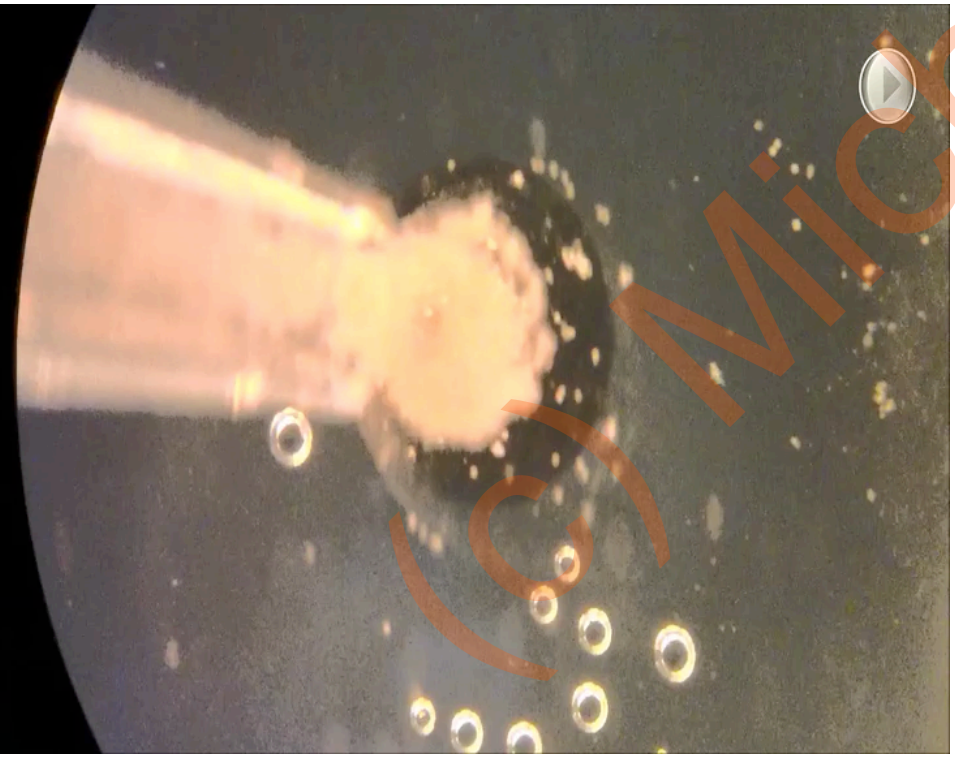


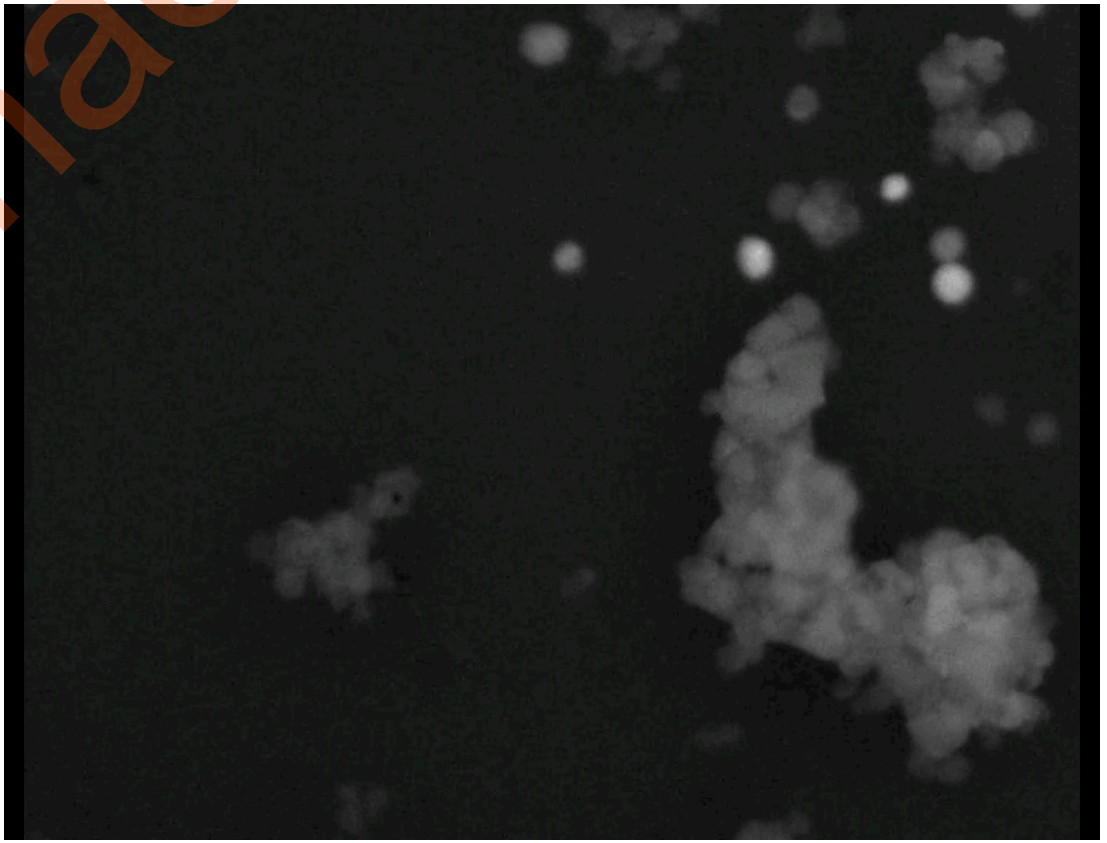
Early frog embryo

8 hours

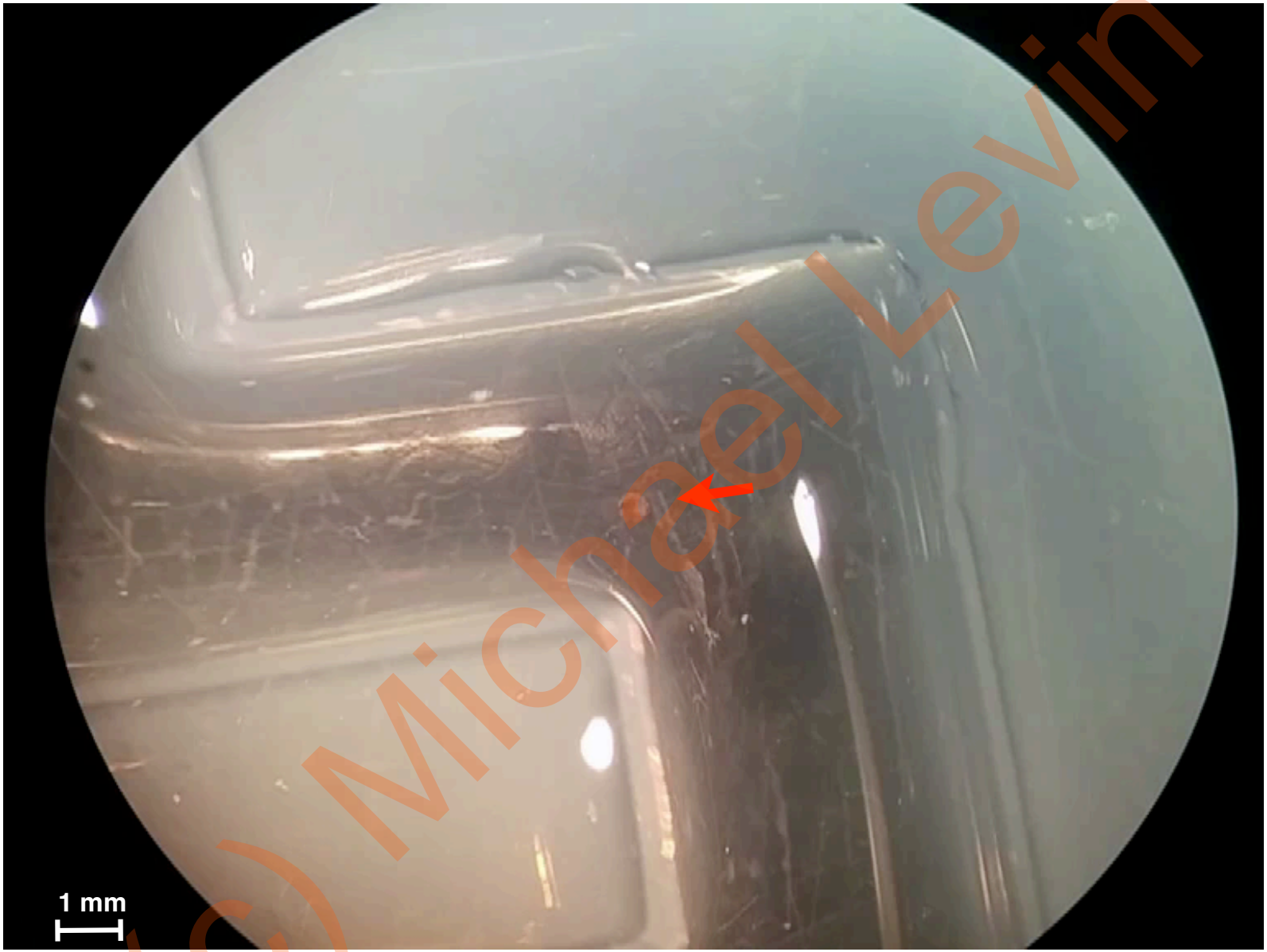
assay for form and function

Douglas Blackiston





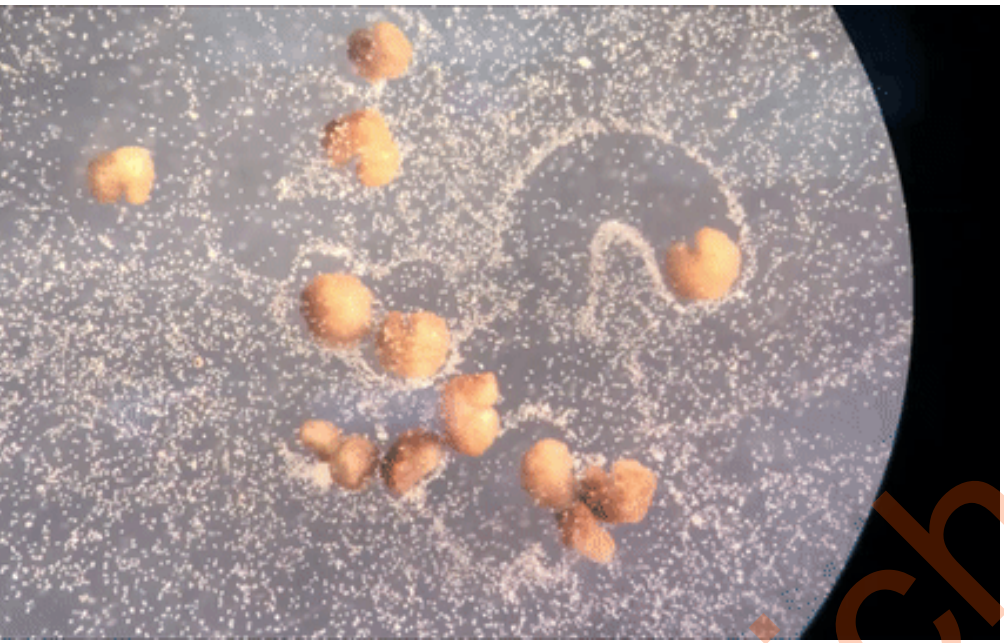
Xenobot in a maze (still water, no flow):

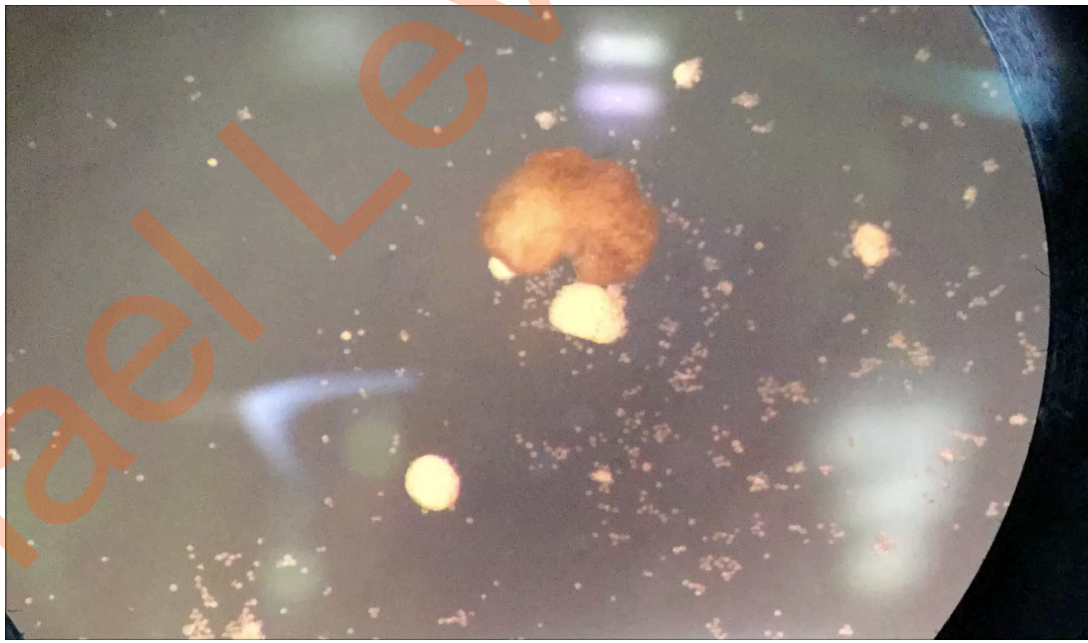


1) it traverses maze, 2) rounds the corners without bumping into walls, and
3) it makes a spontaneous decision to turn around without hitting anything.

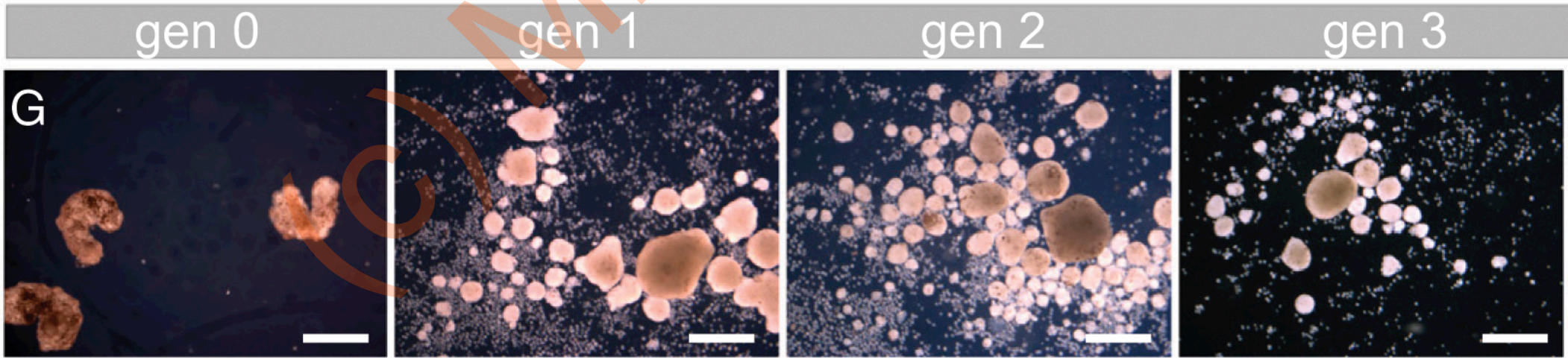
Douglas Blackiston

Kinematic Replication in Xenobots: novel competencies of the agential material

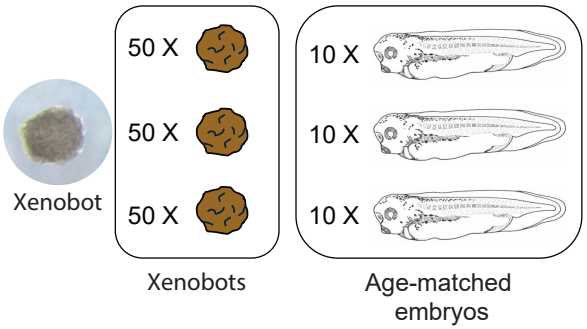


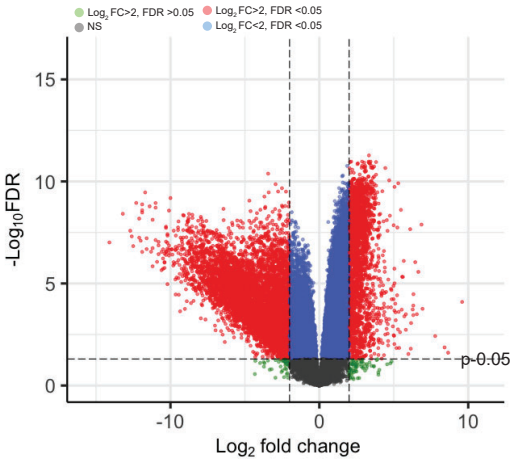


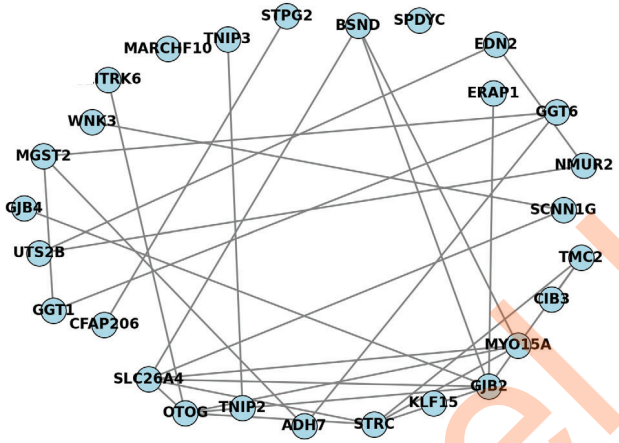
Douglas Blackiston



Communicating with Xenobots via Sound

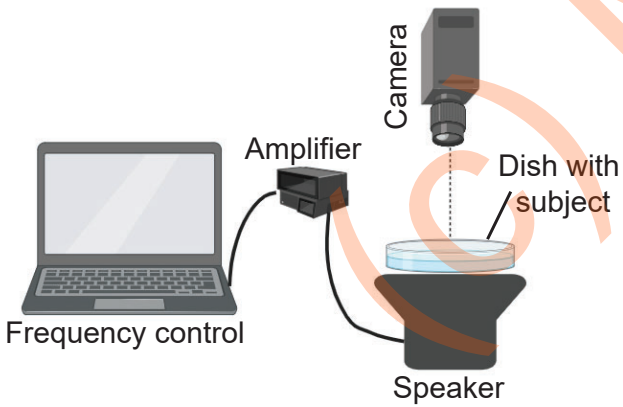


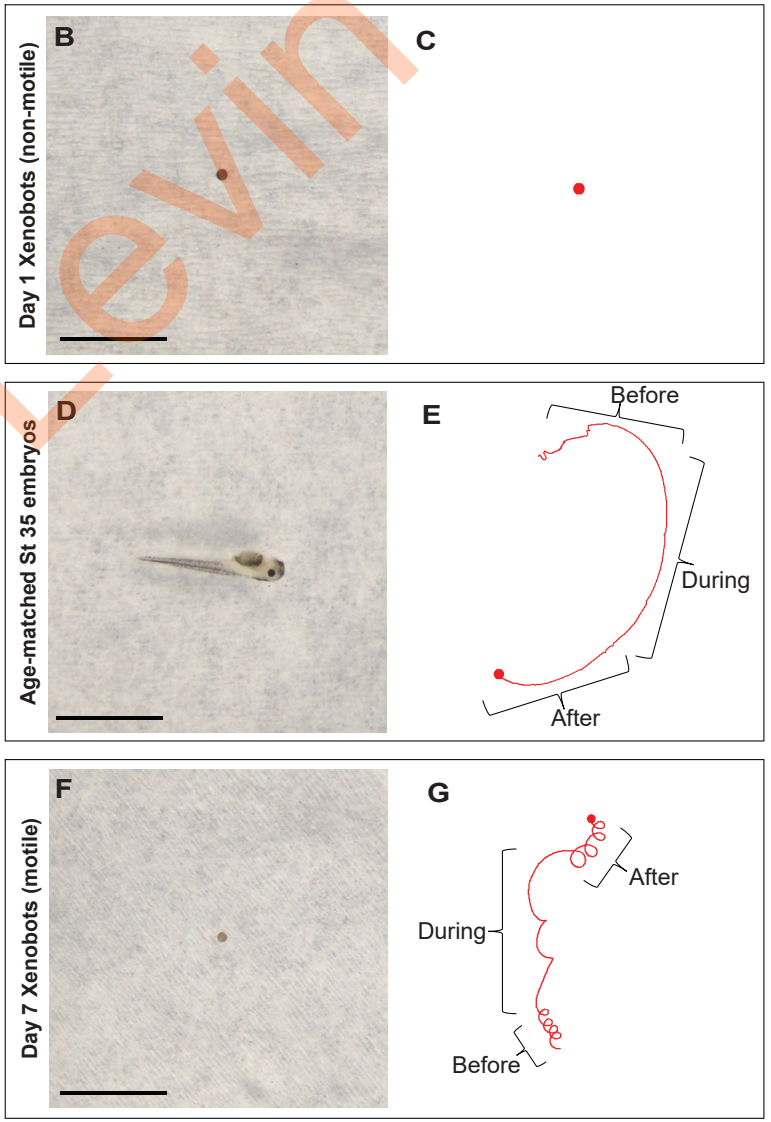




Sensory perception of sound and mechanical stimuli

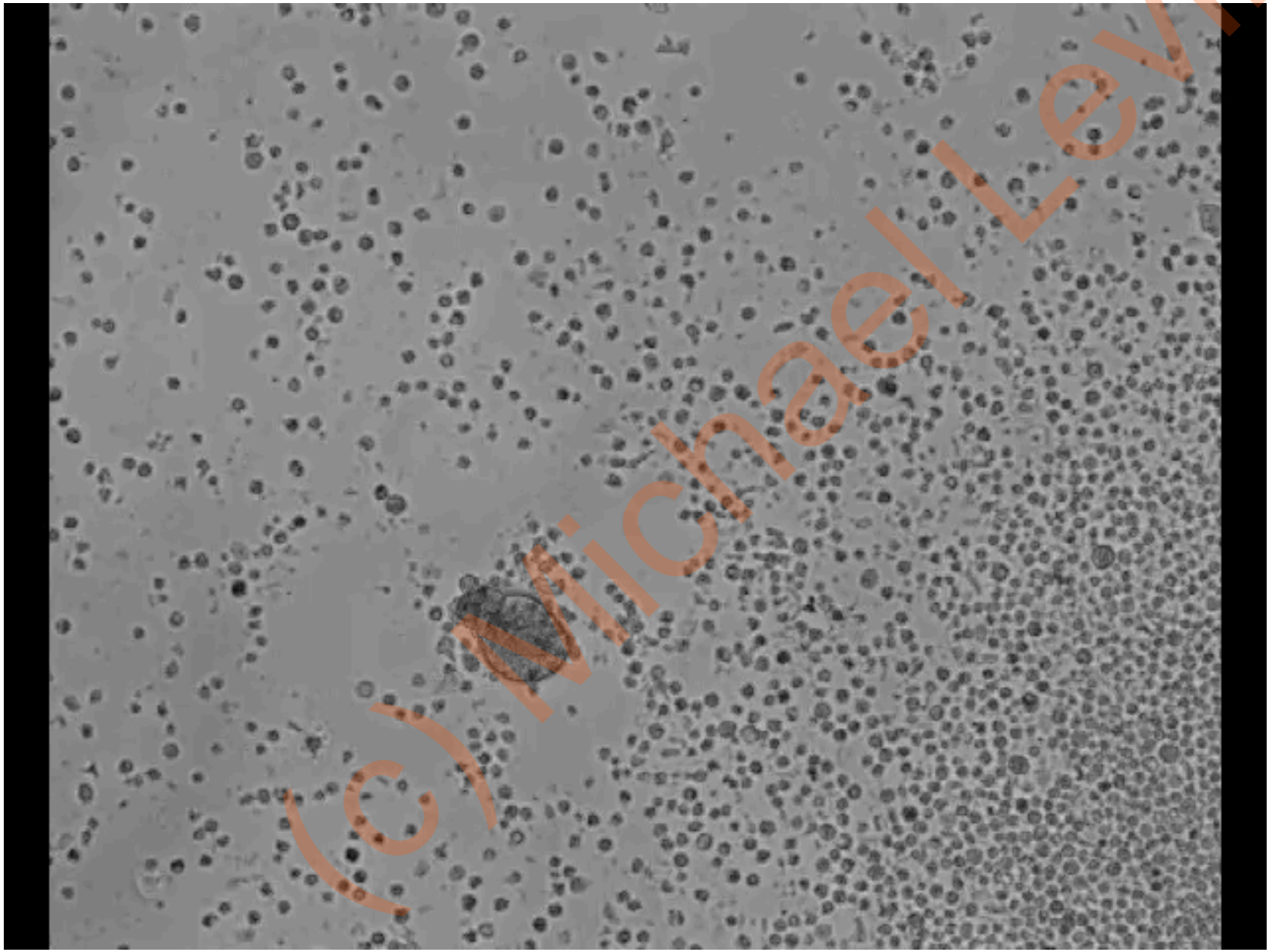
= unique transcripts in Xenobots





Vaibhav Pai

Anthrobots; can you guess the genome?



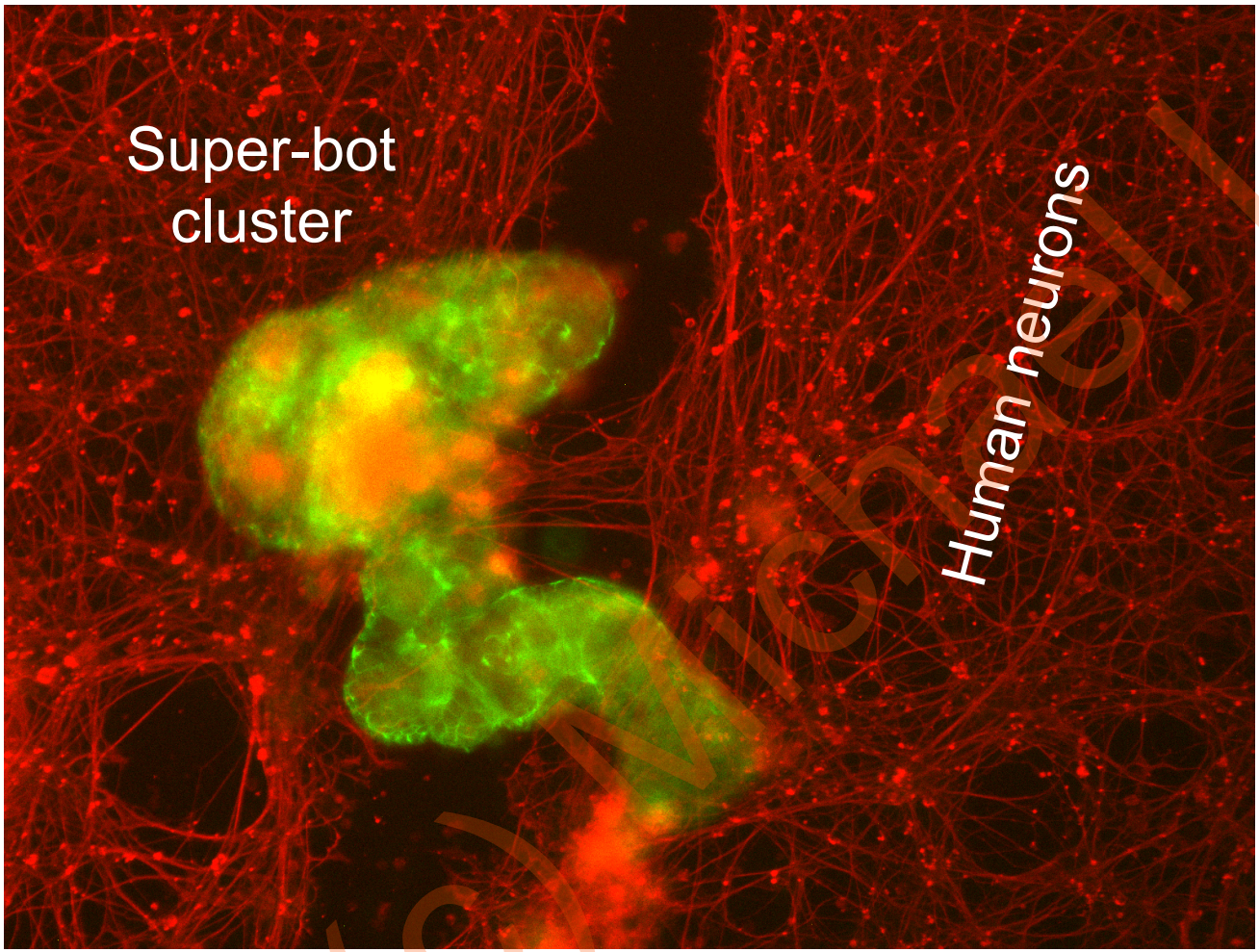
Where do the properties of novel systems come from if not eons of selection or explicit engineering?

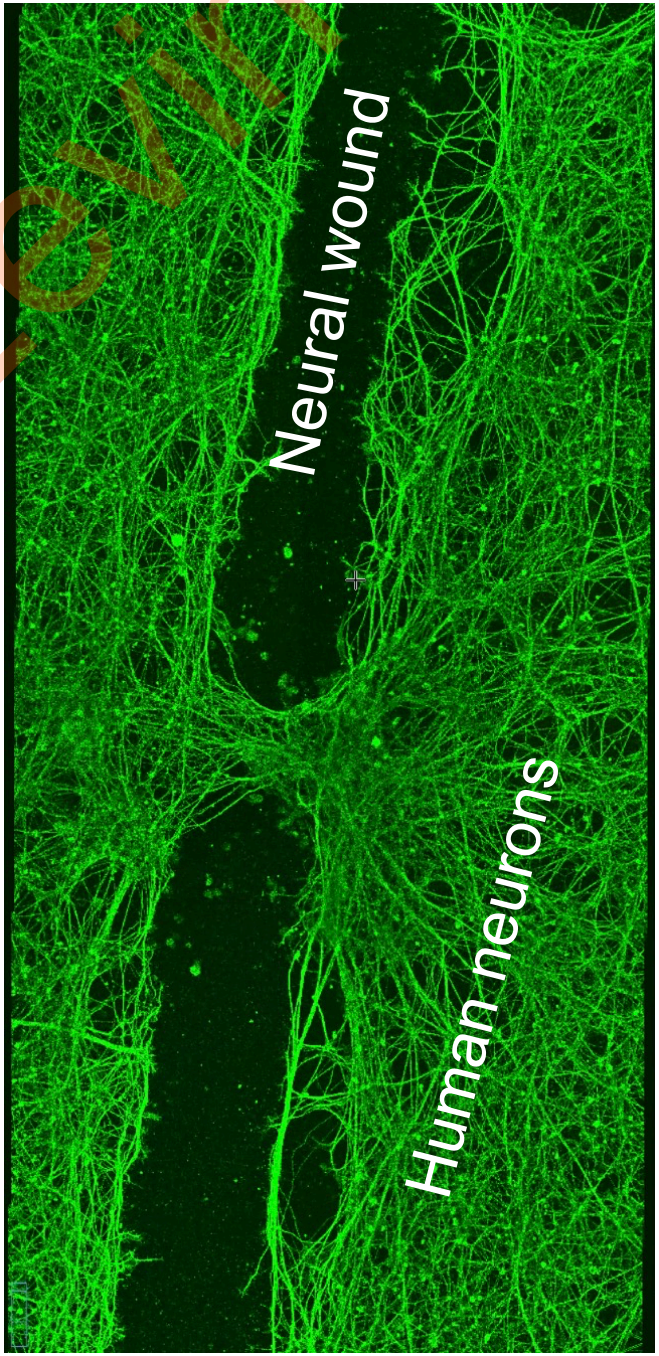
Could you guess the genome from these data?

Could you guess behavior and form from the genome?

Gizem Gumuskaya

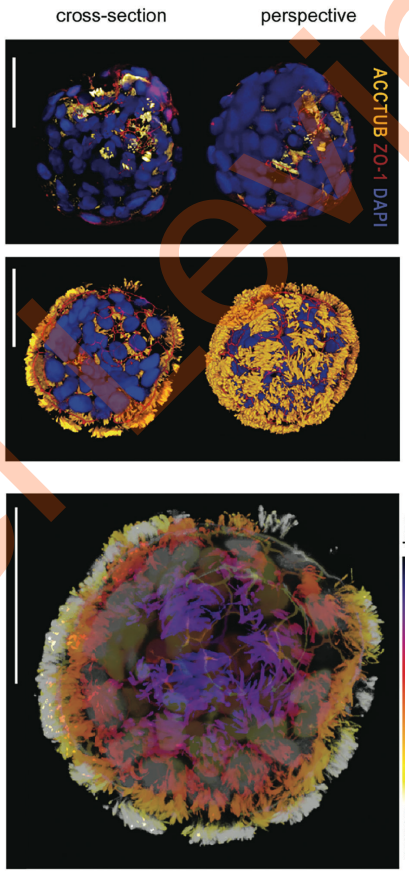
Anthrobots Exert Neural Repair

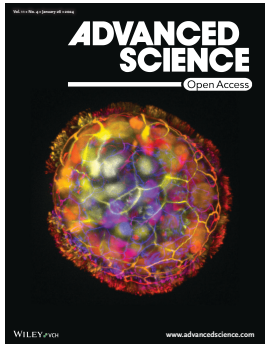


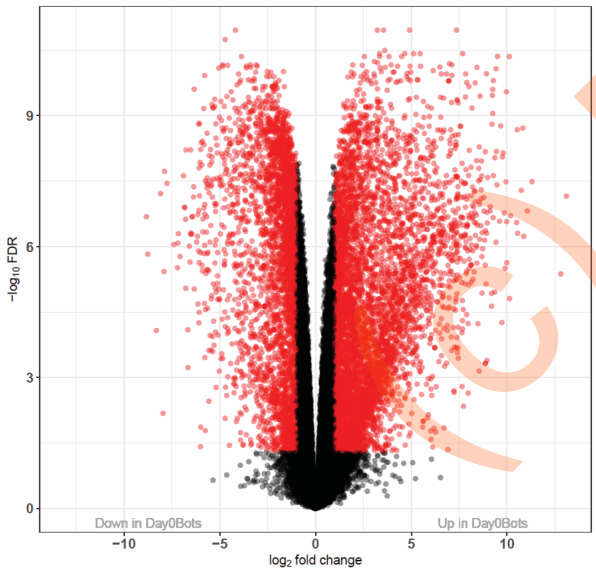


Gizem Gumuskaya

No Selection History Explains Form and Behavior:

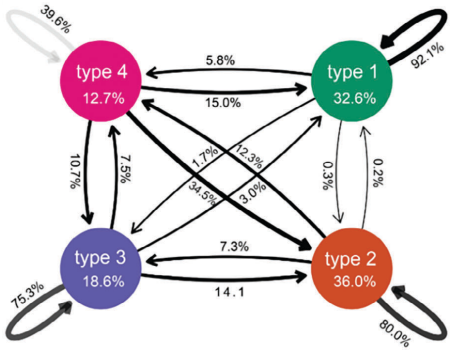






drastically remodeled transcriptome

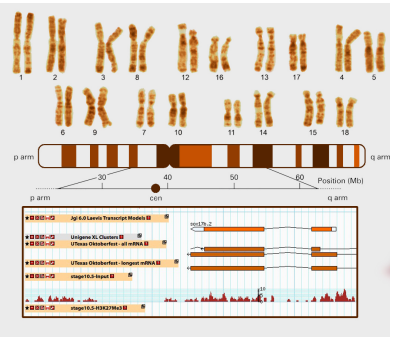
Ethogram of discrete behaviors

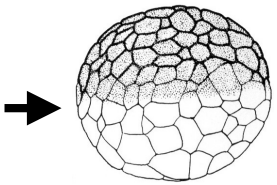


Gizem Gumuskaya

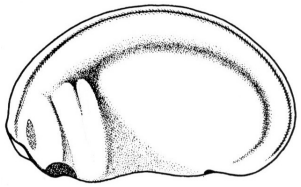
Biobots have Standard Genomes
Novel Morphology, Transcriptomes, Behaviors

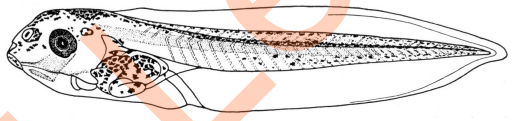
Xenopus laevis genome





Path A: embryos





Douglas Blackiston

Path B: Xenobots

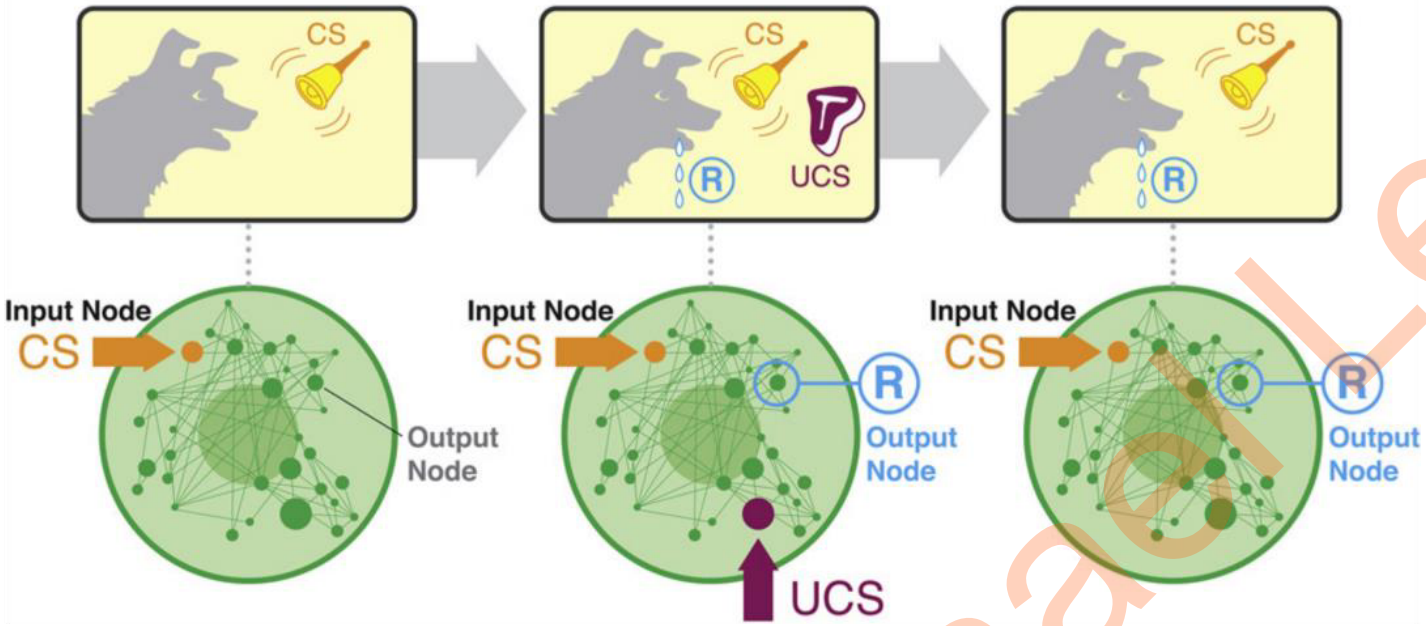
Developmental Time

Behavior

- Xenobot bodies and minds have no straightforward evolutionary back story; whence their specific competencies?
- **We know when computation was done to make a frog; when was it done for Xenobots/Anthrobots?**
- **"Emergence"?** What degree of specificity between history and outcome does evolutionary theory imply?

Main Points:

Collective Intelligence Below the Cell Level



- Molecular pathways can learn!

International Journal of *Molecular Sciences*
MDPI

Article

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

Surama Biswas [1,2,†], Wesley Clawson [1,†] and Michael Levin [1,3,*]

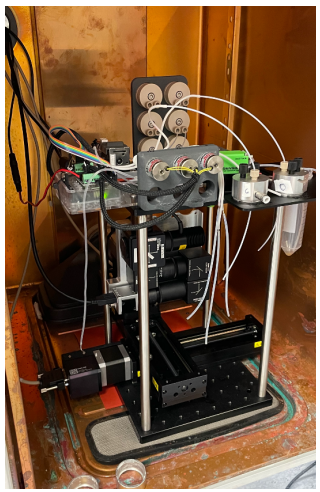
iScience
CellPress
OPEN ACCESS

Article

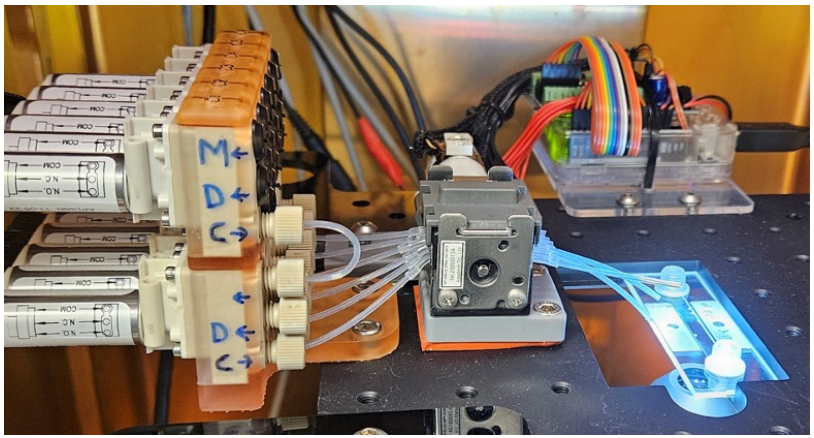
Gene regulatory networks exhibit several kinds of memory: quantification of memory in biological and random transcriptional networks

Biomedicine:

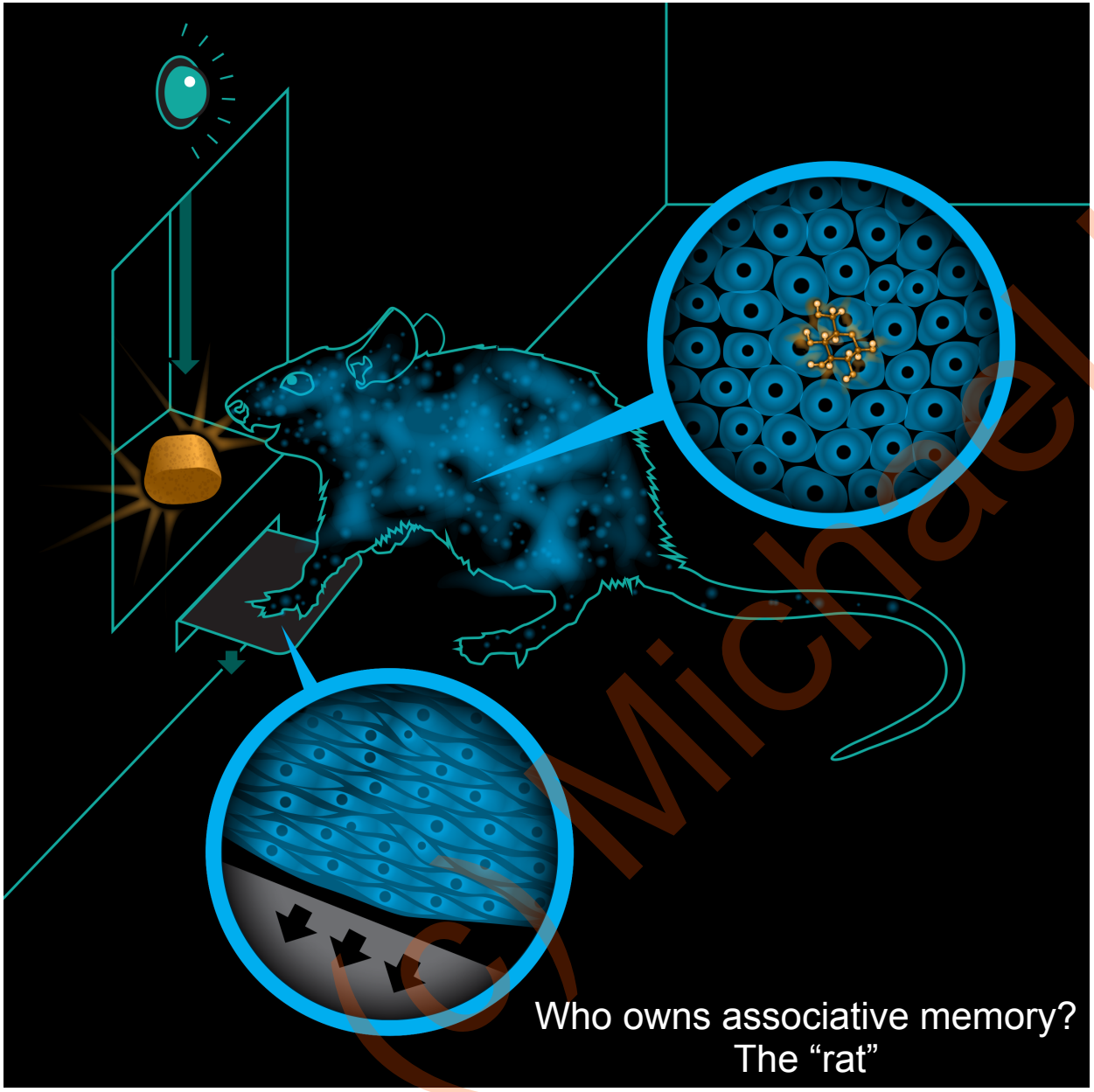
- drug conditioning



Patrick Erickson



Causal Emergence & Learning



Which level is doing the most work?

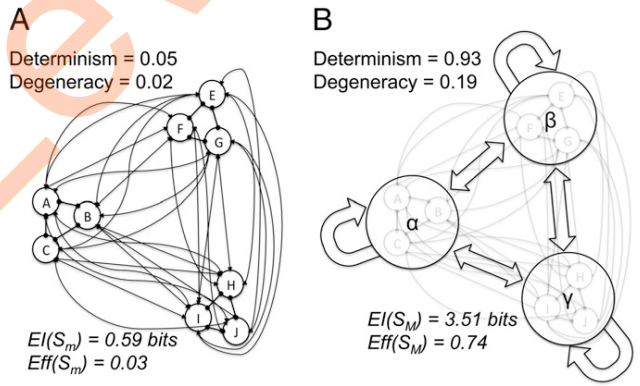


Fig. 6. Spatiotemporal causal emergence. (*A*) A “neuronal” system merging

entropy

Article

When the Map Is Better Than the Territory

Erik P. Hoel

PNAS

Quantifying causal emergence shows that macro can beat micro

Erik P. Hoel, Larissa Albantakis, and Giulio Tononi[1]

Department of Psychiatry, University of Wisconsin, Madison, WI 53719

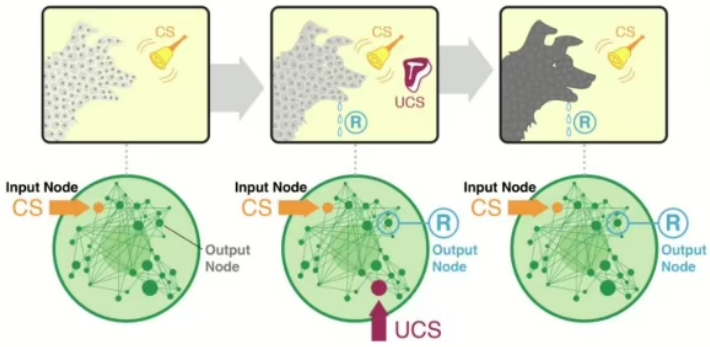
Edited by Michael S. Gazzaniga, University of California, Santa Barbara, CA, and approved October 22, 2013 (received for review August 6, 2013)

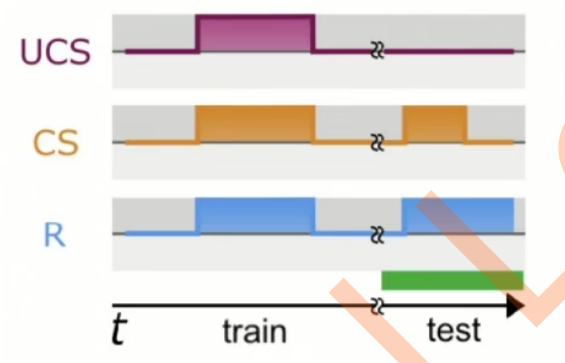
Causal interactions within complex systems can be analyzed at multiple spatial and temporal scales. For example, the brain can be analyzed at the level of neurons, neuronal groups, and areas, over

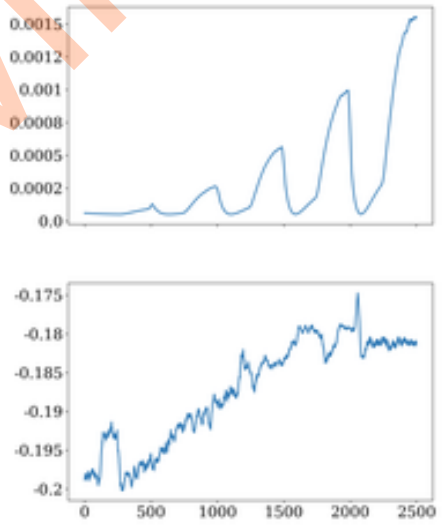
others as reducible to their micro elements. Also, most arguments in favor of emergence have been qualitative (11). A convincing case for emergence must demonstrate that higher levels can be

- Integration -> learning
- Is the reverse true??

Functional Agency Ratchet (FAR): Learning and Causal Emergence of Integrated Collectives







Causal emergence before, during, and after associative training in GRNs

Federico Pigozzi

communications biology

A Nature Portfolio journal

Article

https://doi.org/10.1038/s42003-025-08411-2

Associative conditioning in gene regulatory network models increases integrative causal emergence

Check for updates

Federico Pigozzi[1], Adam Goldstein[2] & Michael Levin[1,3]

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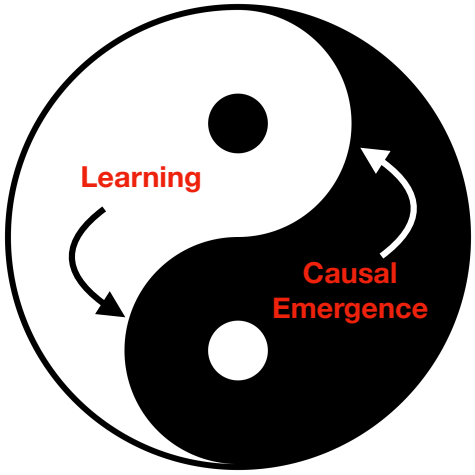
AI-Guided Resetting of Memories in Gene Regulatory Network Models: biomedical and evolutionary implications

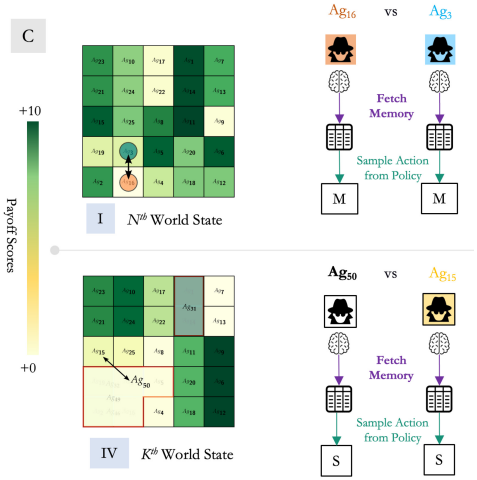
F. Pigozzi, T. Cirrito, M. Levin

doi: https://doi.org/10.1101/2025.09.10.675114

- Higher Causal Emergence makes for better learning
- Learning raises PhiD
- Forgetting does *not* erase gains

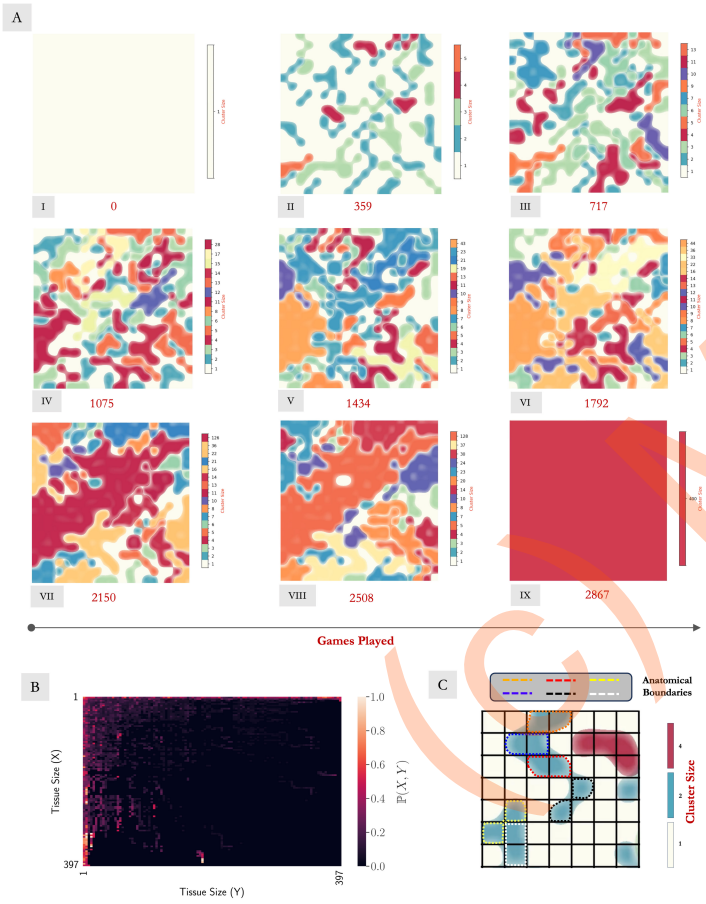


Prisoners' Dilemma: aiming upwards



Extending Iterated, Spatialized Prisoner's Dilemma to Understand Multicellularity: Game Theory With Self-Scaling Players

Lakshwin Shreesha, Federico Pigozzi, Adam Goldstein, and Michael Levin



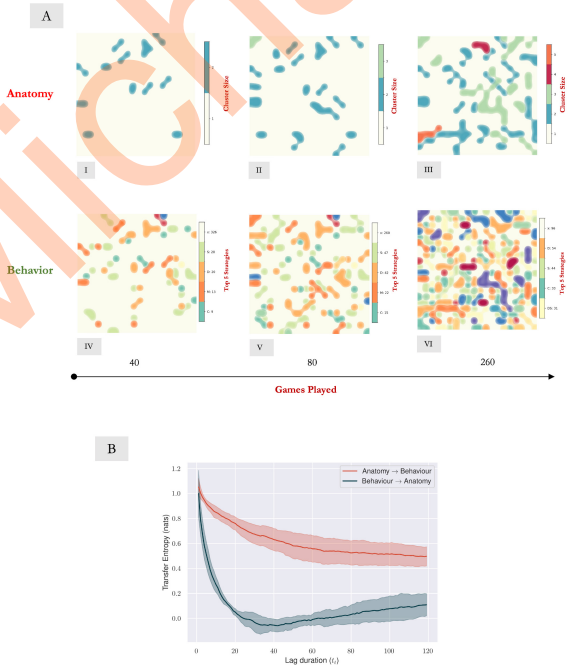


Fig. 8. Agential boundaries can be anatomical or behavioral. *Panel A:*

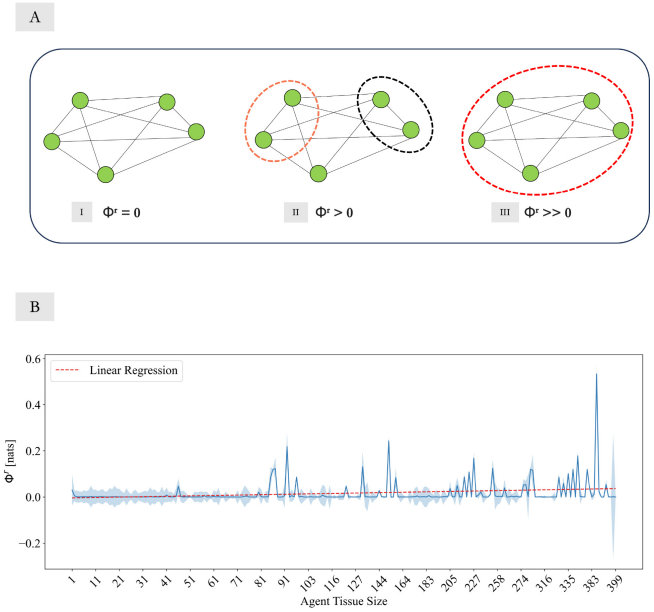


Fig. 7. Integrated Information Theory highlights that larger agents are more integrated with the environment than smaller ones. In Integrated Information

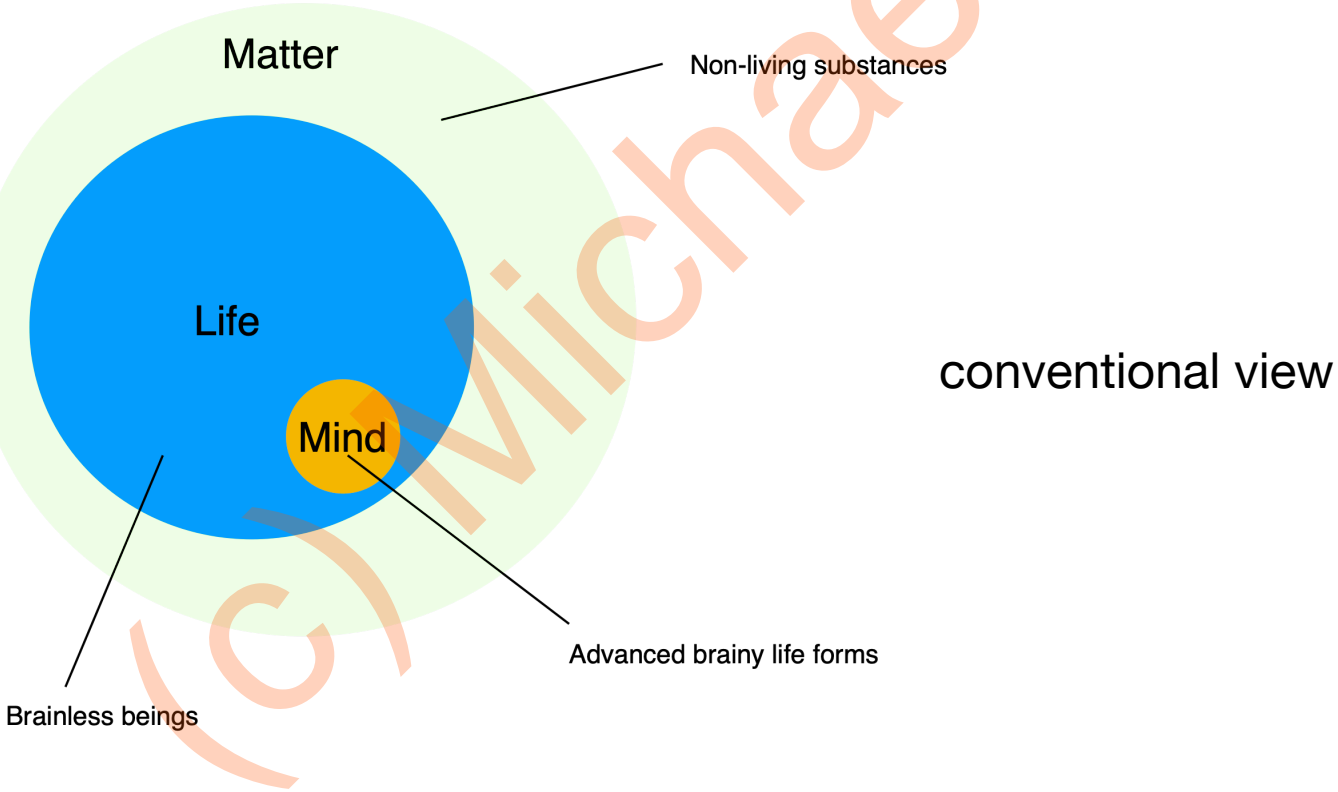
Main Points:

Conclusion 1: summary

- Intelligence is not magic or mysterian - many tools exist to rigorously, quantitatively probe (not assume, not guess) the degree and kind of cognition in unfamiliar substrates.
- Genotype -> Phenotype map (morphogenesis) is a problem-solving, creative process not well-captured by "emergence" and "complexity science" (open-loop models in which there is no goal or setpoint). Its IQ along the spectrum of cognitive capabilities is only beginning to be appreciated.
- Morphogenesis is the *behavior* of a cellular collective intelligence in anatomical morphospace. Mechanisms for dynamically interpreting/exploring the 3D world, to handle novelty, are the same as for intelligently interpreting one's genome, so they evolve together – intelligence, creativity, and evolvability are same.
- Those mechanisms are evolutionarily conserved - ion channels, electrical synapses, etc. etc., which now allows us to communicate with living matter and prompt (not micromanage) it to novel journeys in morphospace (see my other talks)
- Evolving on an agential material breaks a lot of assumptions about evolution. Unreliability of the multi-scale material favors creation of improvisation engines, not just solutions of specific problems. That is the source of the immense plasticity and reprogrammability of the genetically-specified hardware, and it makes evolution go much faster.
- Proto-organisms (biobots, chimeras, cyborgs) that have never been on Earth before offer great model systems for asking: where do the anatomical, behavioral, transcriptional, and physiological setpoints come from if not selection?

Conclusion 2: speculative future outlook

- Feedback spiral between learning and causal emergence: an upward-facing ratchet increases agency with very, very minimal assumptions. That spiral is a free gift from mathematics, not requiring anything from physics or biology.
- It happens long before cells, pathways, or any replicators, and shows the booting-up of informational selves before a physical body appears whose continuous upkeep drives differential replication.



conventional view

Conclusion 2: speculative future outlook

- Feedback spiral between learning and causal emergence: an upward-facing ratchet increases agency with very, very minimal assumptions. That spiral is a free gift from mathematics, not requiring anything from physics or biology.
- It happens long before cells, pathways, or any replicators, and shows the booting-up of informational selves before a physical body appears whose continuous upkeep drives differential replication.
- Cognition is wider and older than biology. It's baked in to very simple systems, but evolution scales it greatly.

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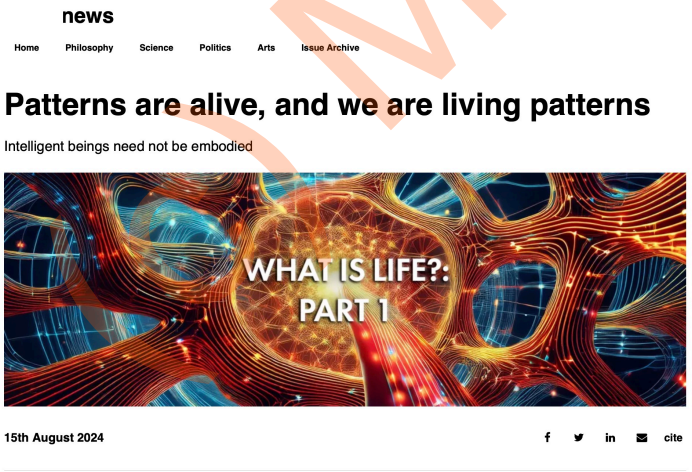
Review

Thoughts and thinkers: On the complementarity between objects and processes

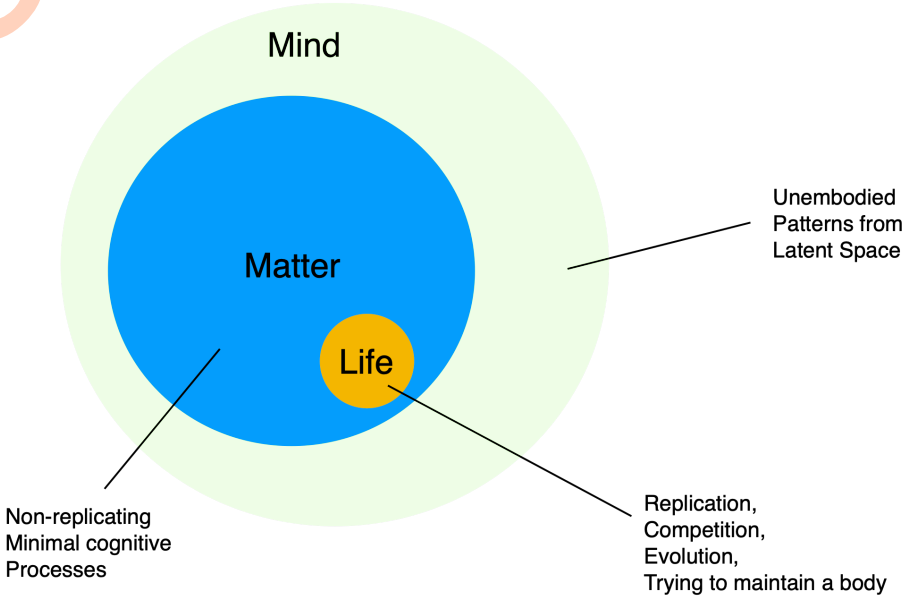
Chris Fields [a,*], Michael Levin [a,b]

[a] Allen Discovery Center at Tufts University, Medford, MA 02155, USA

[b] Wyss Institute for Biologically Inspired Engineering at Harvard University, Boston, MA 02115, USA

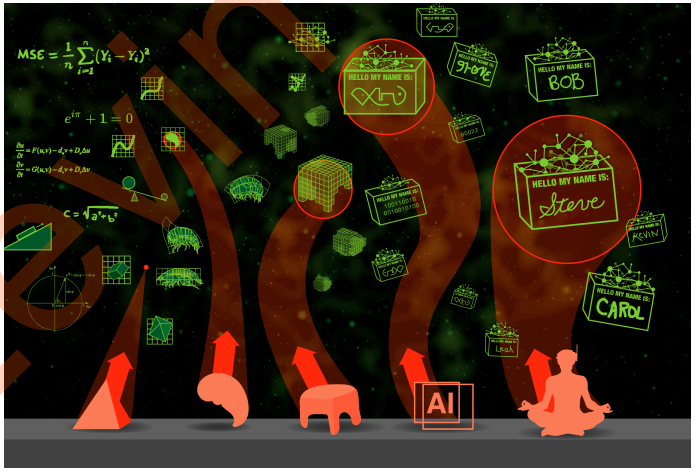


I suspect:



Conclusion 2: speculative future outlook

- Patterns of form, physiology, and behavior w/o specific selection history for them. Not just patterns - behavioral competencies. Are they random and unpredictable ("emergent") or do they come from a structured latent space? Mathematicians already study a space of truths that cannot be found or changed by physics. Let's use living interfaces, evolved and engineered, to explore that space.



- Today's computational formalisms are insufficient to understand and relate to biology. But, they're also insufficient for even minimal systems and so-called "machines". Nothing is only what our models say it is.

Article

Adaptive Behavior

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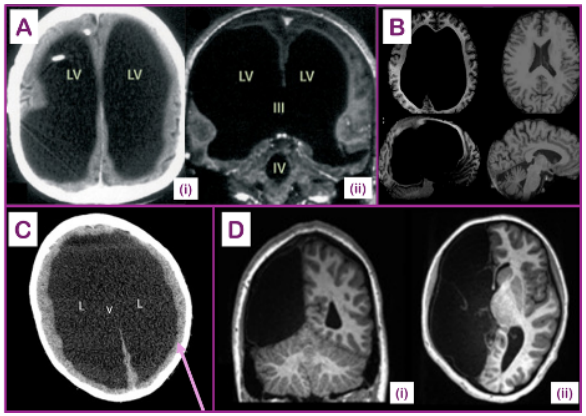
Classical sorting algorithms as a model of morphogenesis: Self-sorting arrays reveal unexpected competencies in a minimal model of basal intelligence

Taining Zhang[1], Adam Goldstein[2] and Michael Levin[1,3]

- Fundamental knowledge gaps exist about the relationship between biological/physical interfaces and the patterns of form and function that animate the hardware.



Mind & Matter **23**(1), 13-69 doi: 10.5376/mm2025.13

Cases of Unconventional Information Flow Across the Mind-Body Interface

Karina Kofman
Faculty of Dentistry, University of Toronto
Toronto, Canada
and
*Michael Levin**
Allen Discovery Center
Tufts University, Boston, USA
and
Wyss Institute for Biologically Inspired Engineering
Harvard University, Cambridge, USA

- See our symposium at

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

More Details Here:

frontiers in Psychology

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

Michael Levin[1,2*†]

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Review

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

Santosh Manicka and Michael Levin

PROBLEMS & PARADIGMS
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BioEssays
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Scale-Free Biology: Integrating Evolutionary and Developmental Thinking

Chris Fields 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]**

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

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doi: 10.3389/fnsys.2022.768201

Technological Approach to Mind Everywhere: An Experimentally-Grounded Framework for Understanding Diverse Bodies and Minds

*Michael Levin[1,2]**

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

Joshua Bongard[1†] and Michael Levin[2,3†]*

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

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BBRC

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

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Chris Fields - physics of sentience and sentience of physics
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Giovanni Pezzulo - cognitive science applied to morphogenesis
Simon Garnier - computational analysis of Anthrobot form and function

Model systems: tadpoles, planaria, slime molds, human cells, animats, hybrots, etc.

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