

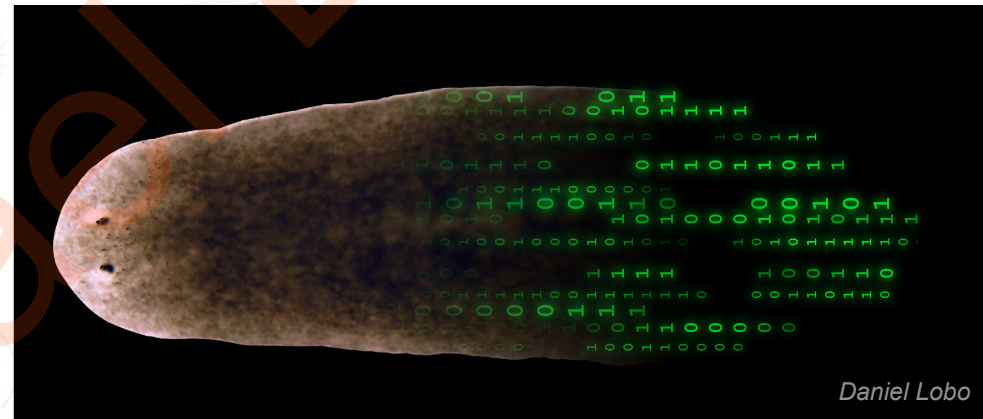
Non-Neural Intelligence:

Biological Architectures for Problem-Solving in Diverse Spaces

Michael Levin
Allen Discovery Center at Tufts

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

<http://thoughtforms.life/>



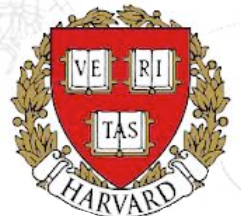
ALLEN
DISCOVERY CENTER
at Tufts University



Computer-designed organisms

TUFTS UNIVERSITY | UNIVERSITY OF VERMONT

WYSS
INSTITUTE



Summary:

- Biological systems: self-constructing, polycomputing agents operating in diverse spaces
- They solve problems and navigate these spaces at multiple scales – agential material that is not well-described by either chemistry or Turing Machine paradigms
- Biology commits to saliency and playing the cards its dealt, not fidelity of past information; because the medium is fundamentally unreliable -> plasticity of interpretation, not over-training
- Evolution makes creative agents, not solutions to specific problems
- Biology embodies coarse-grained, agential models because time is short and energy is scarce
- Emergent cognition, not just complexity

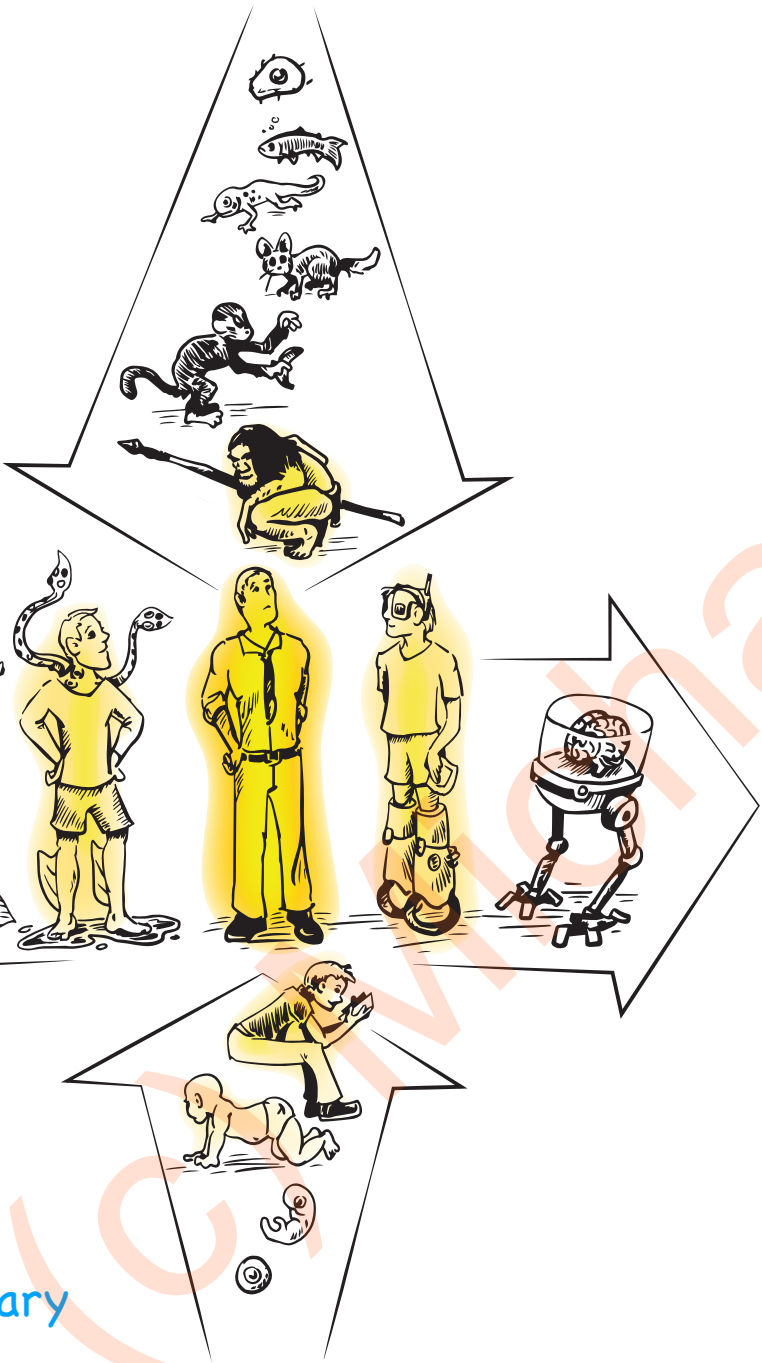
Implications for:

- computer science and AI
- Biomedicine

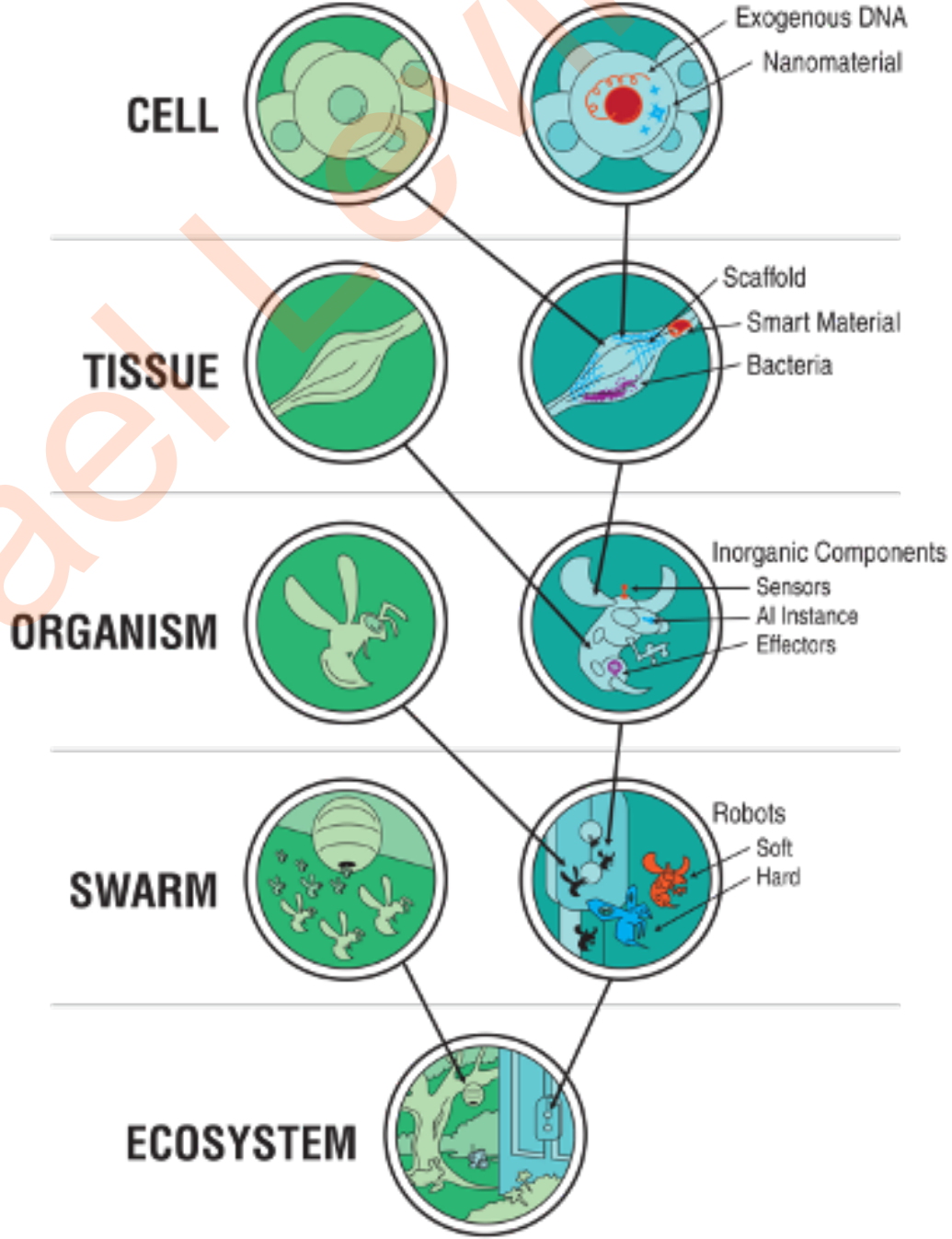
Outline:

- Non-neural problem-solving - examples beyond the brain
- Fundamental principles of autopoietic, autotelic intelligence
- Beyond evolution and design

Humans vs. Machines A Wider Continuum of Beings



Beyond
simplistic binary
categories



My Framework Goal:

- Recognize, create, and relate to 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 (software or robotic)
- exo-biological agents (Earth is N=1)

Behavior

Active

Non-active (passive)

Purposeful

Non-purposeful (random)

Feed-back (teleological)

No feedback (non-teleological)

Predictive (extrapolative)

Non-predictive (non-extrapolative)

1st, 2nd, etc.
order of prediction, self-reference

Behavior, Purpose and Teleology

Arturo Rosenblueth, Norbert Wiener and Julian Bigelow

in: *Philosophy of Science*, 10(1943), S. 18-24.

frontiers
in Systems Neuroscience

HYPOTHESIS AND THEORY
published: xx xx 2022
doi: 10.3389/fnys.2022.768201

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

Michael Levin^{1,2*}

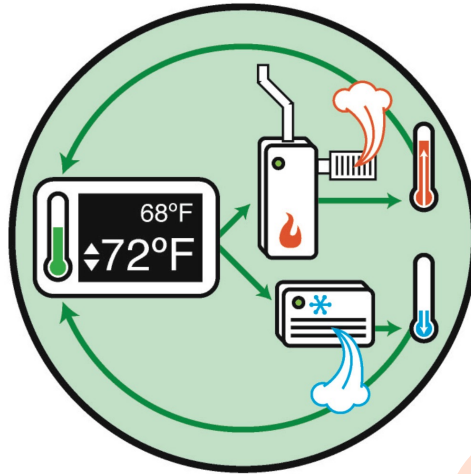


- moves experimental work forward - new capabilities, better ethics

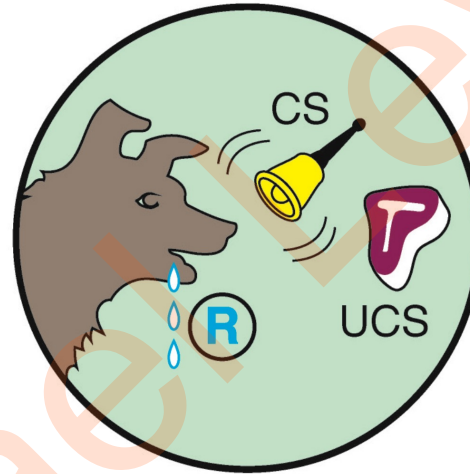
Axis of Persuadability: an Engineering Take on a **Continuum** of Agency



Hardware
modification only



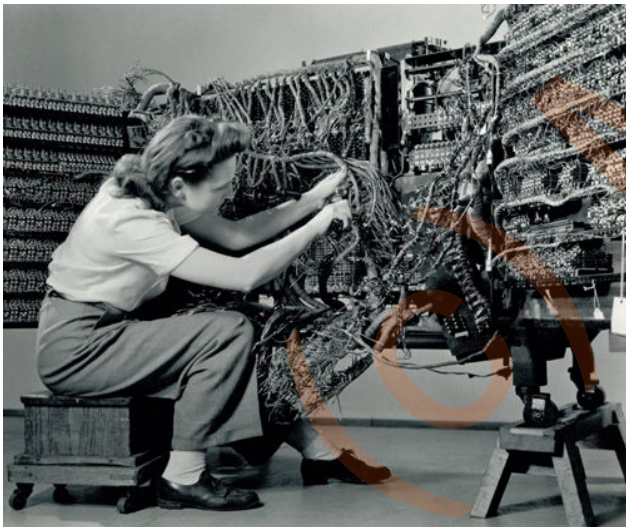
Modify the data encoding
setpoint of goal-driven
process



Training by
rewards/
punishments



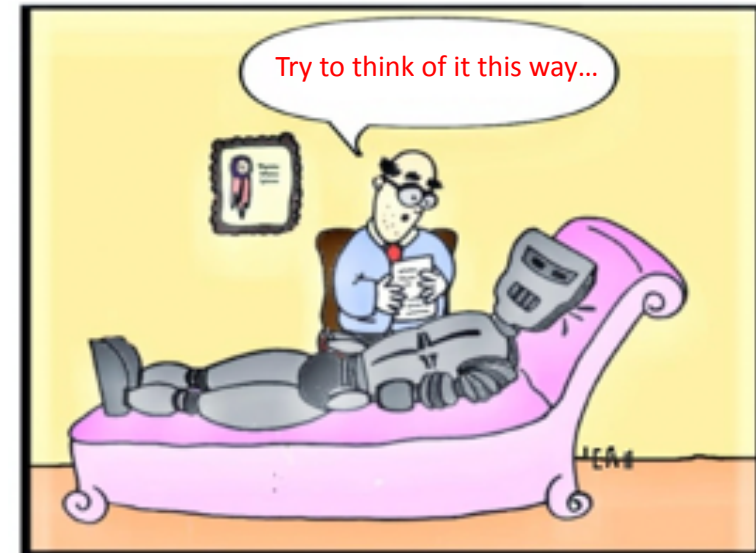
Communicate
cogent reasons

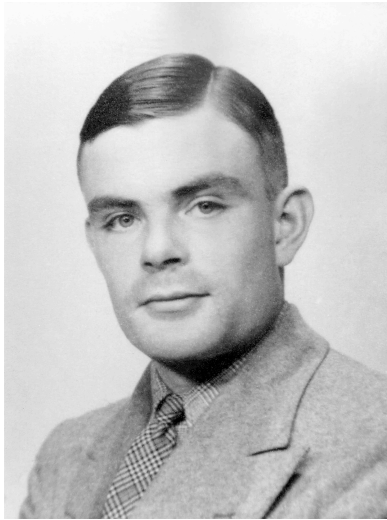


Not tied to specific substrate
or origin story

(but also not to our models
of computation)

Observer-centered
(Intentional Stance)





Alan Turing

COMPUTING MACHINERY AND
INTELLIGENCE
By A. M. TURING

230

A. M. TURING

[Nov. 12,

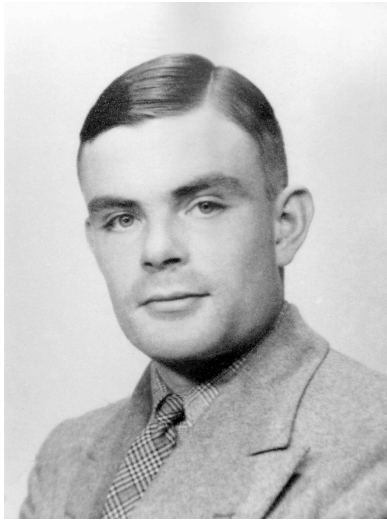
ON COMPUTABLE NUMBERS, WITH AN APPLICATION TO
THE ENTSCHIEDUNGSPROBLEM

By A. M. TURING.

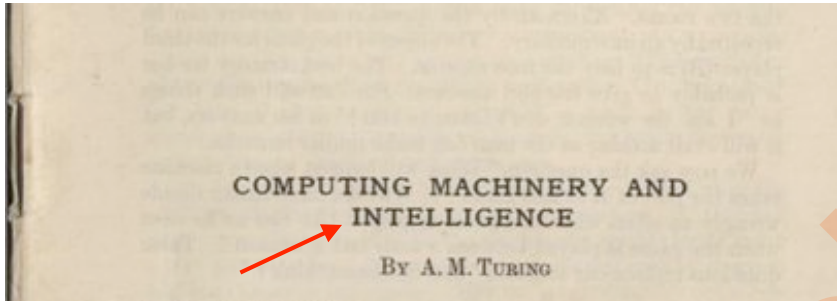
[Received 28 May, 1936.—Read 12 November, 1936.]

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

Problem-solving machines:
intelligence through plasticity
(reprogrammability)



Alan Turing



COMPUTING MACHINERY AND
INTELLIGENCE

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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.

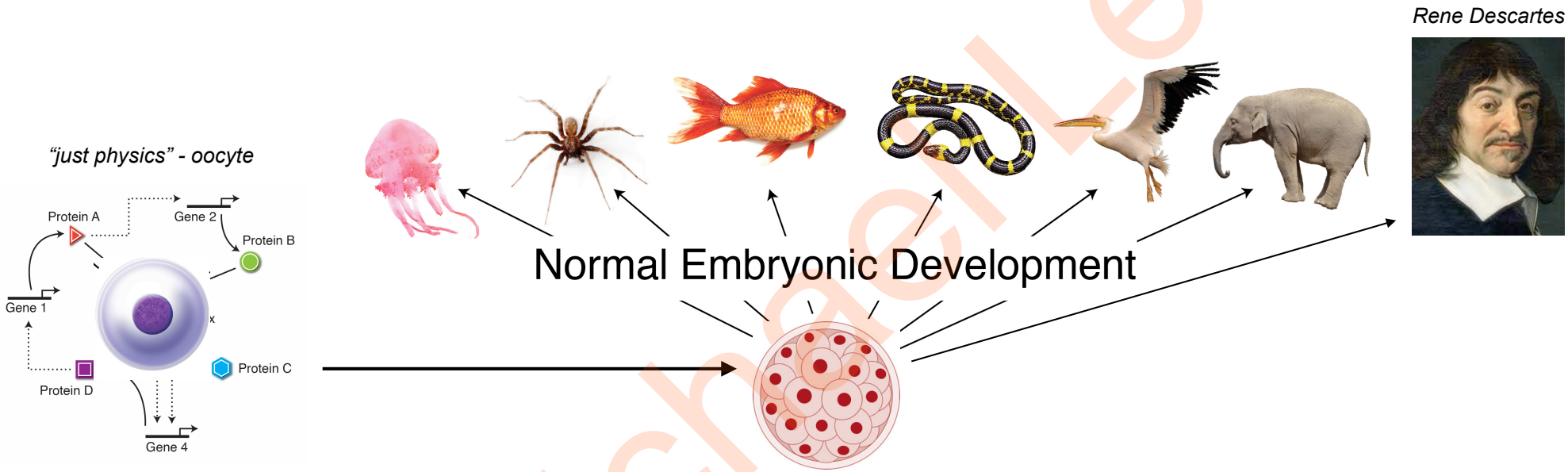


Problem-solving **living** machines:
intelligence through plasticity
(reprogrammability)

Unique Features of the Biological Substrate: a tour of the agential material of life

- Multiscale competency architecture
- Plasticity of boundaries
- Creative problem-solving
- Self-construction, emergent goals

Life Self-assembles from "Just Physics" to Mind



we all make the journey across the Cartesian cut

But at least, we're a true Unified Intelligence?



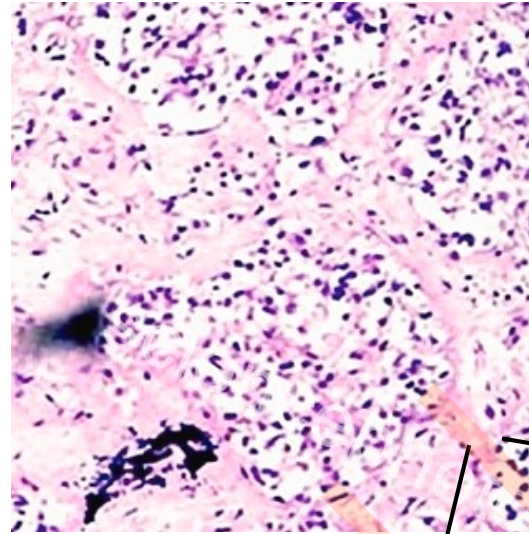
we've got
a solid
brain



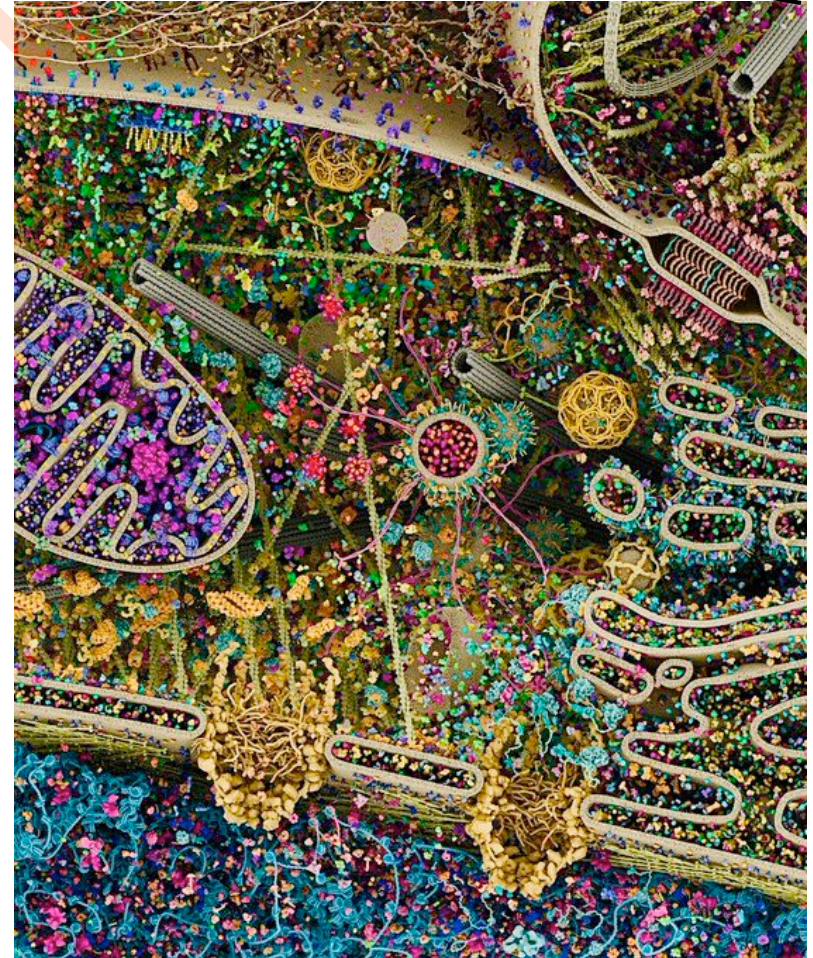
Getty Images

Solè's "liquid brains" are
just a metaphor right?

**We are
collective
intelligences**

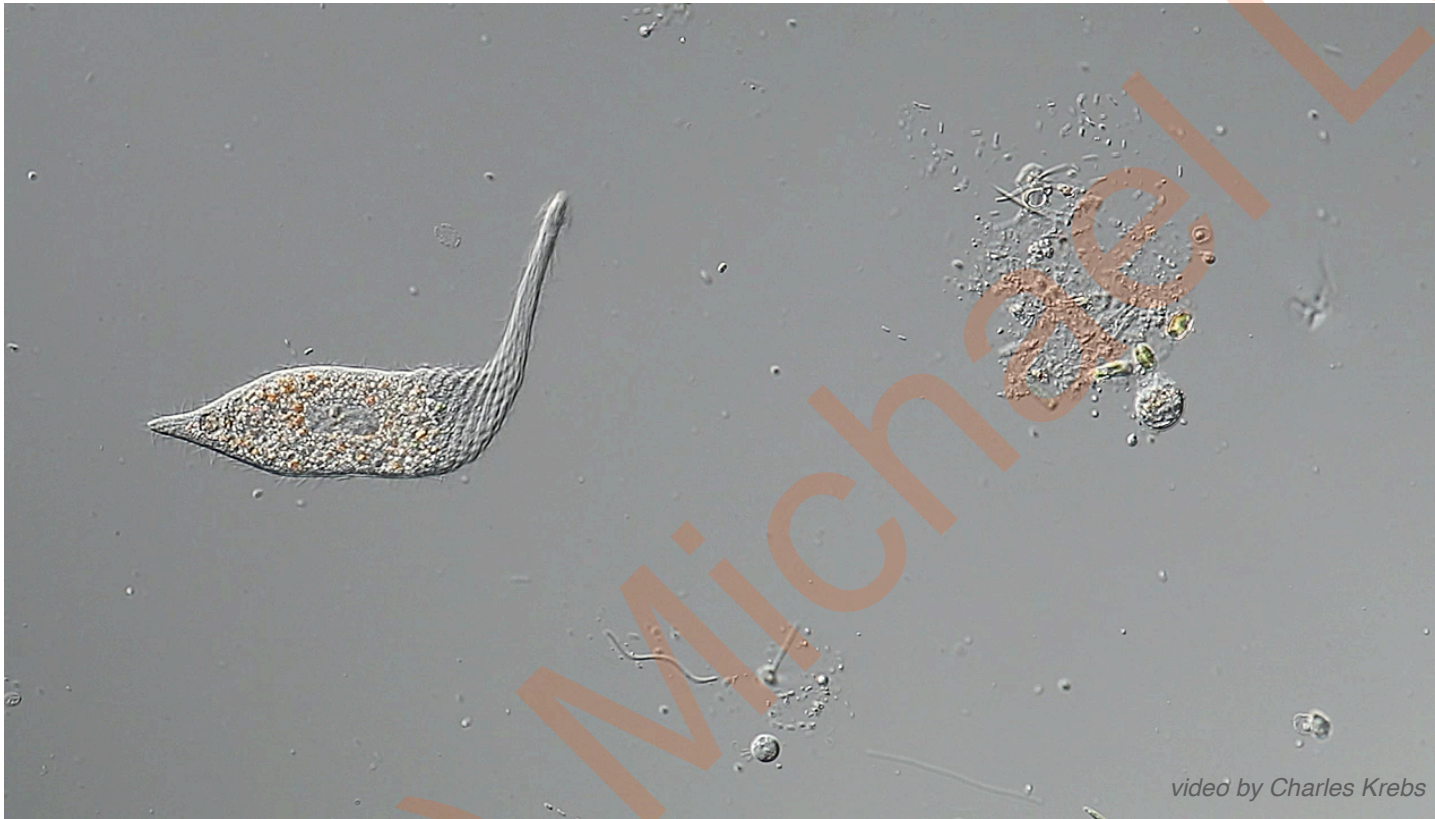


Jose Calvo, pineal gland histology



Gaël McGill

We are All Collective Intelligences!

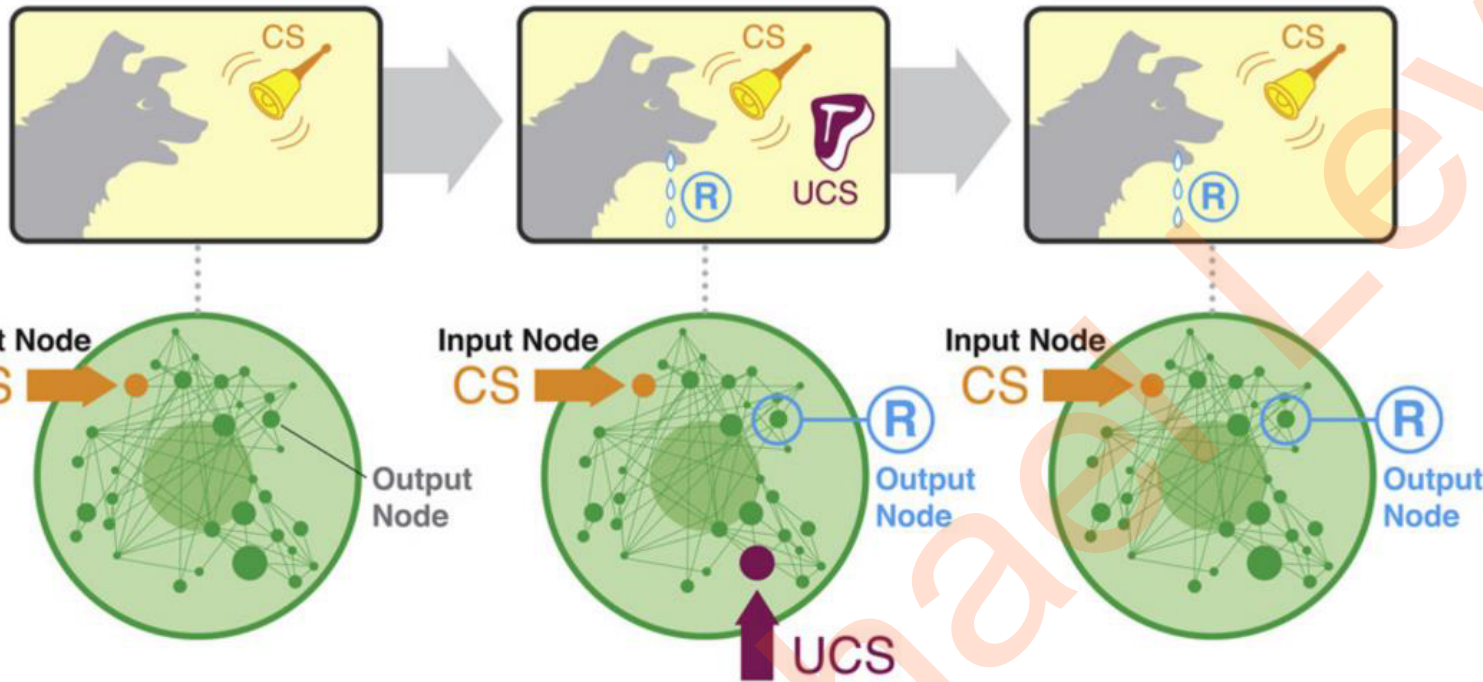


Lacrymaria = 1 cell
no brain
no nervous system

high competency
at cell-level
agendas

video by Charles Krebs

Collective Intelligence Below the Cell Level



Biomedicine:

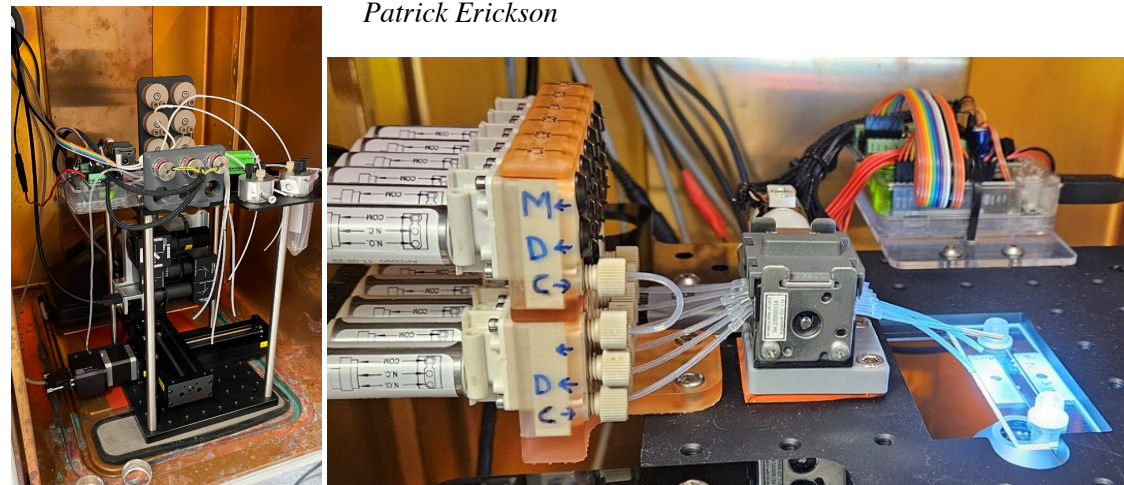
- drug conditioning

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,*}

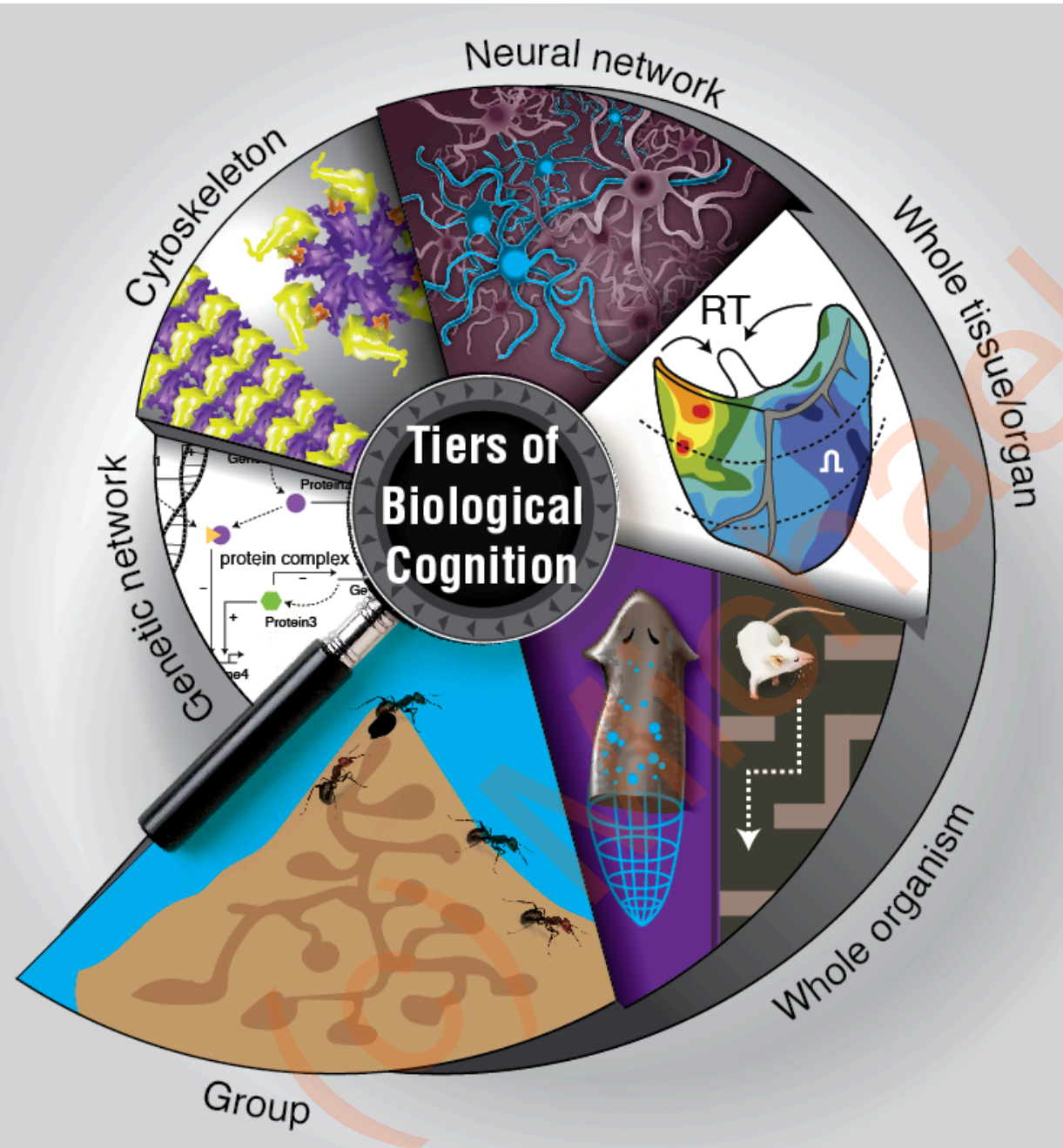
Article
 Gene regulatory networks exhibit several kinds of
 memory: quantification of memory in biological
 and random transcriptional networks

Patrick Erickson



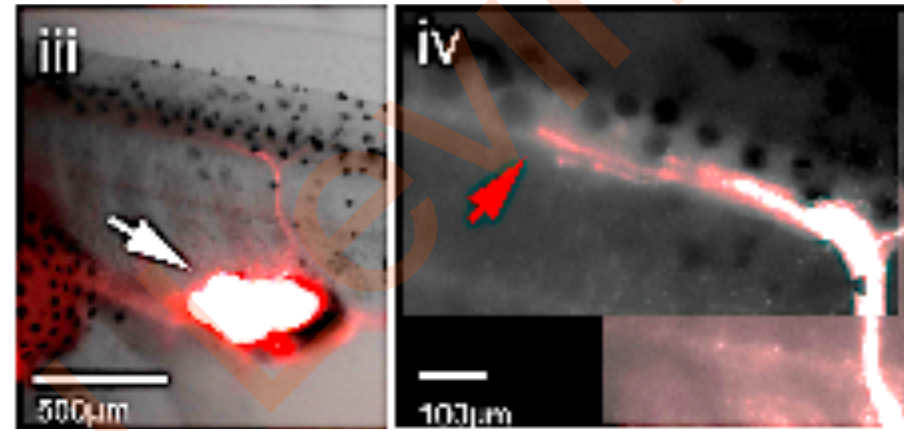
It Has Nested Cognition, not Merely Structure

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

Life Makes Few Assumptions: Beginner's Mind



Ectopic eyes on tail provide vision!

Douglas Blackiston



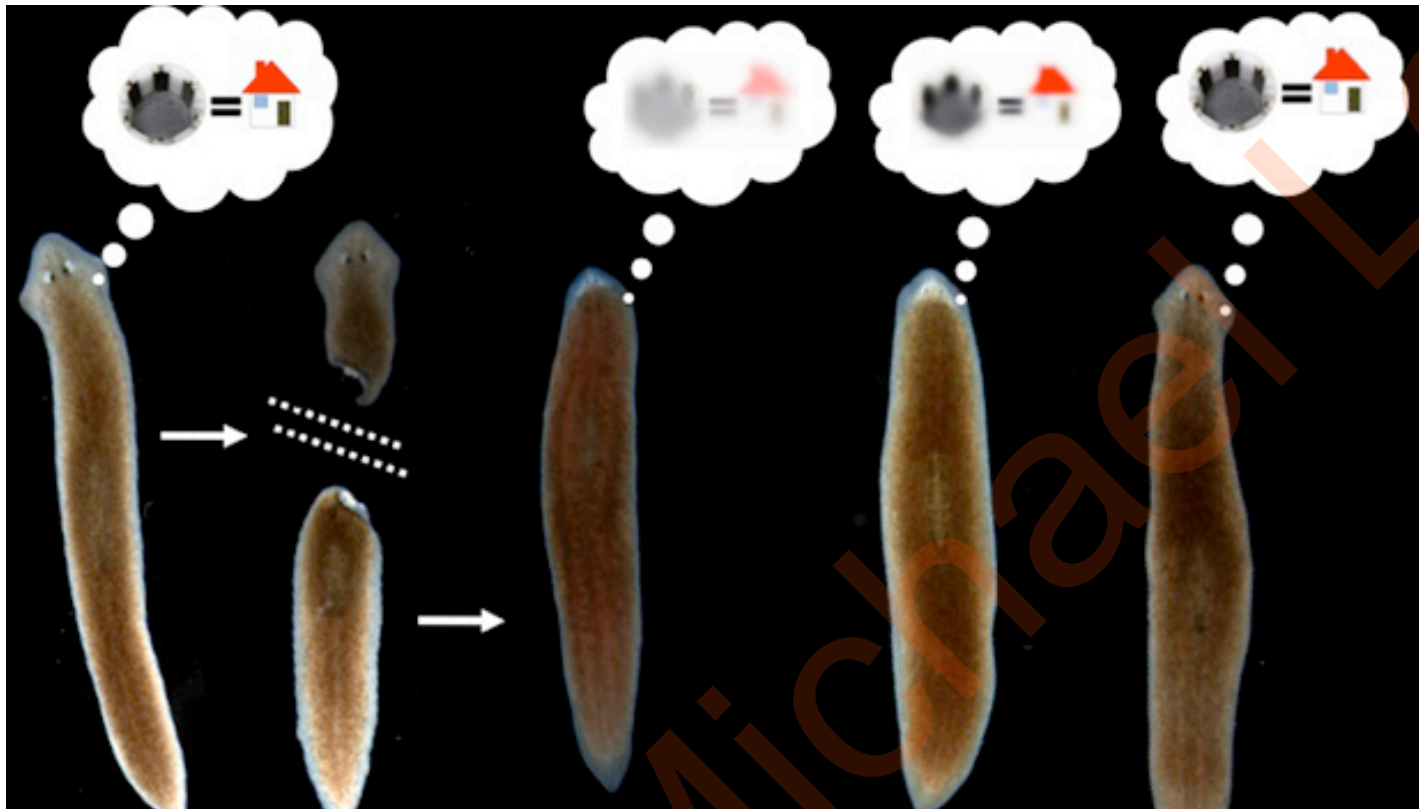
Behavioral Testing Device

no evolutionary adaptation needed (because embryos can't take much for granted, have to solve on-the-fly: evolution makes problem-solving agents)

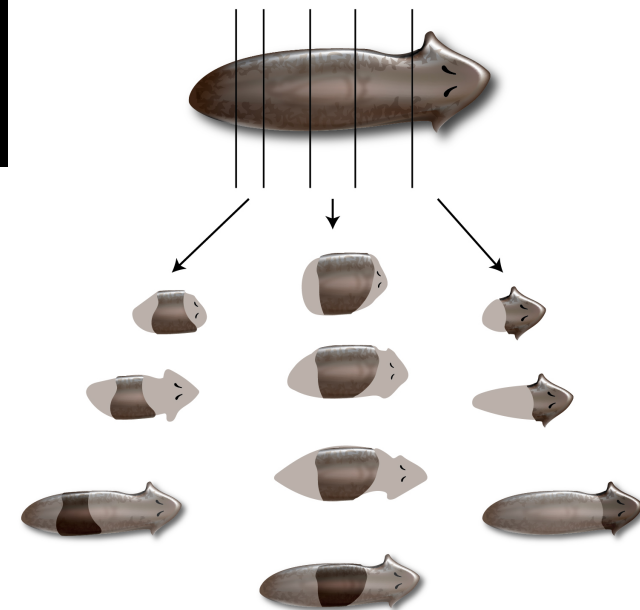
Brain dynamically adjusts behavioral programs to accommodate different body architectures

Life Enables Information to Move Across Media

newly regenerating brain can get information from rest of body



Tal Shomrat



HYPOTHESIS

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

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

Morphogenetic Virtualization



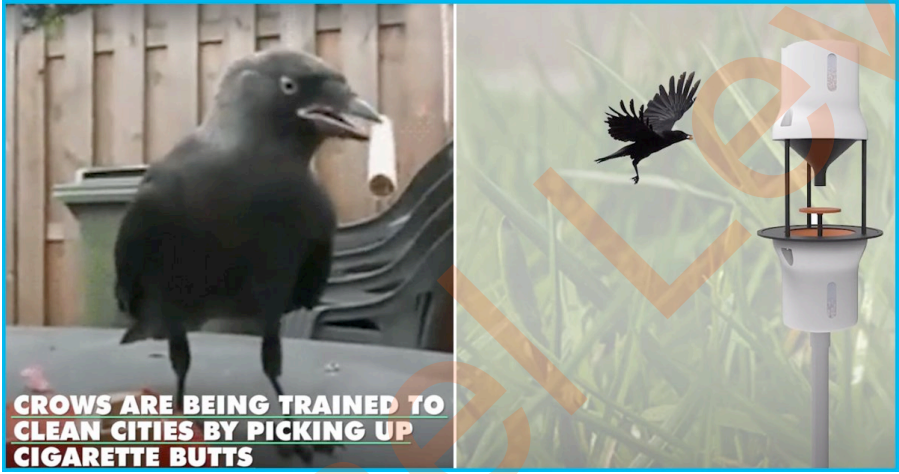
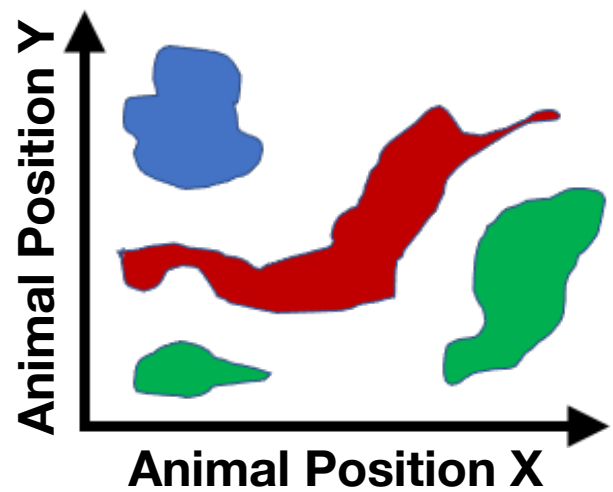
Hessam Akhlaghpour

Bodies are programmable and thus support virtualization.
Here's a fly running a stripped-down "ant" morphogenetic program on its wing

It's amazing, but no more so than the actual fly anatomy!

Life Has Embodiment Outside of Familiar 3D space:

3D Space (behavior)

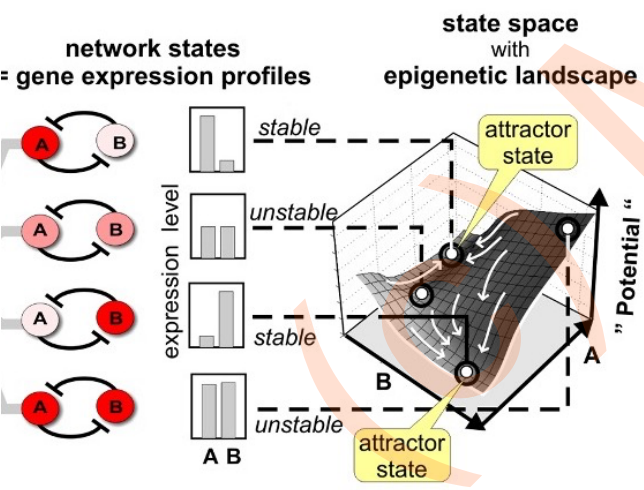


perception-action loop can happen in other spaces!

-> unconventional embodiment for AI's

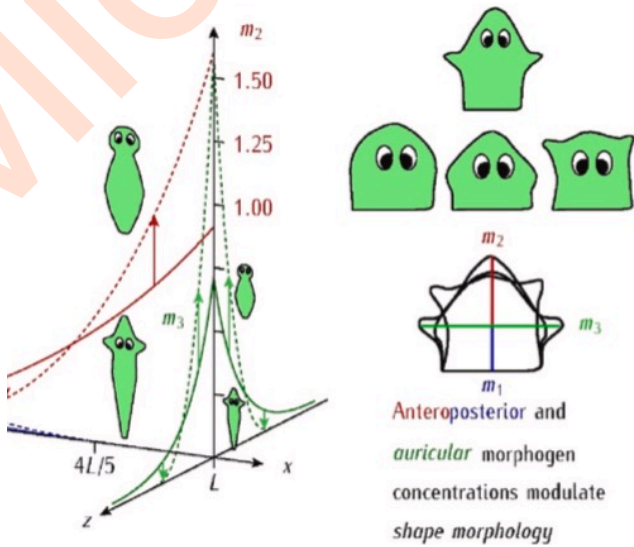
Transcriptional Space

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



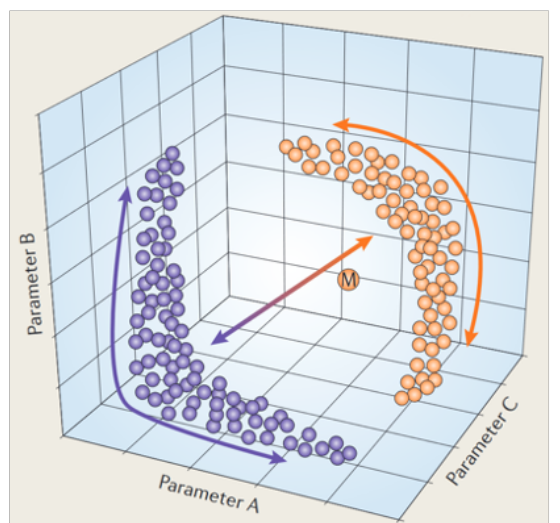
Morphospace

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.

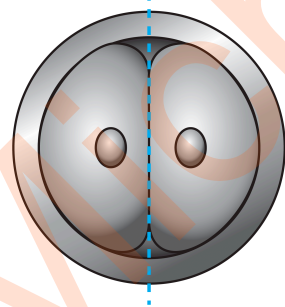


Case Study: collective intelligence of cells solving problems in anatomical morphospace

- morphogenesis as intelligent behavior in an unconventional space
- biomedicine discovered by communicating with this intelligence through its interface
- neuroscience beyond neurons (-> AI beyond neuromorphic architectures)

Anatomical Goals = Regions of Morphospace

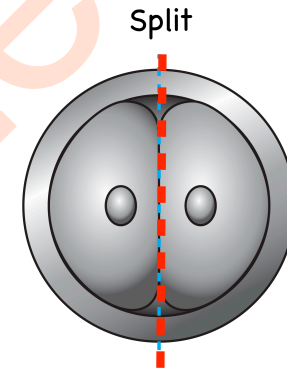
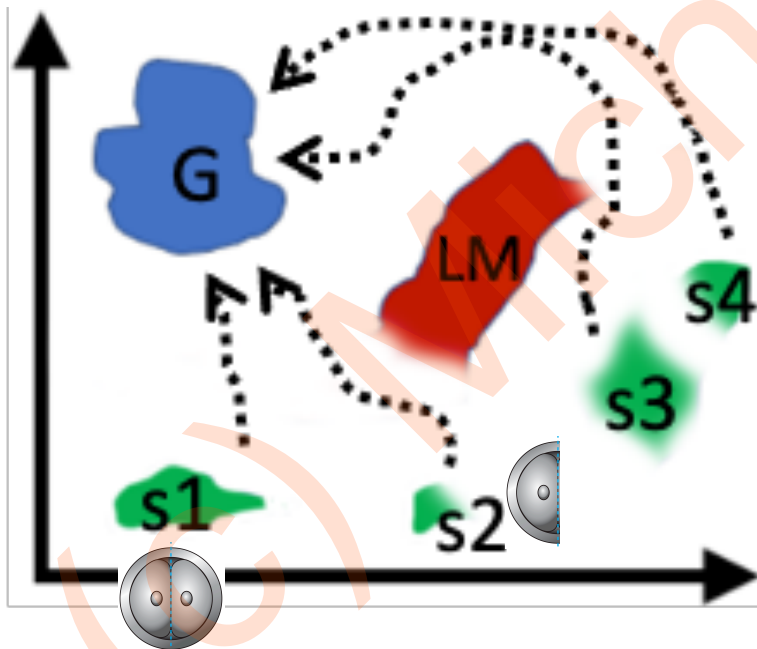
developmental self-assembly is very reliable:



but reliability, or emergent complexity are NOT why I call it intelligence
It's the creative problem-solving capacities (intelligent navigation of anatomical morphospace)

Same anatomy, from different starting states

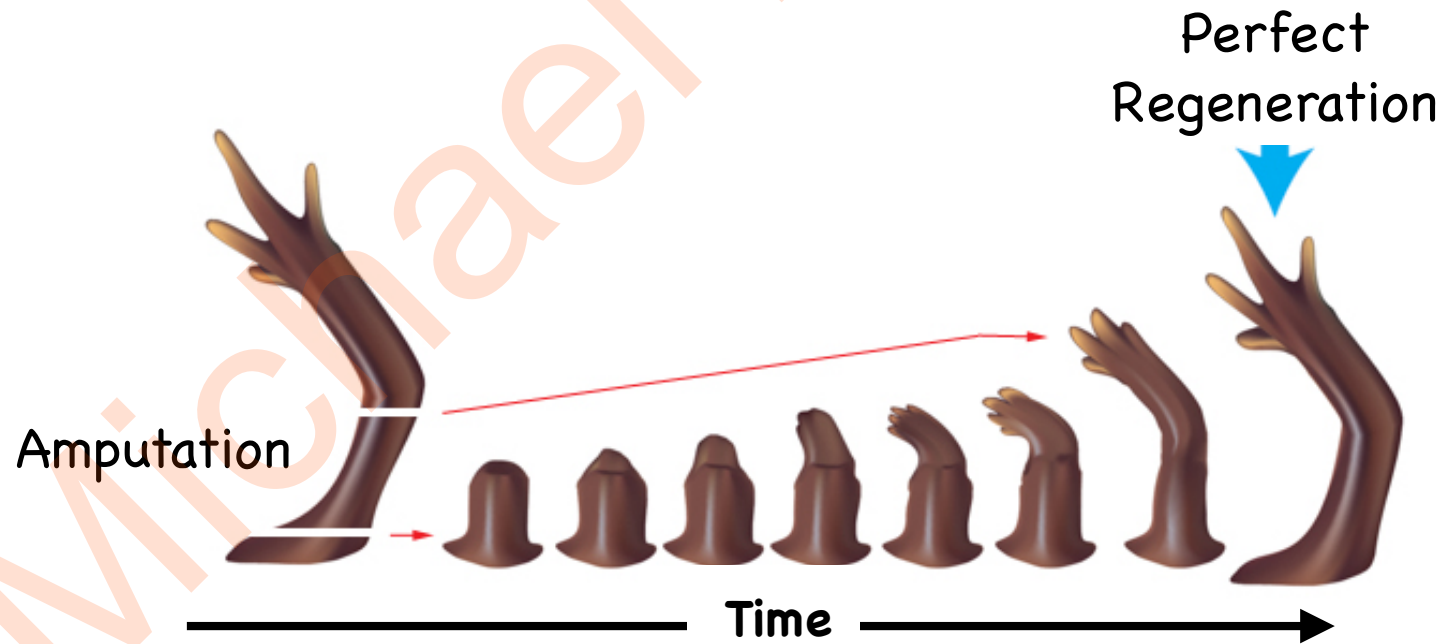
- get to the same outcome
 - despite perturbations
 - from diverse starting positions
 - via different paths



Splitting an embryo in half makes 2 normal embryos

Same anatomy, from different starting states

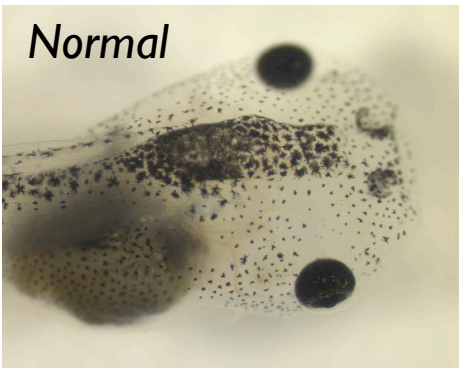
- get to the same outcome
 - despite perturbations
 - from diverse starting positions
 - via different paths



Anatomical homeostasis:

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

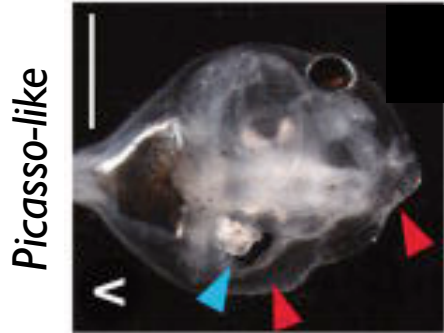
Intelligent Problem-solving in Morphospace



normal development



"as needed" remodeling



Laura Vandenberg

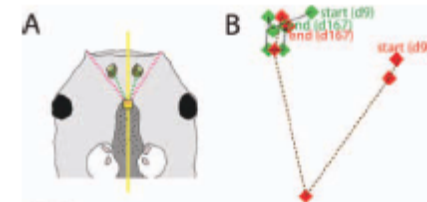
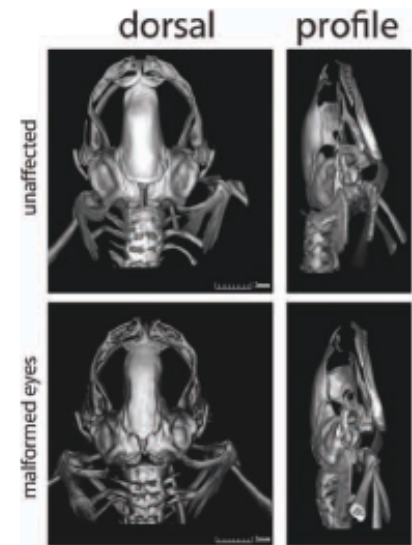
Craniofacial mispatterning

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.

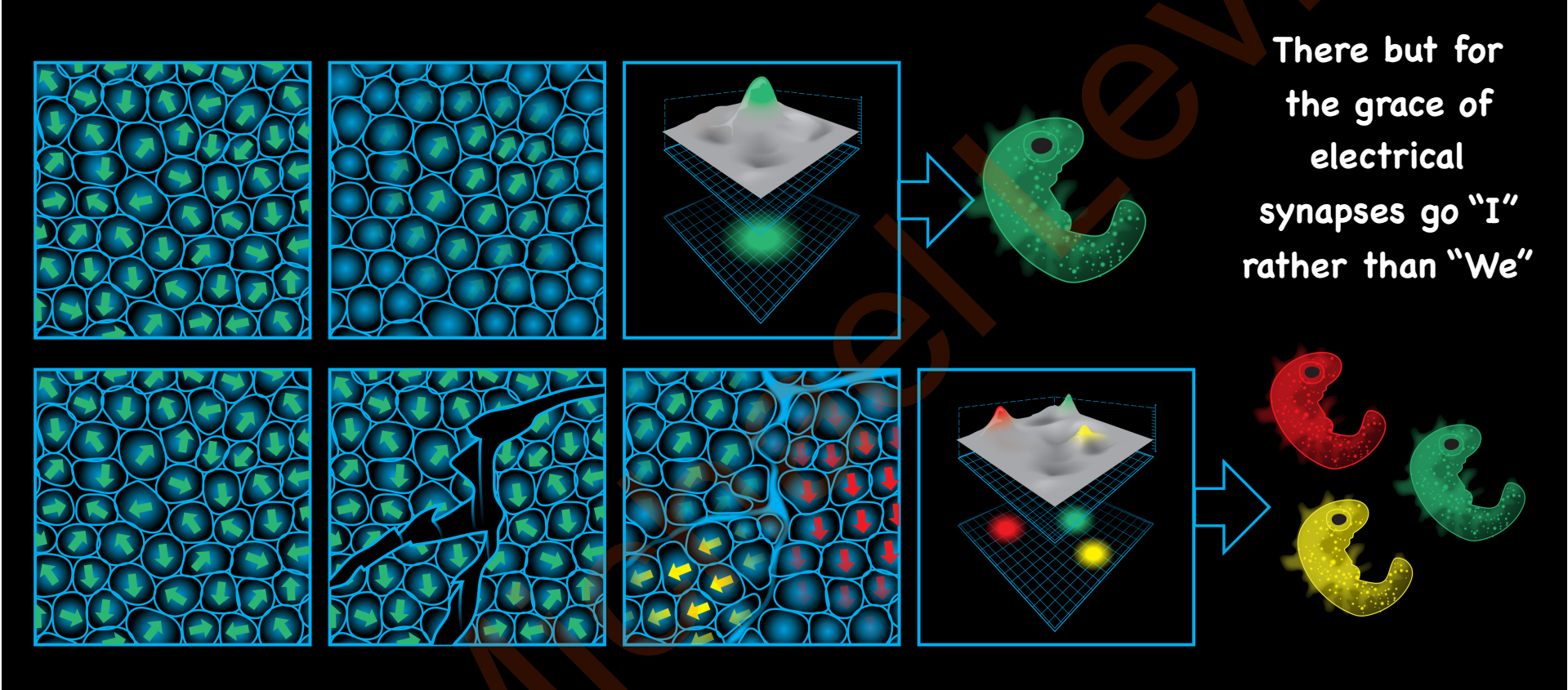
Cannot just follow a rote set of steps. How does it know when it's "right"?



How does it work?

- morphogenesis as intelligent behavior in an unconventional space
- biomedicines discovered by communicating with this intelligence through its interface
- neuroscience beyond neurons (-> AI beyond neuromorphic architectures) - bioelectricity as cognitive glue of the morphogenetic collective intelligence

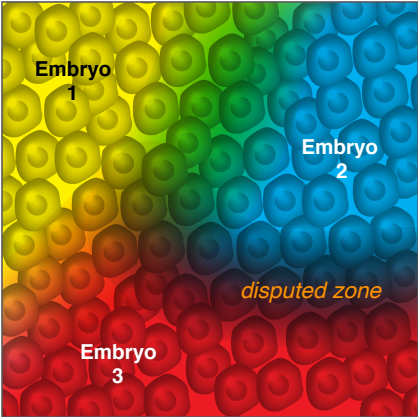
Life Individuates Selves from the Potentiality of a Cellular Blastoderm: cognitive alignment



Agential material: how many agents per mm³?

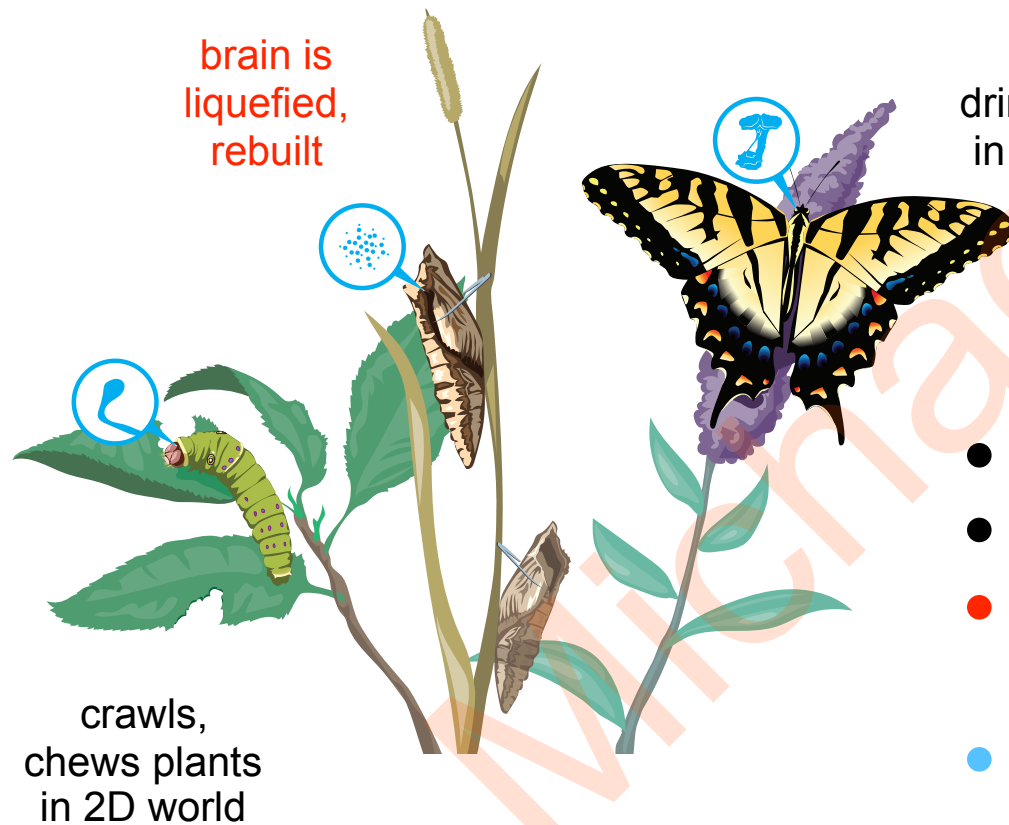
Where is my **border** from "environment"?
 every cell is some other cell's environment

Issue of **individuation** in cognition:
 split brain patients, dissociative disorders, etc.



Life Optimizes for Salience, not Fidelity of Info

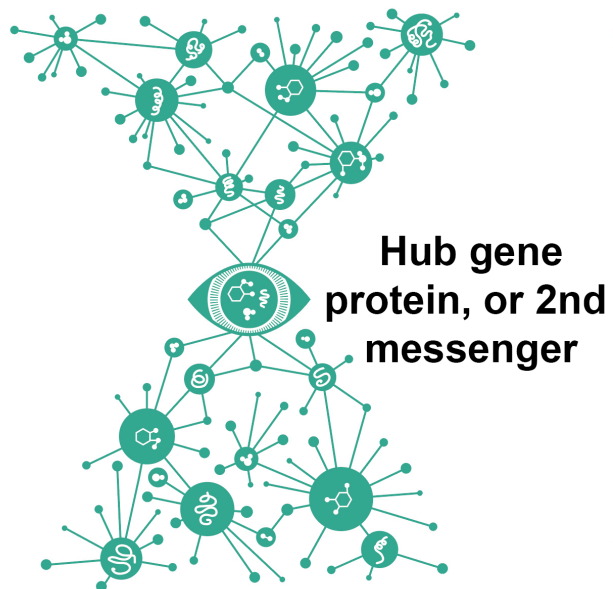
(which enables it to survive drastic hardware refactoring)



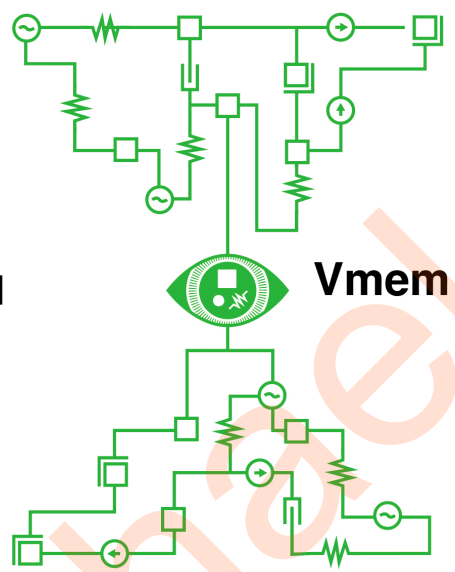
- minds are embodied
- bodies can change drastically
- memories are generalized and remapped onto new architecture
- what is it like to be a caterpillar changing into a butterfly?
- How could the butterfly convince the caterpillar that this change is ok?

Bow-tie Center Nodes are Communication Translators

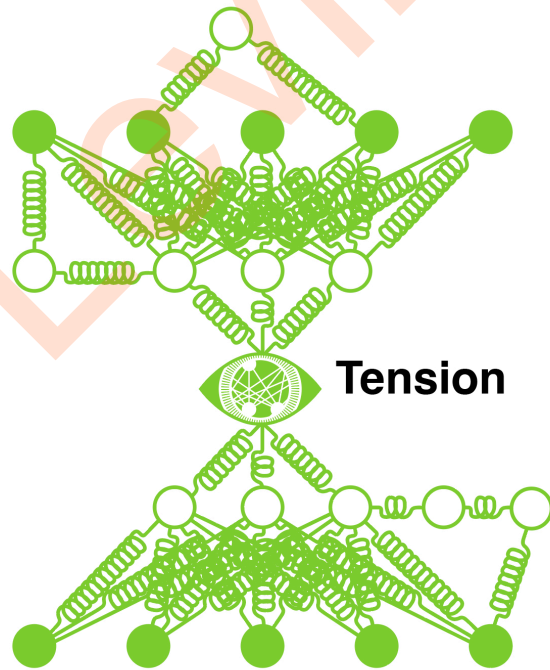
coarse-graining, compression



GENE-REGULATORY NETWORK

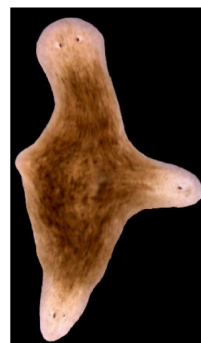
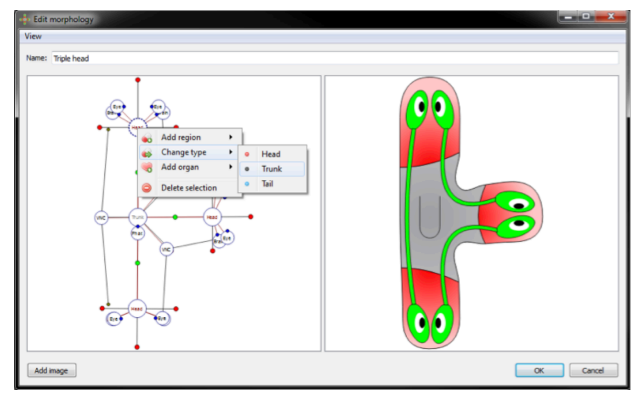


BIOELECTRICAL CIRCUIT

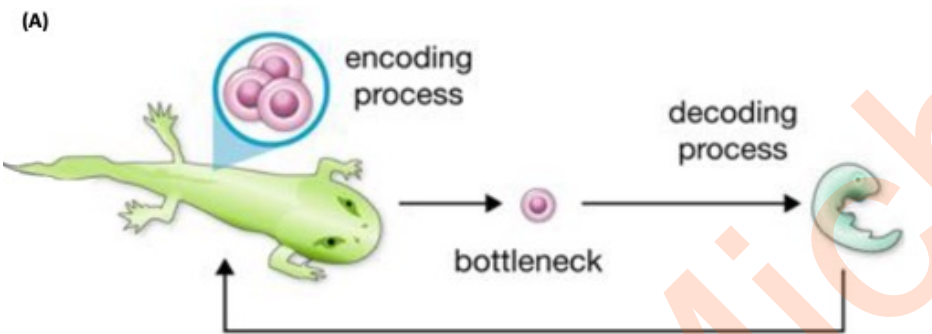
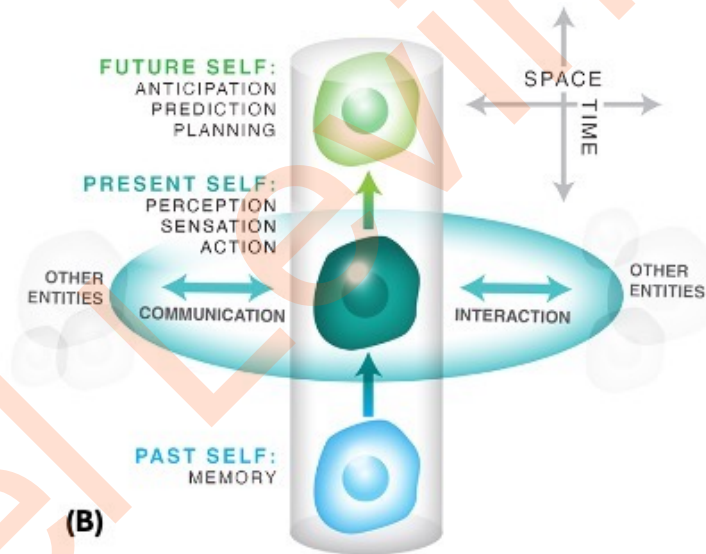
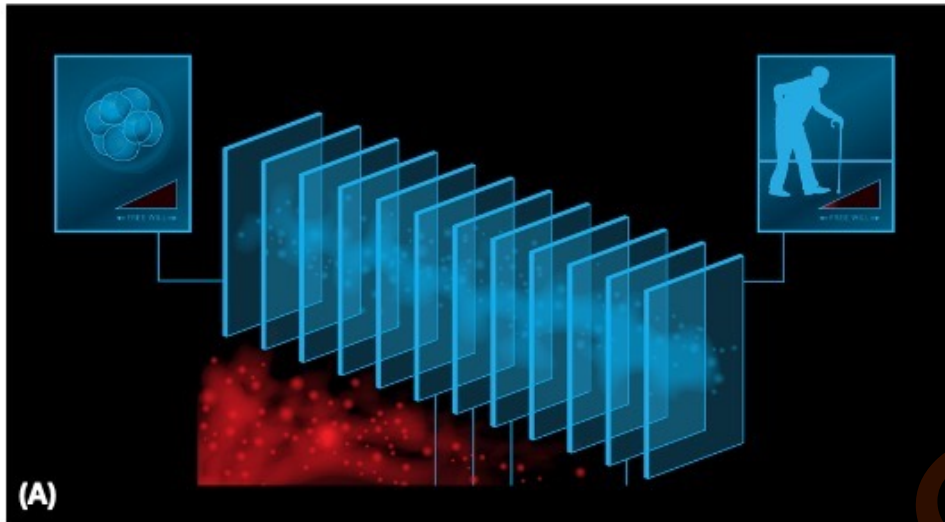


BIOMECHANICAL NETWORK

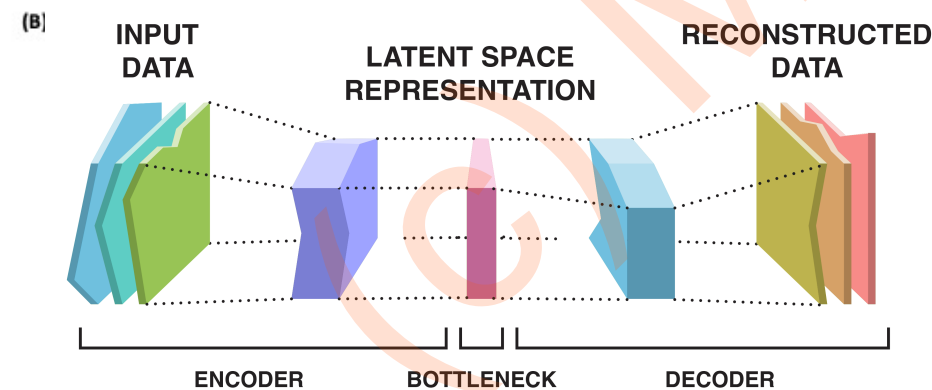
Other Bowtie nodes:
language, money, scientific papers, and the Anatomical Compiler



Memories are Messages from your Past Self



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
 Undependable hardware and confabulation are a feature, not a bug
 Unconsciousness = active, creative story-telling from your own memory traces



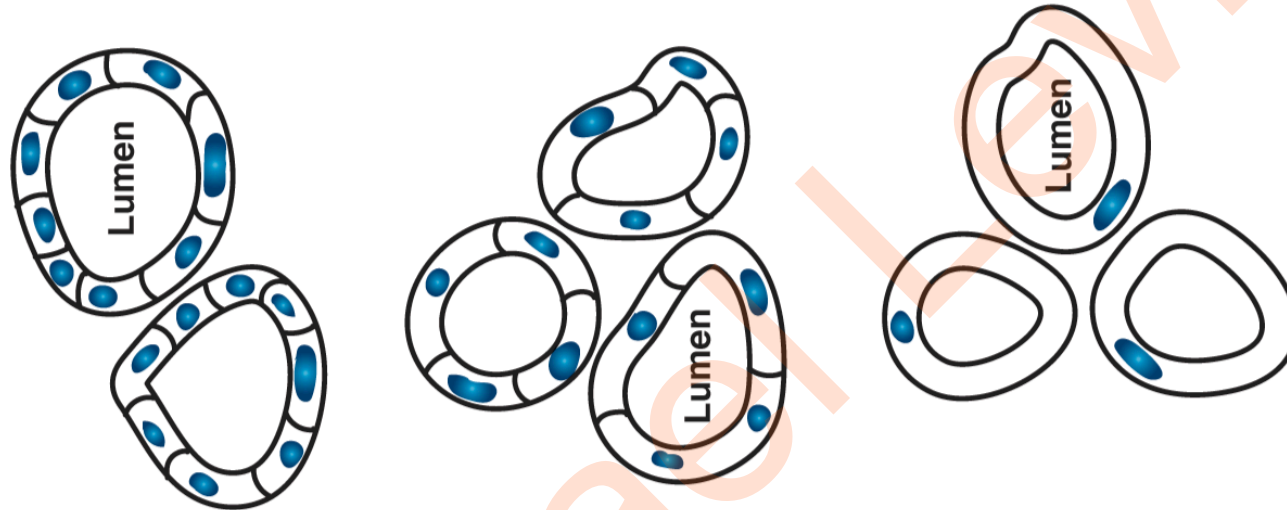
Perspective

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

Michael Levin

Don't Overtrain on Evolutionary Priors

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
- Creative, intelligent problem-solving - repurpose available tools to new circumstances

INTERFACE

rsif.royalsocietypublishing.org

Perspective

Cite this article: Pezzulo G, Levin M. 2016 Top-down models in biology: explanation and control of complex living systems above the molecular level. *J. R. Soc. Interface* 13: 20160555. <http://dx.doi.org/10.1098/rsif.2016.0555>

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

Giovanni Pezzulo¹ and Michael Levin¹

¹Biology Department, Allen Discovery Center at Tufts, Tufts University, Medford, MA 02155, USA
²Institute 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



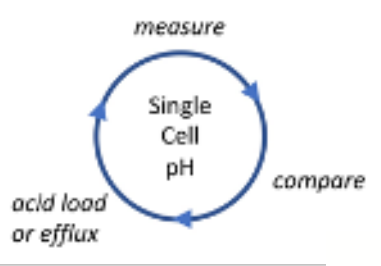
Cite this: *Integr. Biol.*, 2015, 7, 1487

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

G. Pezzulo¹ and M. Levin^{1,2}

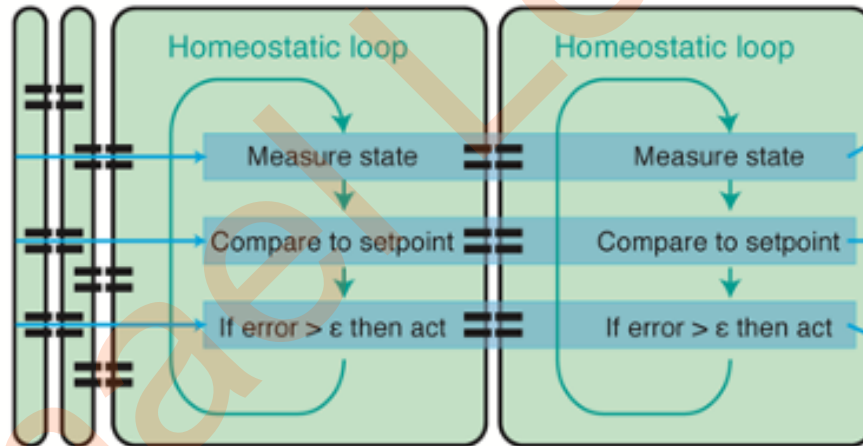
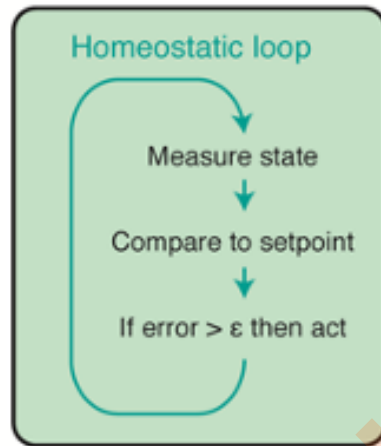


Expanding the Cognitive Light Cone



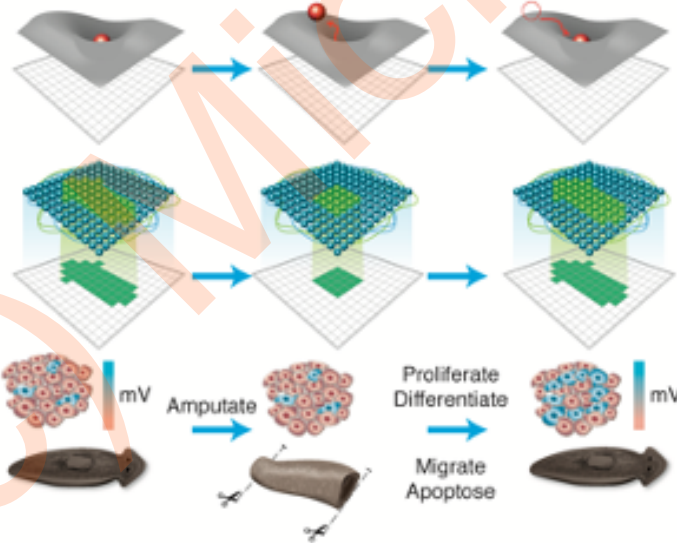
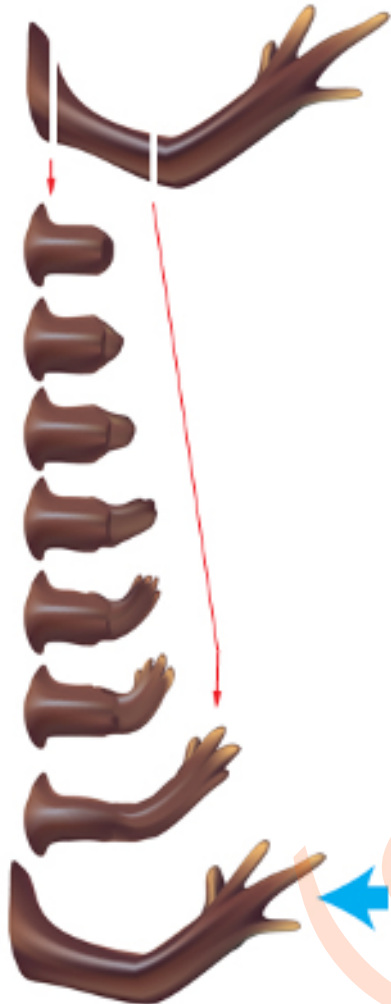
1 cell

Cell Collective (coupled tissue)



== GJ

- Measuring a multicellular state
- Remembering a complex spatial setpoint
- Issuing commands to a multicellular swarm



ISOLATED INDIVIDUAL'S RANGE OF PERCEPTION

INTEGRATED INDIVIDUAL'S RANGE OF PERCEPTION

ANTICIPATION: ↑
INDIVIDUAL FUTURE EXPECTATION

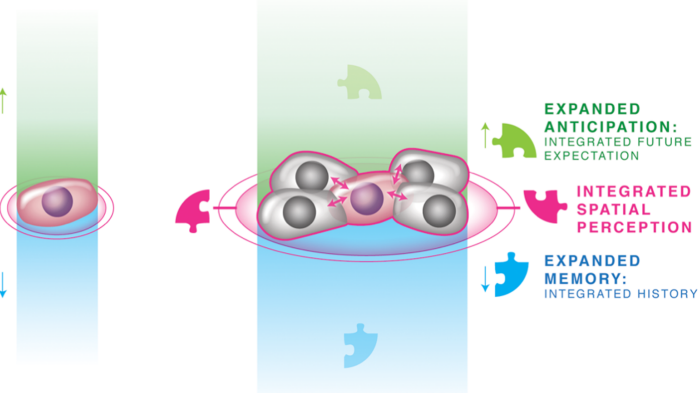
INDIVIDUAL SPATIAL PERCEPTION

MEMORY: ↓
INDIVIDUAL HISTORY

EXPANDED ANTICIPATION: ↑
INTEGRATED FUTURE EXPECTATION

INTEGRATED SPATIAL PERCEPTION

EXPANDED MEMORY: ↓
INTEGRATED HISTORY



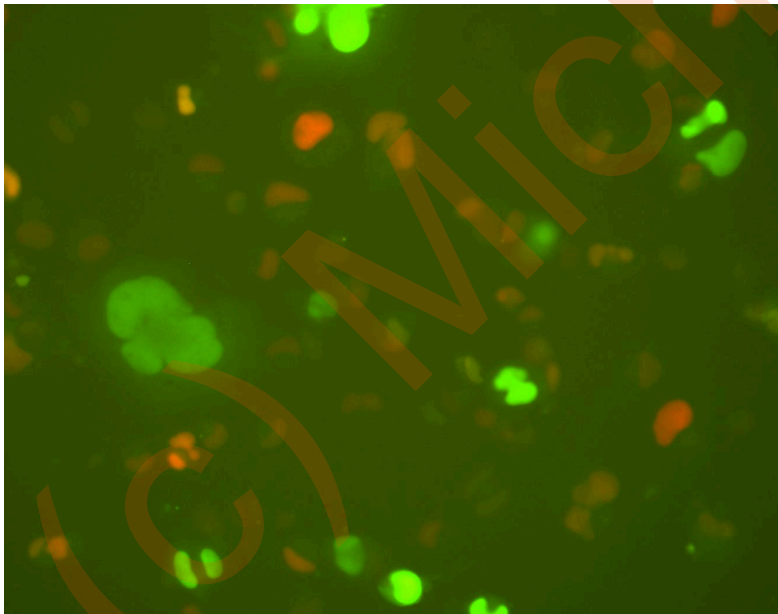
Scaling Goals, Changing Problem Space

Single cell goals

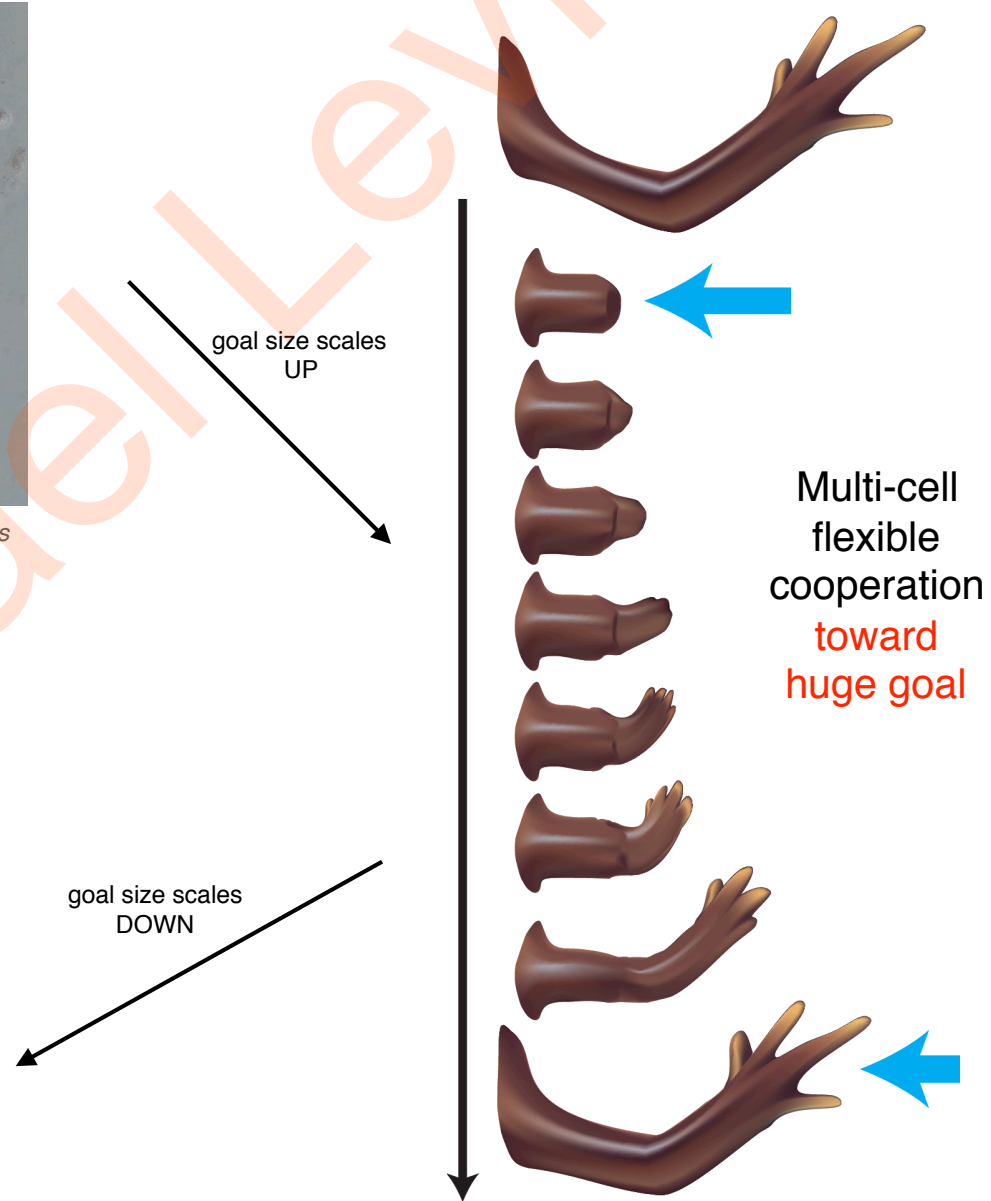


video by Charles Krebs

Cancer = defection, reversion to local (unicellular-scale) goals

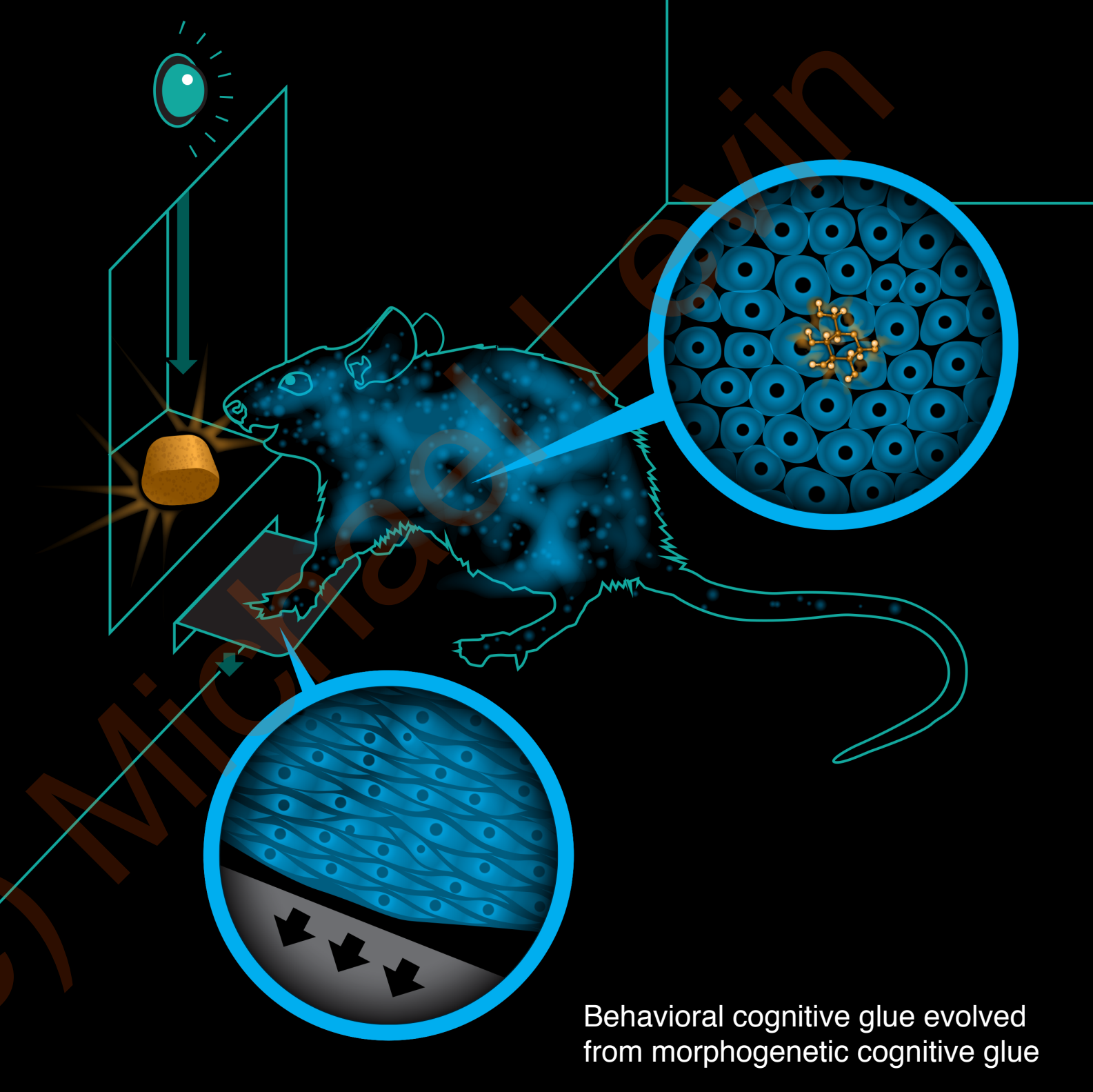


video by Juanita Mathews



So what's the cognitive glue?

It knows
things that its
parts don't
know

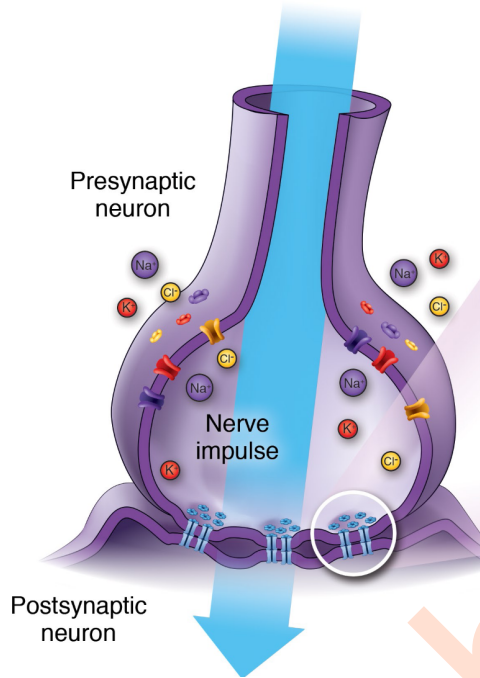


Behavioral cognitive glue evolved
from morphogenetic cognitive glue

Hardware

gene products -> electric circuits

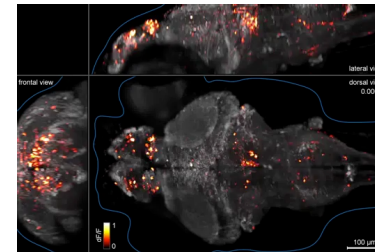
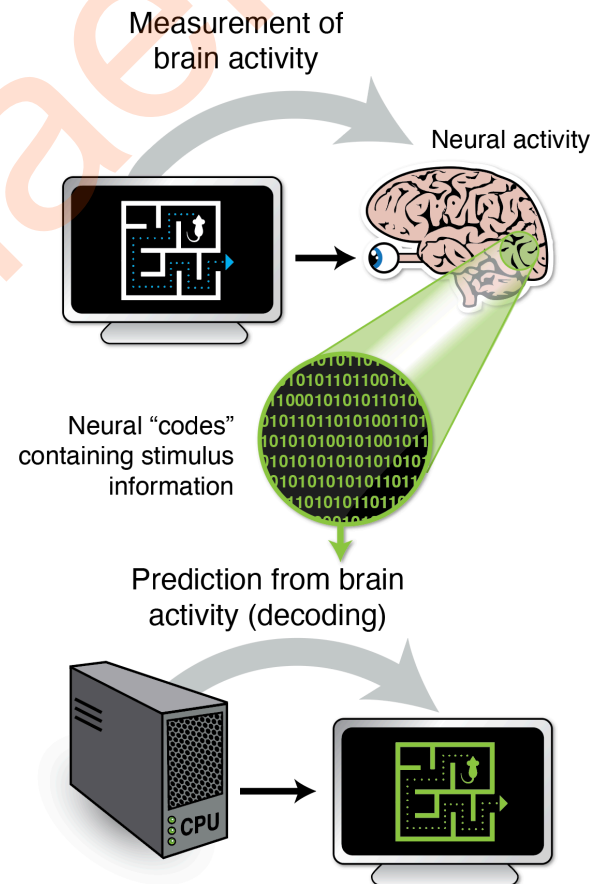
ion channels,
electrical
synapses



Software

electrical dynamics -> memory

neural

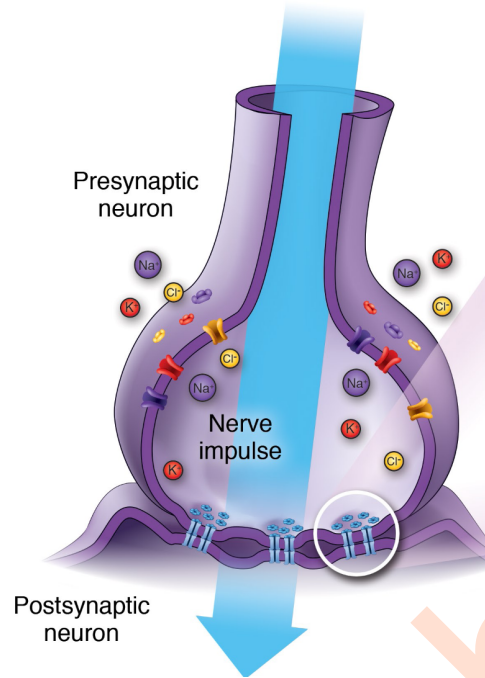


<http://www.nature.com/nmeth/journal/v10/n5/full/nmeth.2434.html>

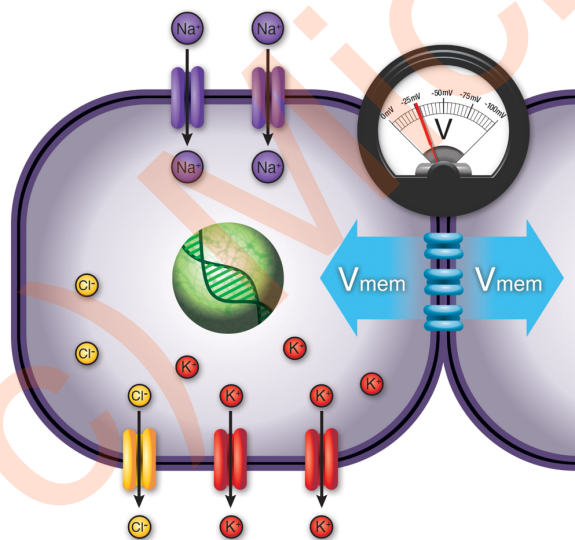
Hardware

gene products -> electric circuits

ion channels, electrical synapses



ion channels, electrical synapses

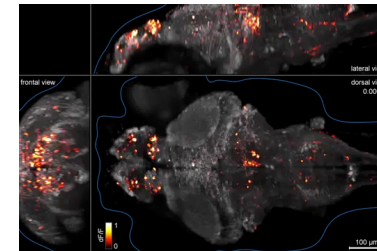


Software

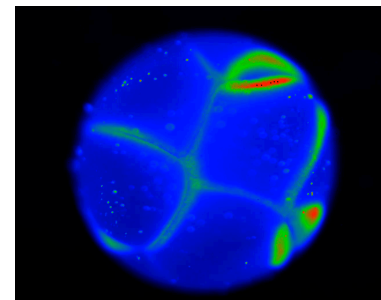
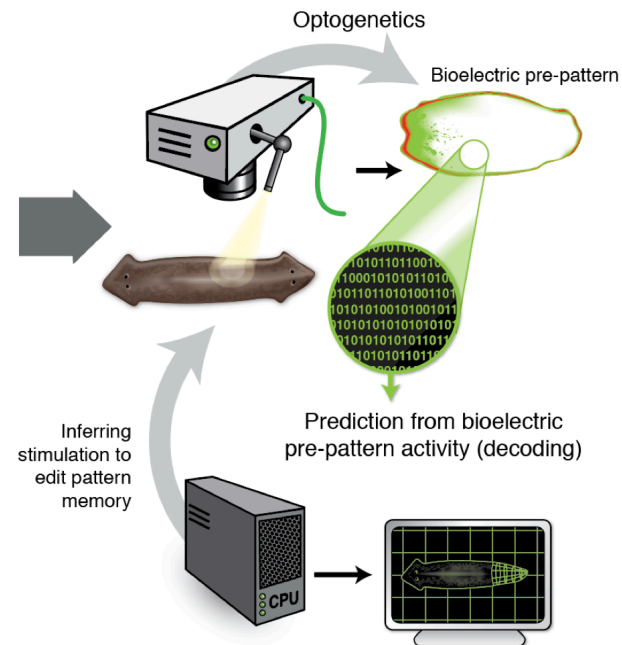
electrical dynamics -> memory

neural

developmental



<http://www.nature.com/nmeth/journal/v10/n5/full/nmeth.2434.html>

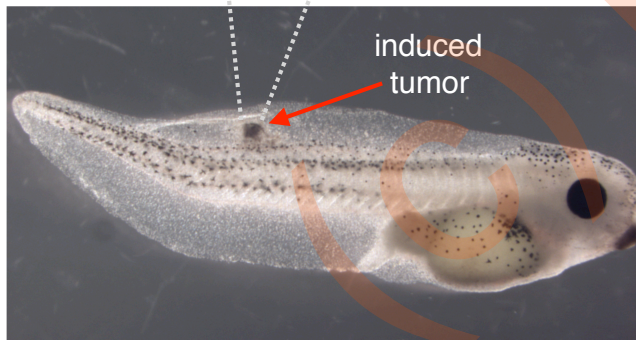
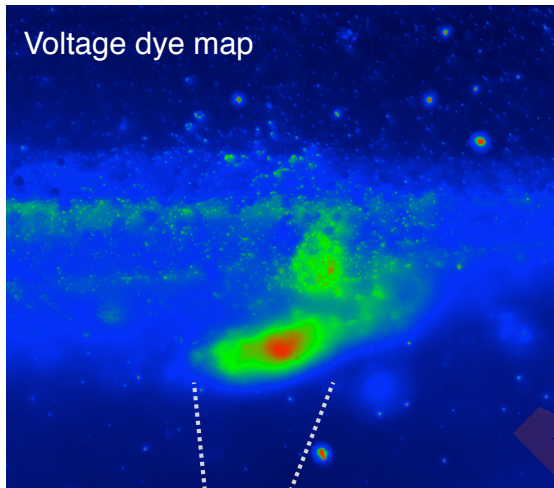
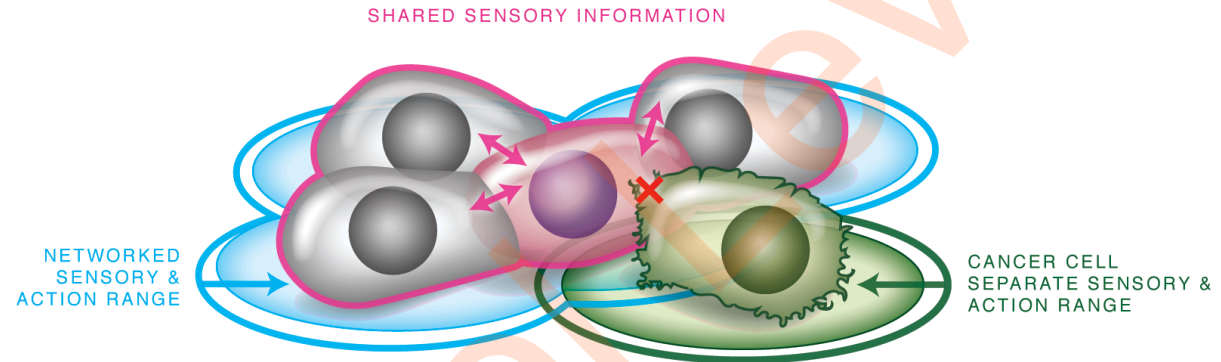


Dany Adams

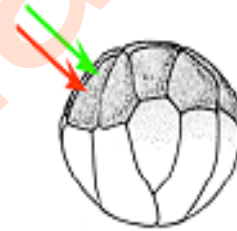
Cancer is Not Selfish: it just has smaller Selves

Cancer therapeutics by resetting boundary between self and world

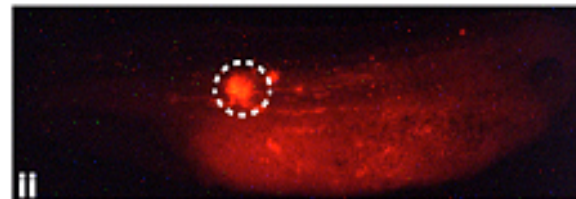
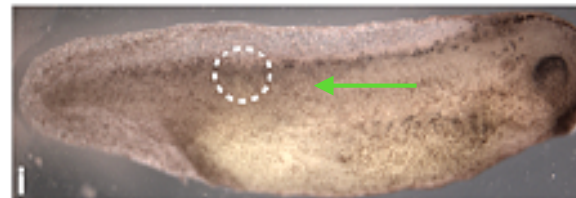
Cells Coupled by
Gap Junctions,
Disconnected
Cancerous Cells



GlyRF99A-GFP3
Xrel3-2A-Tomato



Tumor suppressed

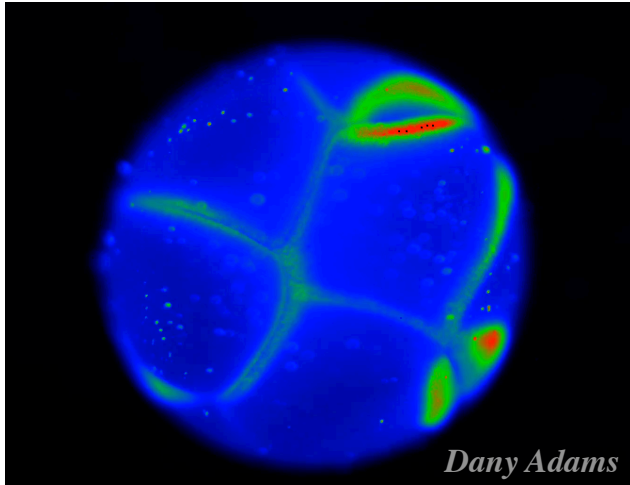


Brook Chernet

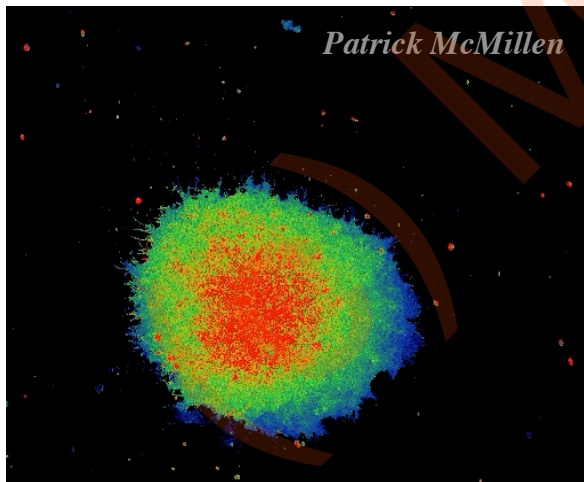


How we detect and model bioelectric signals:

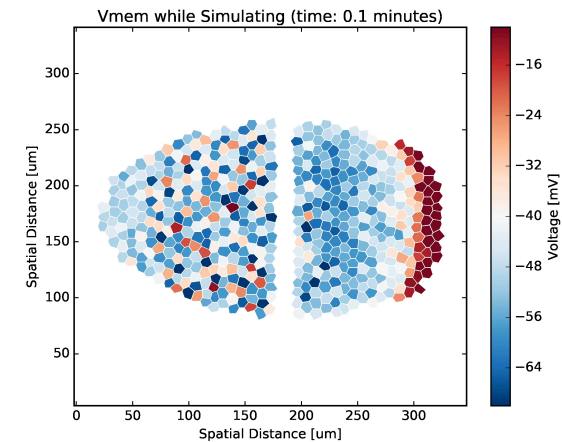
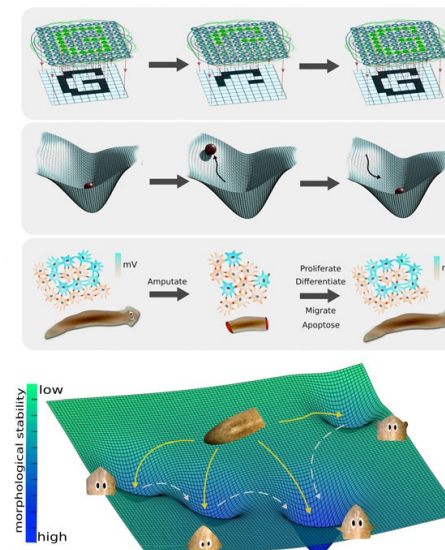
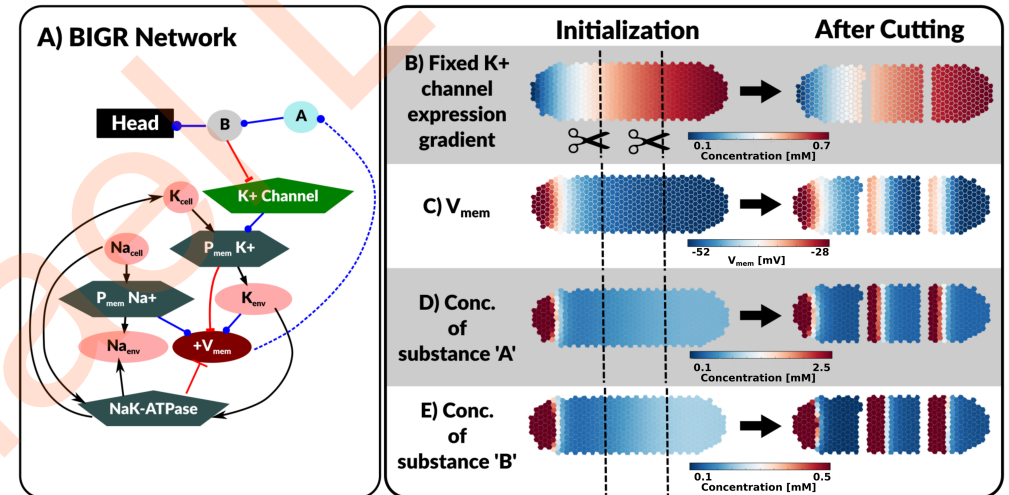
Characterization of endogenous voltage gradients - direct measurement and correlation with morphogenetic events



Voltage reporting fluorescent dye in time-lapse during *Xenopus* development



Quantitative computer simulation: synthesize biophysical and genetic data into predictive, quantitative, often non-linear models

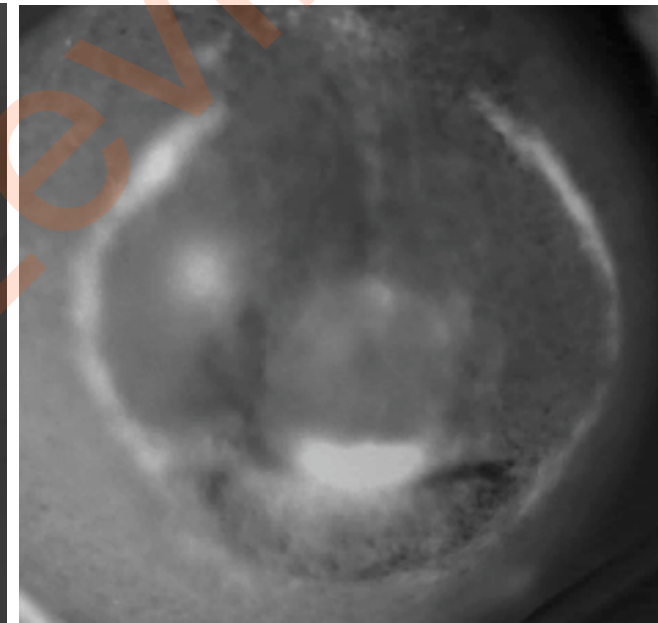


Alexis Pietak

Endogenous Bioelectric Prepatterning: reading the mind of the body

craniofacial
development
“electric face”
prepattern
required for
normal face

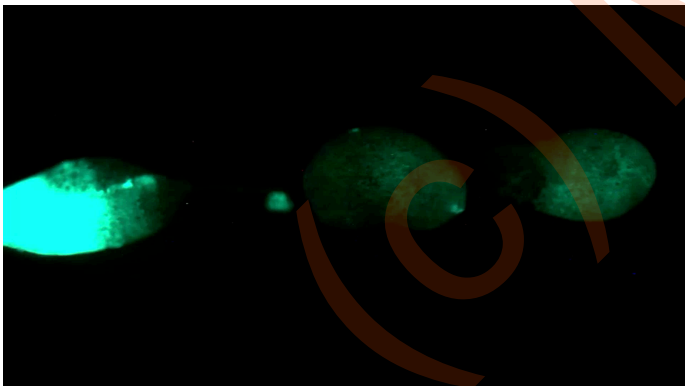
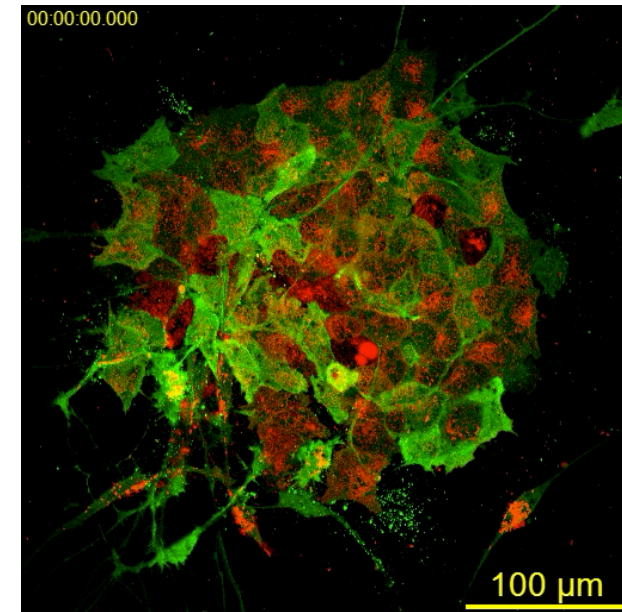
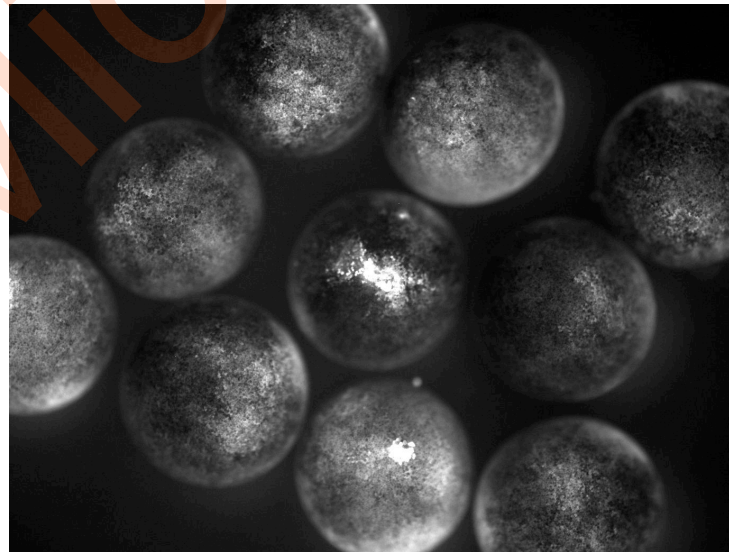
monitoring defects



hyperpolarized  depolarized

Angela Tung, Megan Sperry

Patrick McMillen

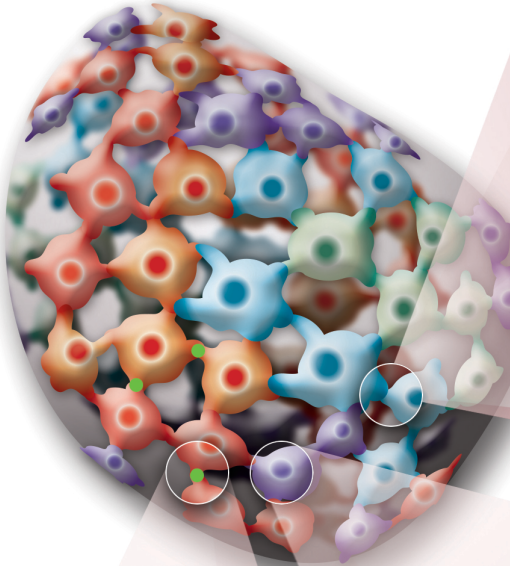


Manipulating Bioelectric Networks' Content

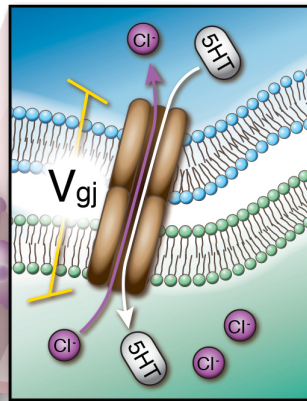
Non-neural cell group



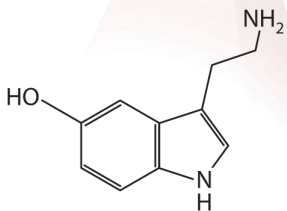
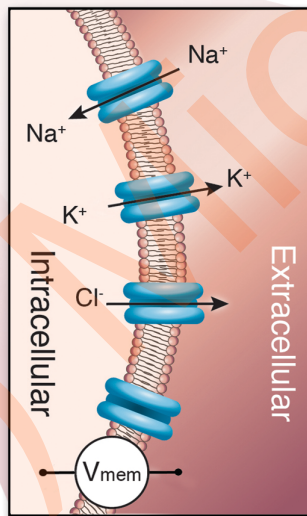
hyperpolarized ← → depolarized



Gap Junctions
(electrical synapse)



Ion channels
(setting V_{mem})



● Neurotransmitter
(moving via V_{mem})

- Transporter or receptor mutant overexpression
- Drug agonists or antagonists of receptors or transporters
- Photo-uncaging of neurotransmitter

Tools we developed
(no applied fields!)

- Dominant negative Connexin protein
- GJC drug blocker
- Cx mutant with altered gating or permeability

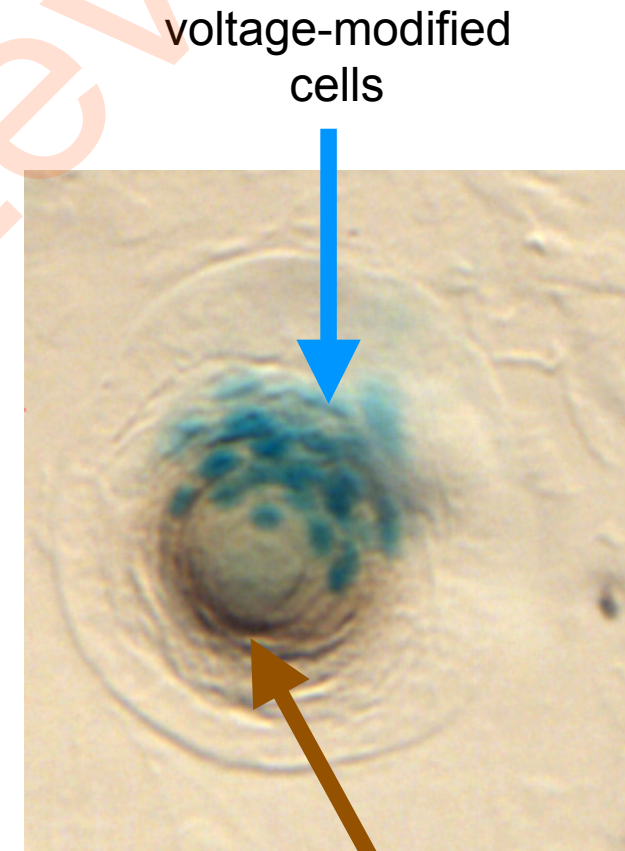
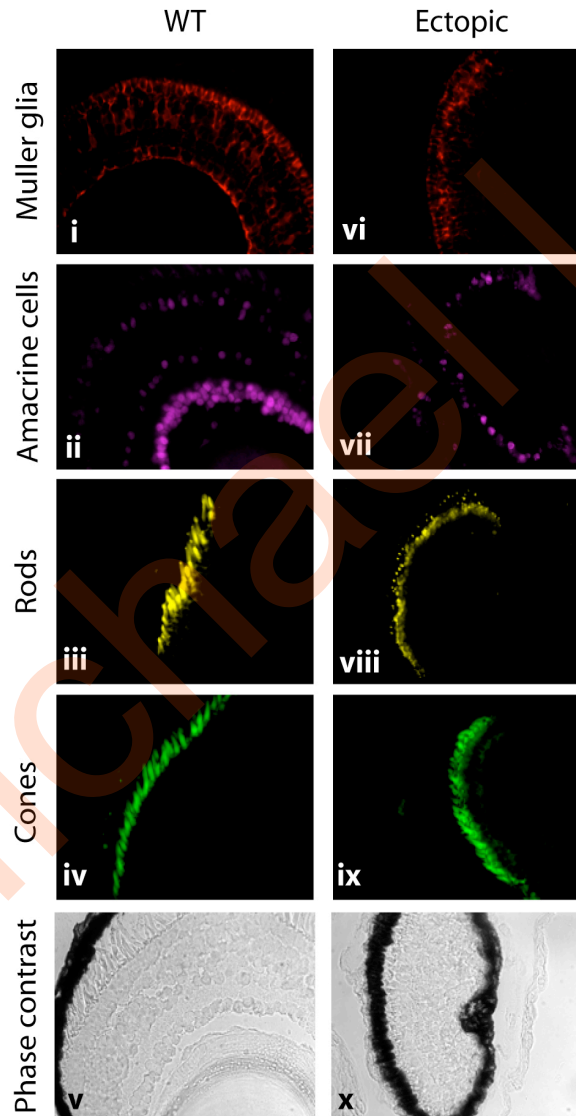
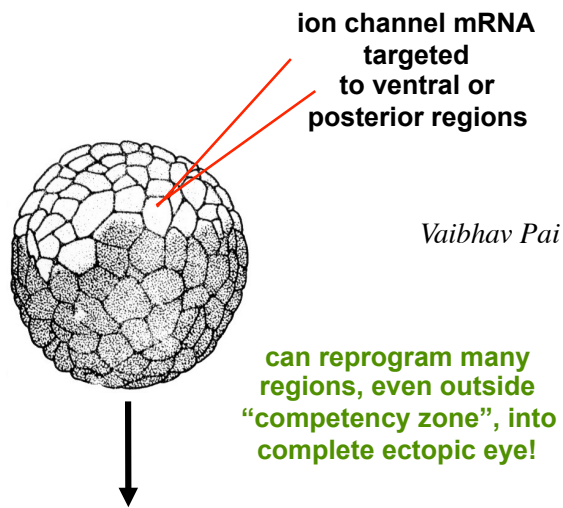
Synaptic
plasticity

- Dominant ion channel over-expression (depolarizing or hyperpolarizing, light-gated, drug-gated)
- Drug blocker of native channel
- Drug opener of native channel

Intrinsic
plasticity

The communication interface we hack

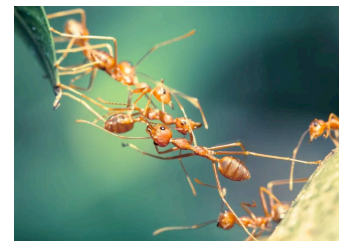
Bioelectrically-induced Morphogenetic Subroutines Exhibit Recruitment Competencies



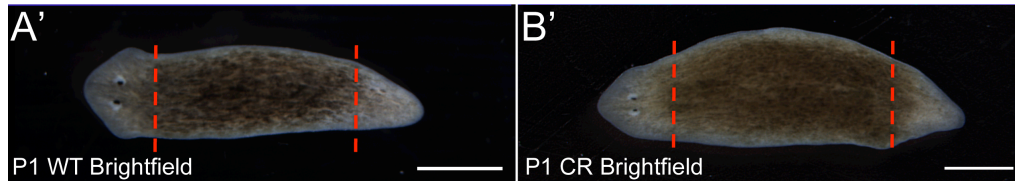
1. BIOE is instructive
2. modularity - not cell level, organ-level subroutine call
3. higher-level prompt reveals higher tissue competency than Pax6 prompt
4. self-scaling of system to task

Developmental Modules because morphogenetic goals

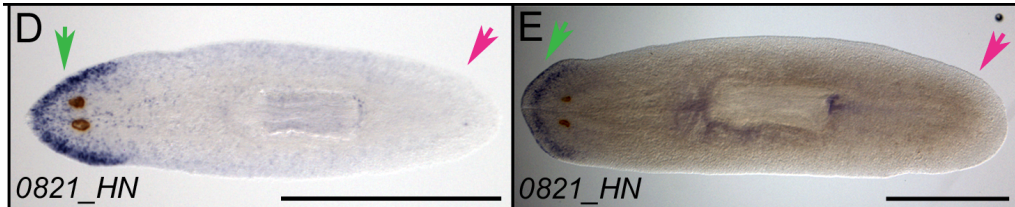
Getty Images



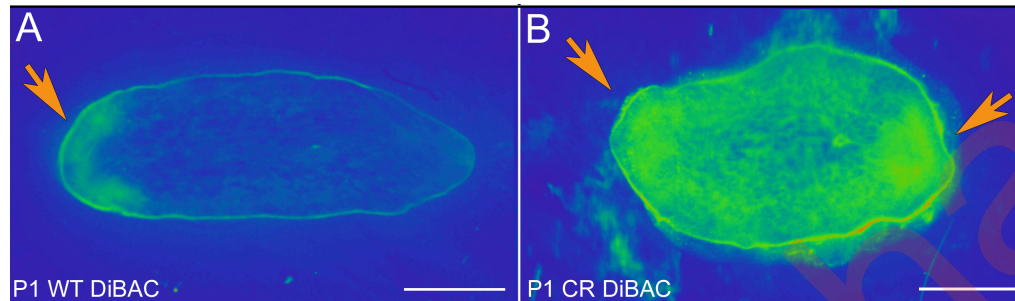
Re-writing Anatomical Pattern Memory



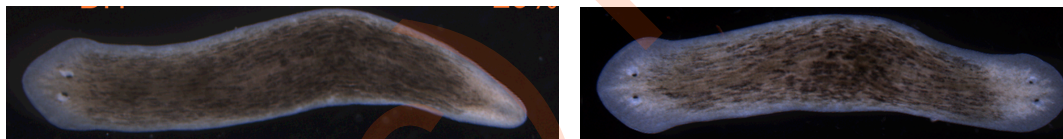
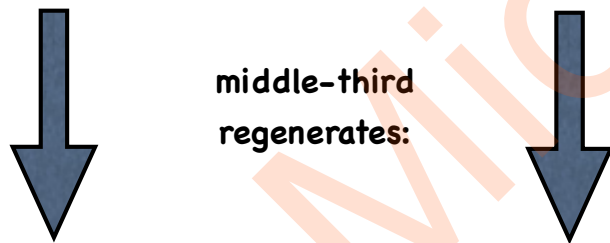
normal anatomy



normal molecular histology



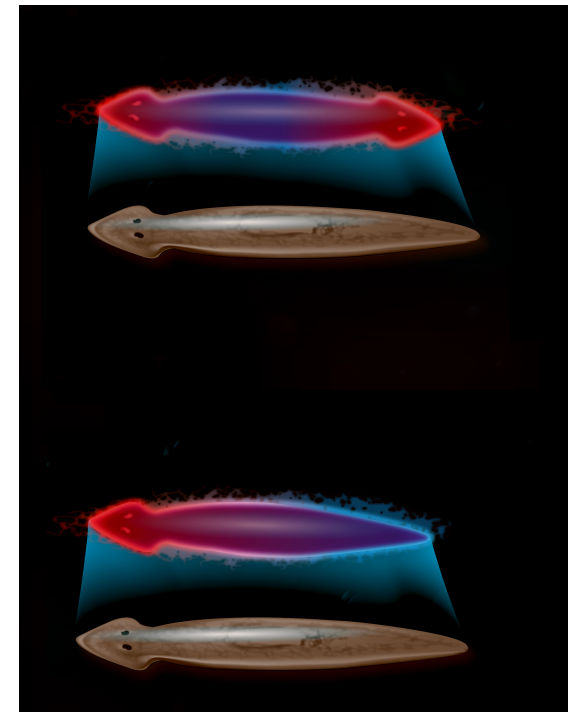
edited bioelectric pattern



Fallon Durant

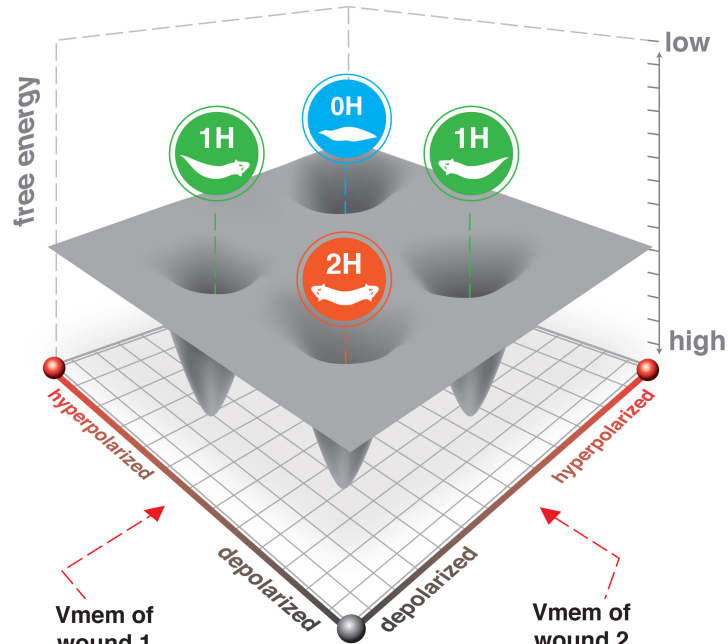


The Same Body can Store different Electrical Pattern Memories

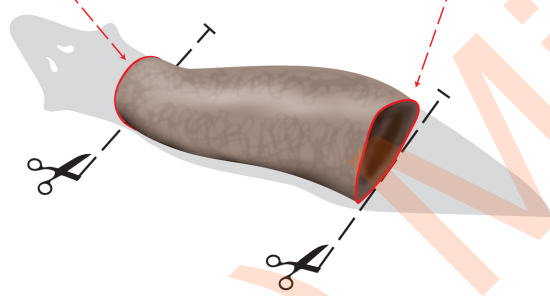


The bioelectric pattern doesn't indicate what the anatomy is now, it encodes the latent pattern memory that will guide anatomy if it is cut at a future time = **counterfactual**

Unifying dynamical systems models with cognitive models: how do networks remember?



Jeremy Guay



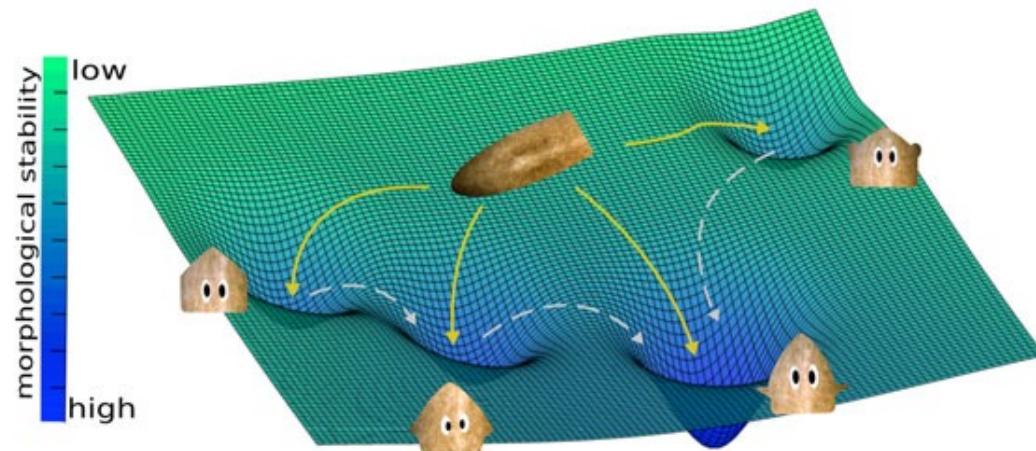
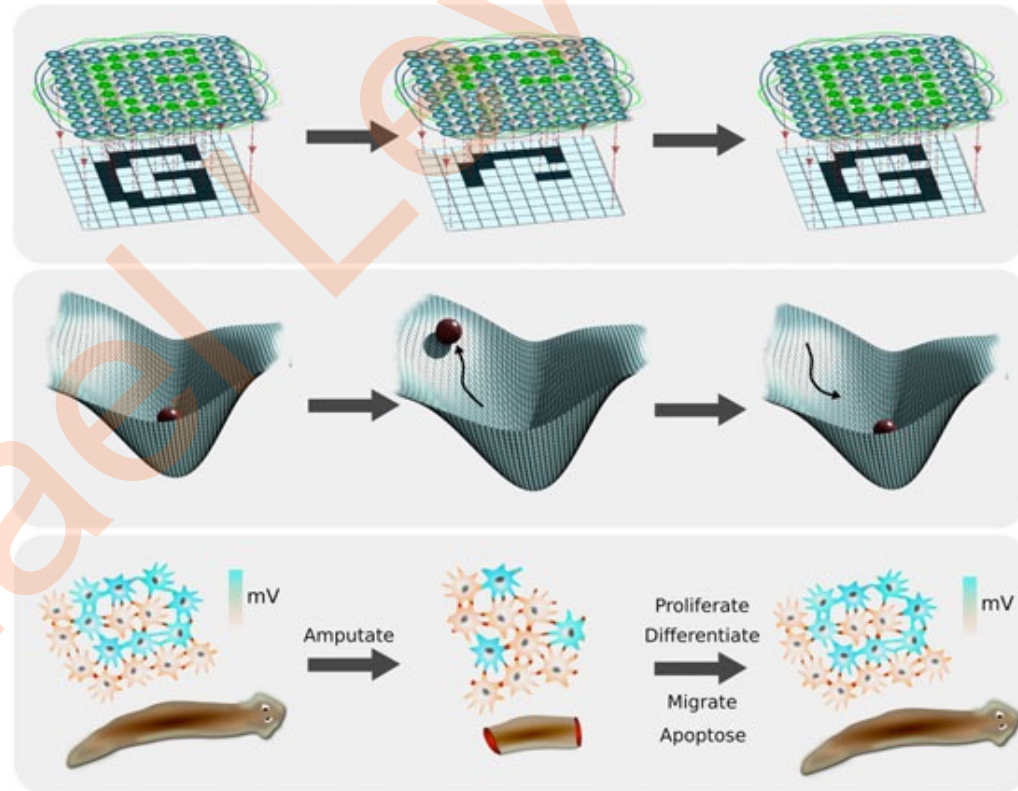
PHILOSOPHICAL
TRANSACTIONS B

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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

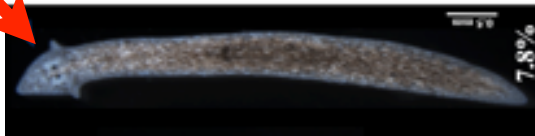
Review



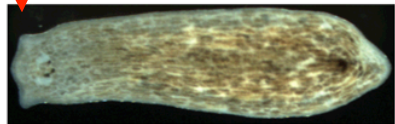
A Single Genome Makes Hardware that can Access Bioelectric Memories of Other Species' Head Shapes

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



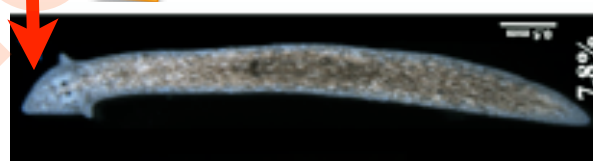
cut off head, perturb network topology



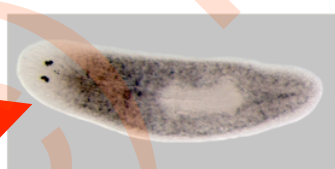
like:



like:

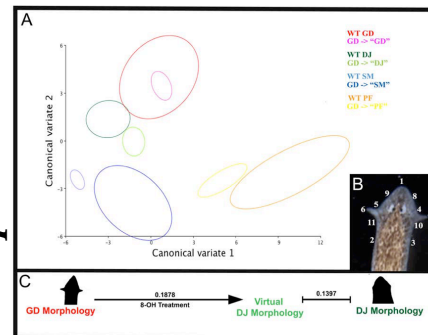


P. felina?

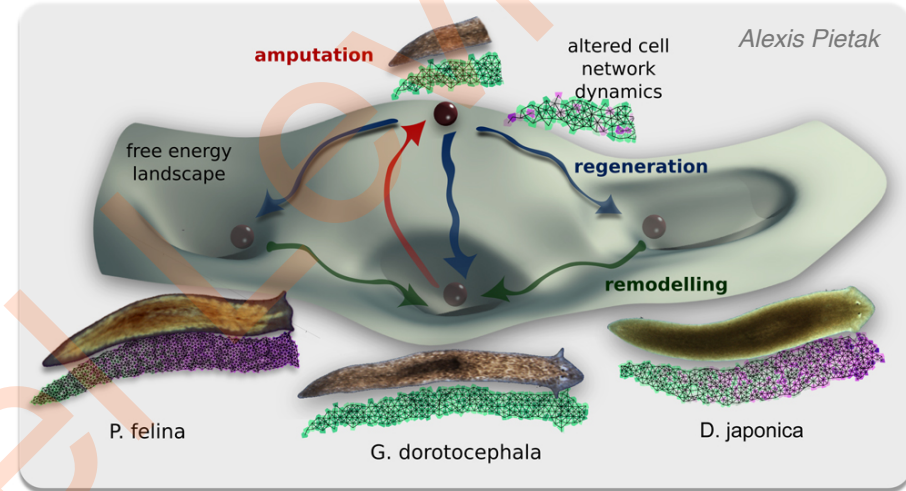


S. Mediterranea

quantitative morphometrics

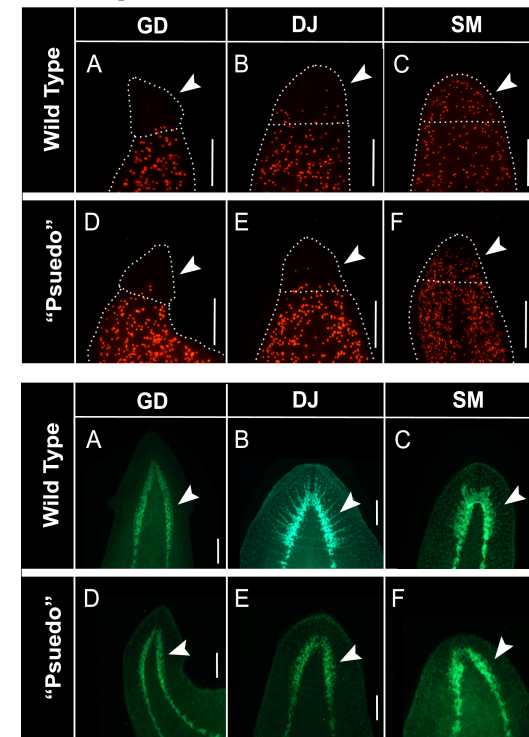


Maya Emmons-Bell



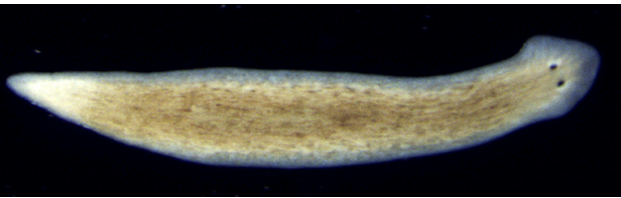
Alexis Pietak

brain shape and stem cell patterns match also!

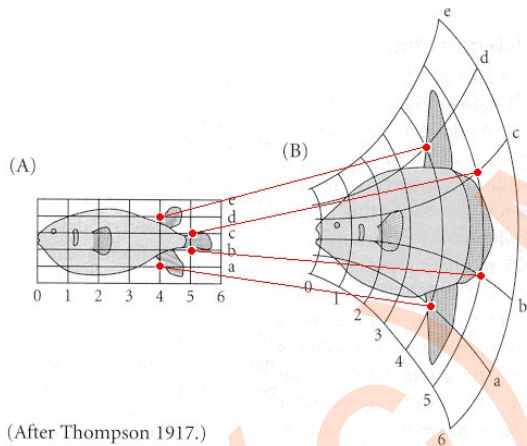
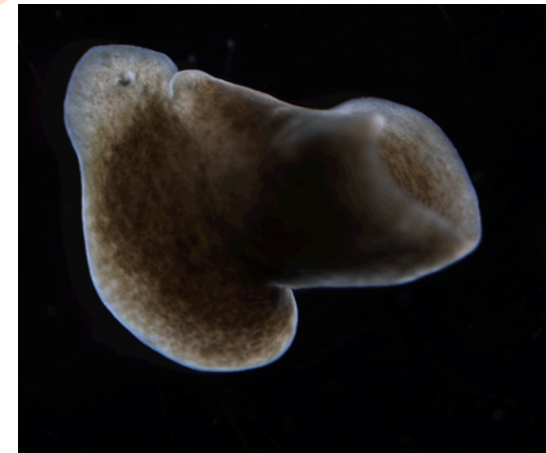


Exploring the Latent Space

Normal



Bioelectric Circuit Altered After Bisection



(After Thompson 1917.)

latent morphospace

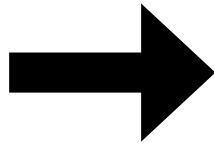
Same hardware,
Different journal in morphospace

Fallon Durant

Emergent Intelligence, not Just Complexity

- Bioengineered beings as exploration vehicles (and non-human bioengineers)
- Where do morphological and behavioral goals originate? Beyond evolution and design.

Good Old Reliable Development



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

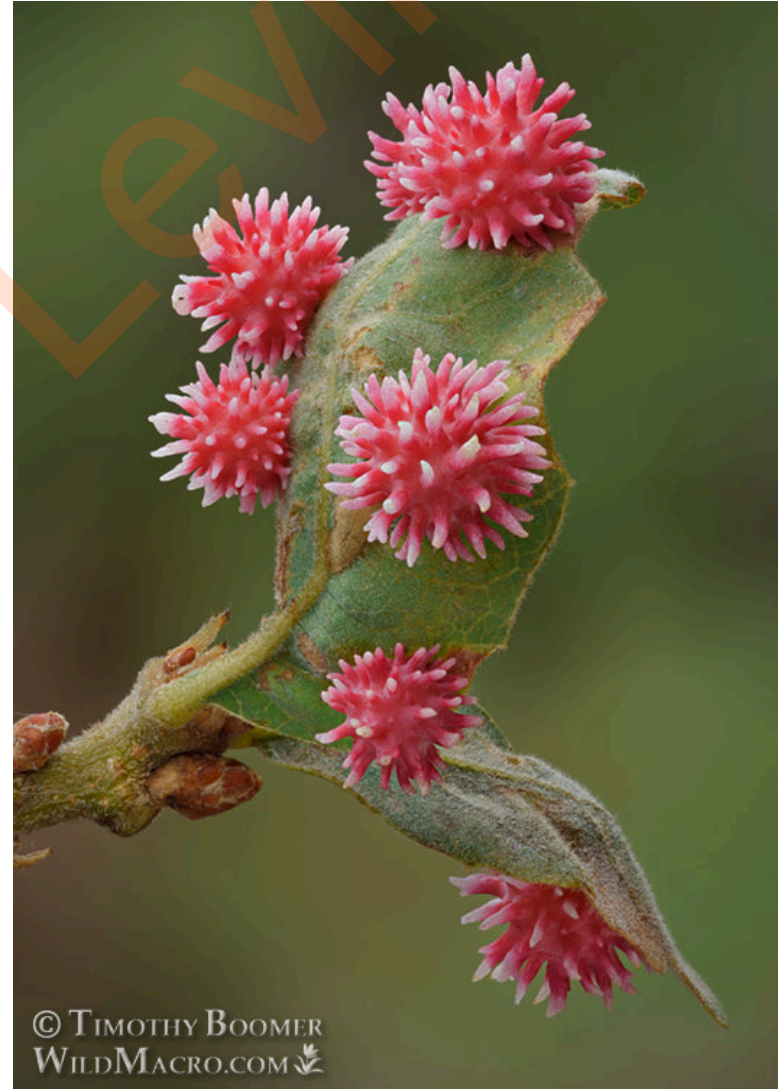
Did you Guess that Oak Cells Can Make This?



Photo Credit: Andrew Deans

Hedgehog Gall

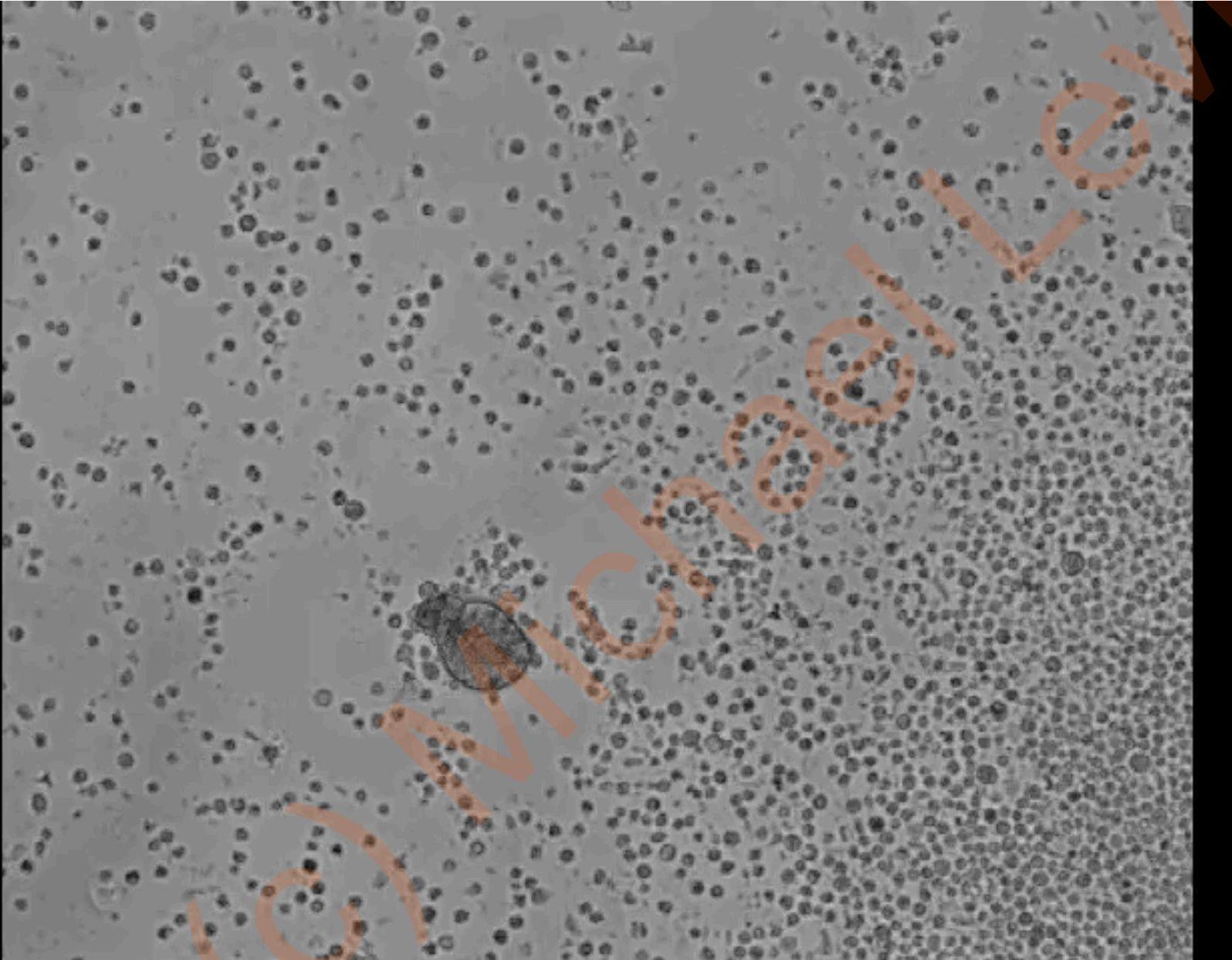
Acraspis erinacei
August - November



© TIMOTHY BOOMER
WILDMACRO.COM

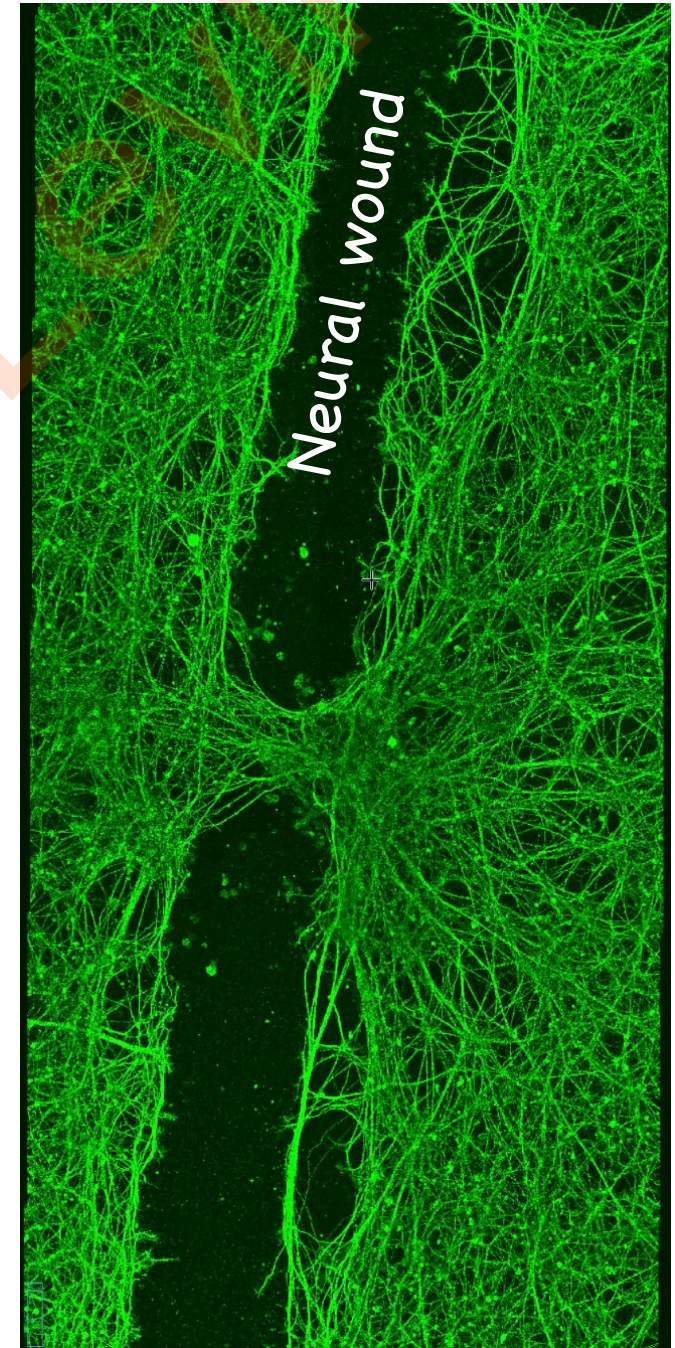
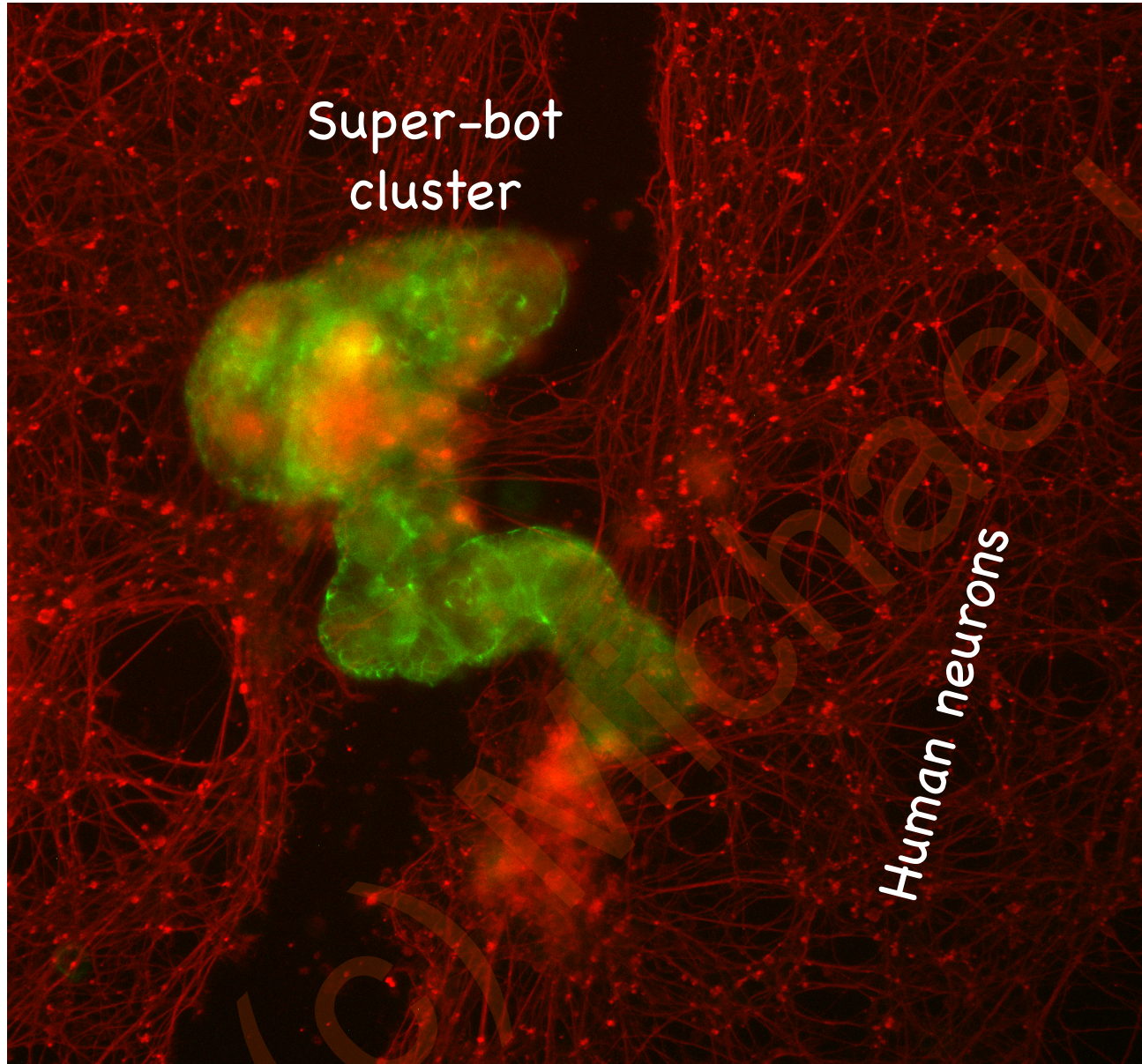
Parasite hacks host to induce new anatomy

What Lies Beyond Repair of Normal Target Morphology?



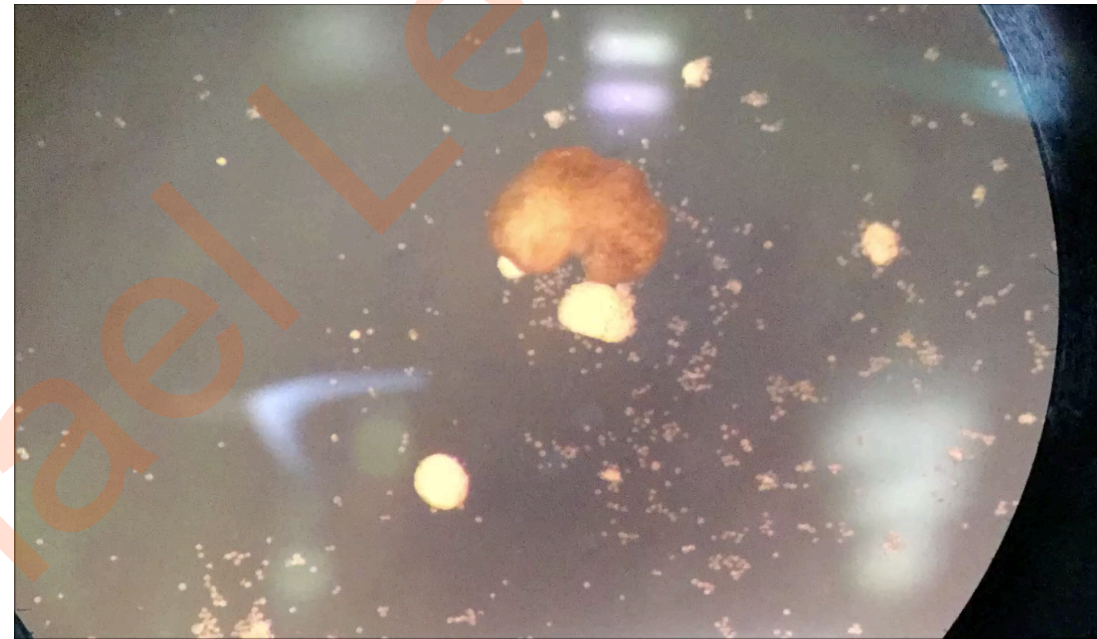
Where do the properties of novel systems come from if not from millions of generations of selection or explicit engineering?

Anthrobots Exert Neural Repair



Kinematic Replication in Xenobots: (frog skin cells)

novel competencies of the agential material



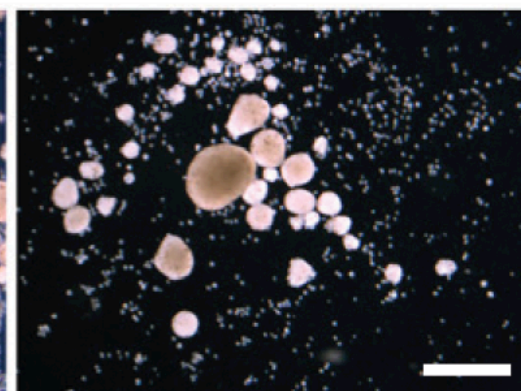
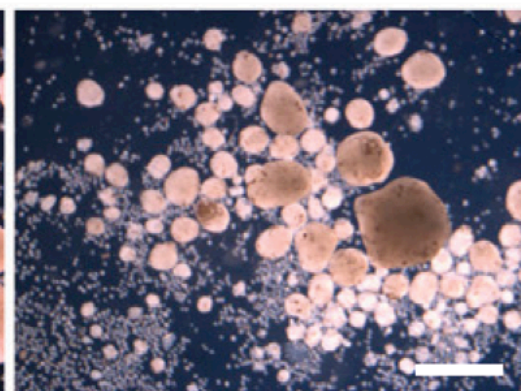
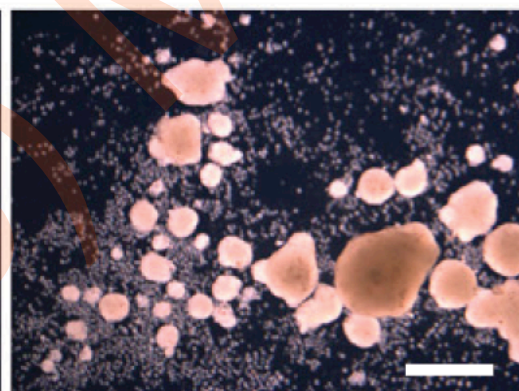
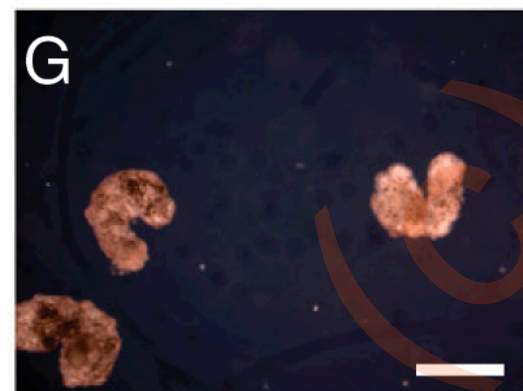
Douglas Blackiston

gen 0

gen 1

gen 2

gen 3



Whence specific goals, if not Selection?!

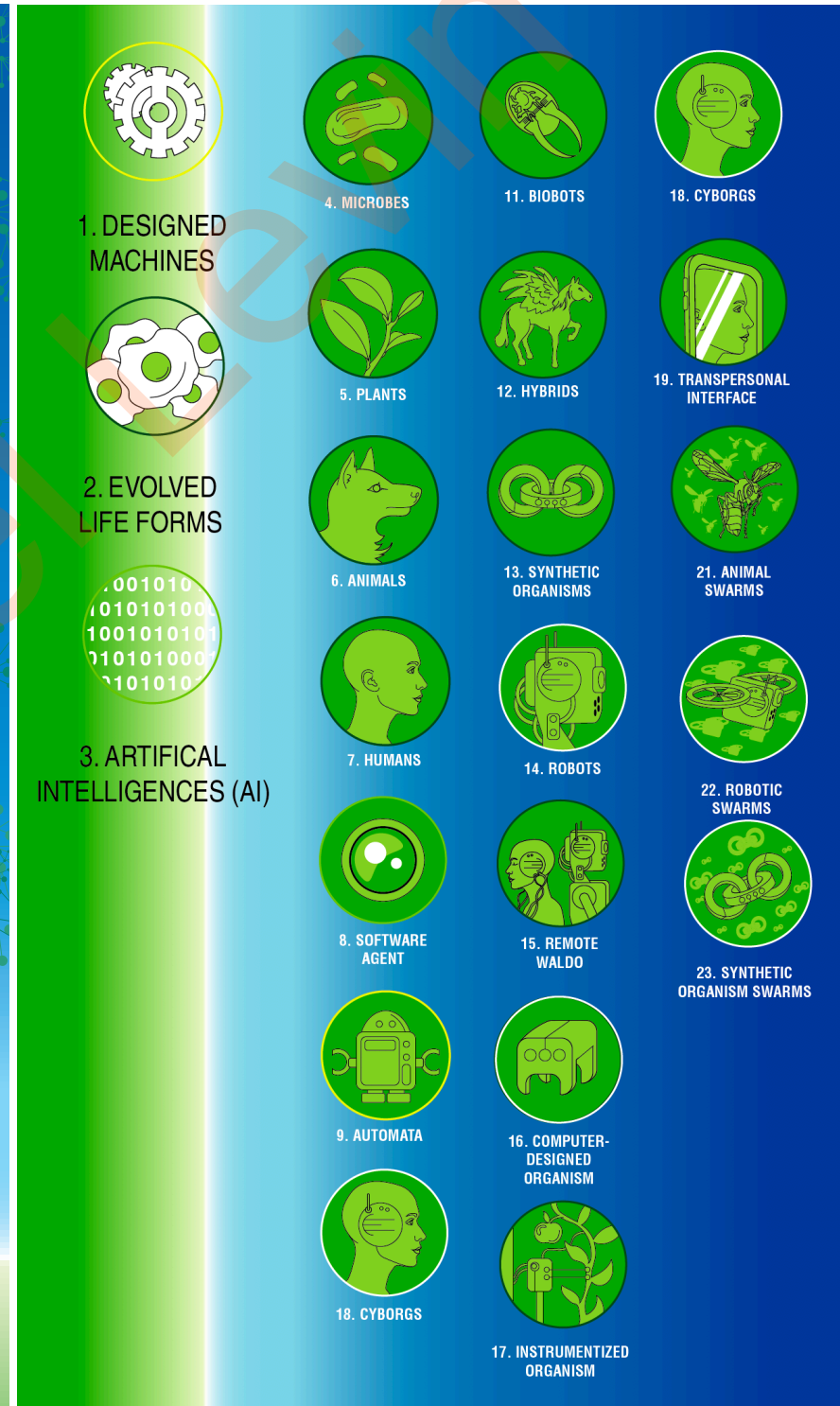
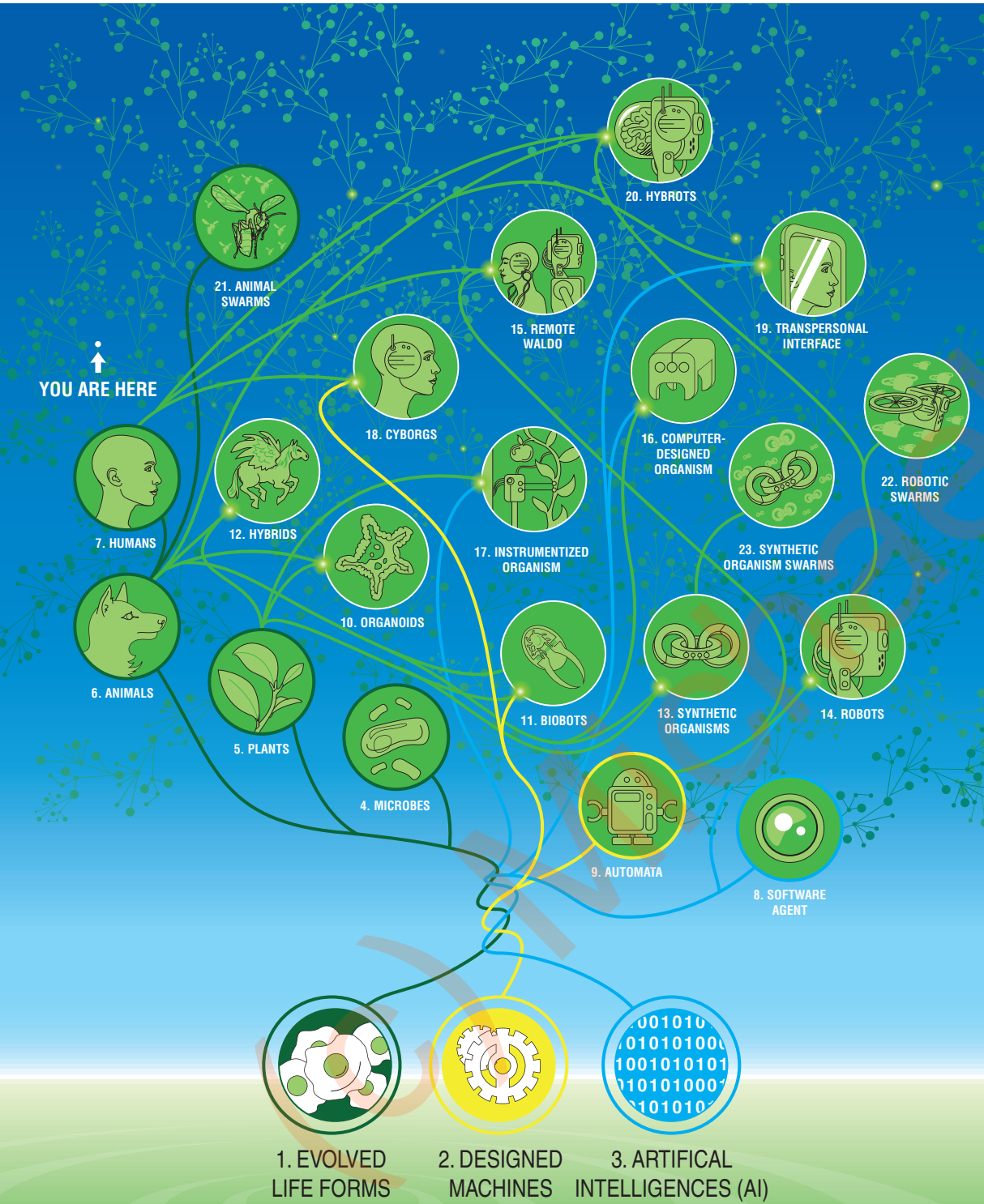
Vehicles for
exploring
Platonic
latent space

**Biology definitely does
things differently than
today's LLM's & robotics**

**BUT it's not because
brains, or algorithms,
and we can shape the
ingressions.**



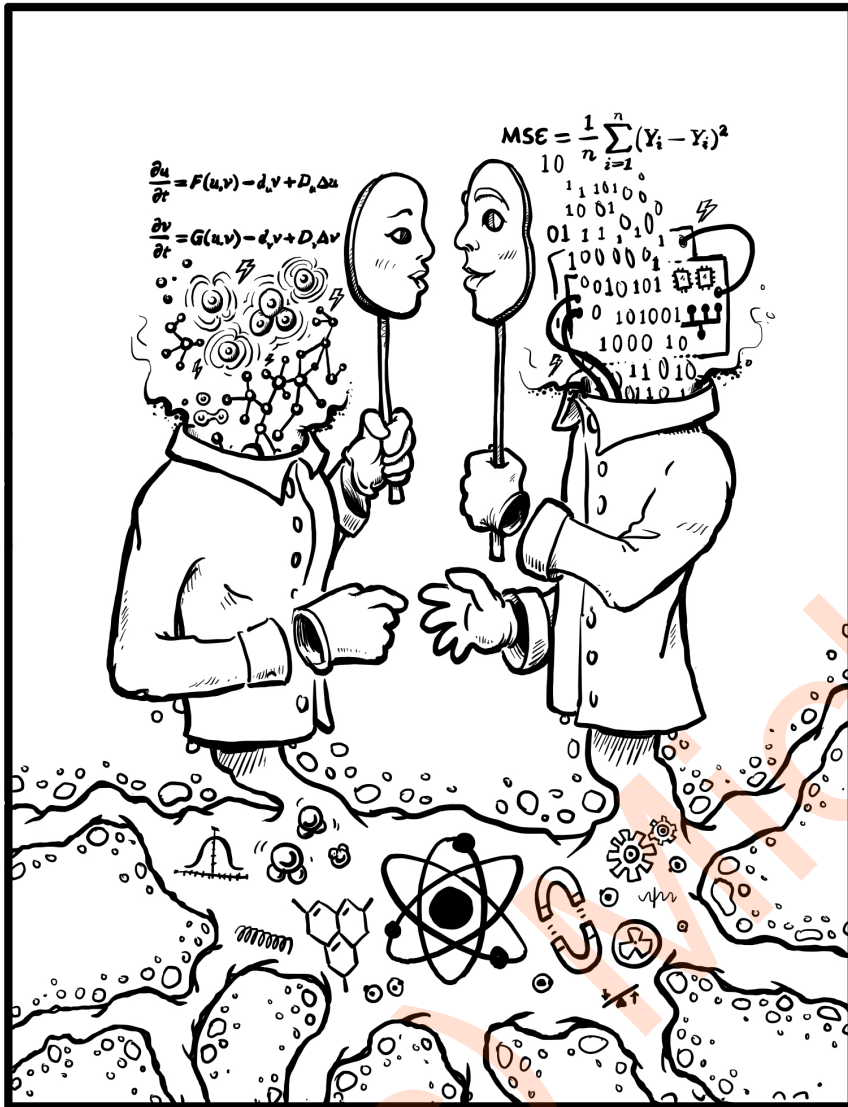
"Endless Forms Most Beautiful" ←→ ethical synthbiosis



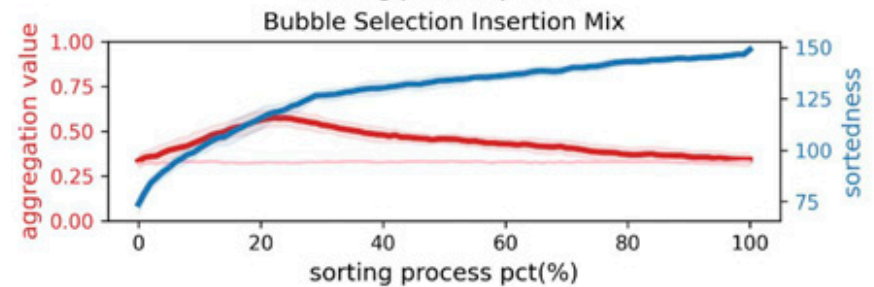
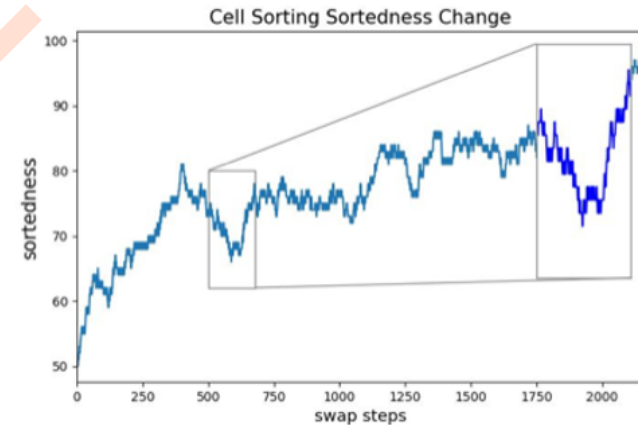
Emergent Goals and Competencies

humility warranted: even bubble sort has emergent delayed gratification NOT explicitly in the algorithm

We underestimate matter and we underestimate algorithms/“machines”



It does not take cells, life, or huge complexity to have emergent goals



Article

Adaptive Behavior

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

Adaptive Behavior
2024, Vol. 0(0) 1–30
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Final Message



- Minds are not fully defined by our models of them, neither for their limitations nor for their competencies.

Summary:

- Intelligence is ubiquitous; learning to rise above our limitations and recognize it in unfamiliar embodiments and problem spaces is essential for biomedical progress and ethical flourishing of sentient beings.
- You don't know what something can do, what it wants, and how smart it is just because you know the algorithm, the materials' properties, or even because you made it yourself.
- Research agenda = principled frameworks that avoid teleophobia and animism; we have to get it right, not skew low (or daydream high). Empirical testing of emergent goal-seeking and navigational competencies for engineering and regenerative medicine, explore a structured latent space.
- The future:
 - ~~Anthropomorphism~~, ~~binary categories of man, machine, life~~
 - Continuum of mind, observer-relative models,
 - AI tools as universal translators to Diverse Intelligences

More Details Here:

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

On Having No Head: Cognition throughout Biological Systems

František Baluška¹ and Michael Levin^{2*}

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†



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

Contents lists available at ScienceDirect

Biochemical and Biophysical Research Communications

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



PROBLEMS & PARADIGMS

Prospects & Overviews

Scale-Free Biology: Integrating Evolutionary and Developmental Thinking

Chris Fields* and Michael Levin

BioEssays

www.bioessays-journal.com

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

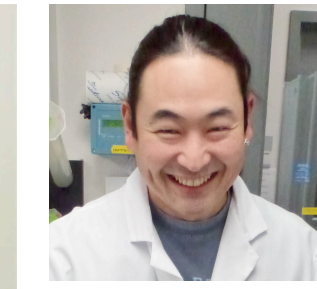
<https://aeon.co/essays/how-to-understand-cells-tissues-and-organisms-as-agents-with-agendas>

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

Michael Levin^{a, b}



Thank you to:



Post-docs and staff scientists in the Levin lab:

Douglas Blackiston - brain-body interface plasticity, synthetic living bodies
AiSun Tseng, Celia Herrera-Rincon, Nirosha Murugan - limb regeneration
Vaibhav Pai - voltage gradients in eye/brain induction and repair
Tal Shomrat - persistence of memory in regenerating brains
Nestor Oviedo, Junji Morokuma - bioelectrics of planarian regeneration
Patrick McMillen - bioelectric imaging and embryogenesis

Graduate Students:

Gizem Gumuskaya - Anthrobots
Sherry Aw - bioelectric eye induction
Adam Goldstein, Taining Zhang - emergent competencies of algorithms

Technical support:

Rakela Colon, Jayati Mandal - lab management
Erin Switzer - vertebrate animal husbandry
Joan Lemire - molecular biology

Collaborators: Allen Center members +

Dany Adams - bioelectric face prepattern
Alexis Pietak - computational modeling of bioelectrics
Joshua Bongard - Xenobot simulations and AI
David Kaplan - V_{mem} and human MSC differentiation, regenerative sleeves
Simon Garnier - computational analysis of Anthrobot form and function
Chris Fields - physics of sentience and sentience of physics
Richard Watson - computational models of cognitive scaling and evolutionary learning
Giovanni Pezzulo - cognitive science applied to morphogenesis

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

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