Patterns of Form and Behavior Beyond Emergence:

how Platonic Space in-forms evolved, engineered, and hybrid embodied minds

Michael Levin
Allen Discovery Center at Tufts

http://www.drmichaellevin.org/

http://thoughtforms.life/
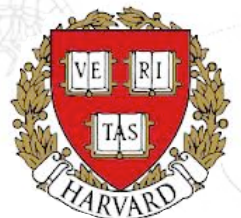
ALLEN DISCOVERY CENTER at Tufts University

Computer-designed Organisms
TUFTS UNIVERSITY | UNIVERSITY OF VERMONT

WYSS INSTITUTE

VERITAS HARVARD
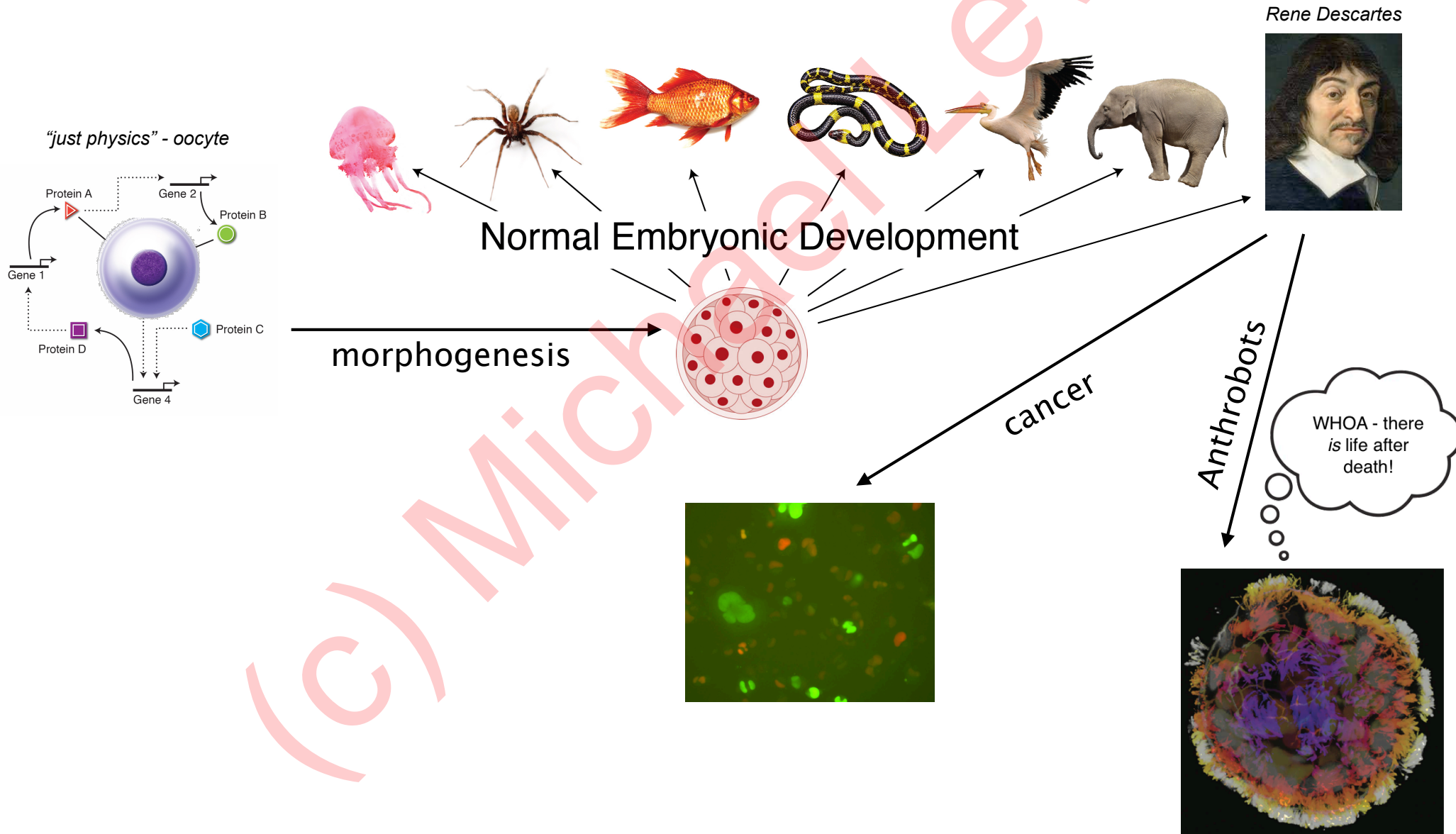
Outline:

- Generalize "patterns" = forms of structure and behavior

- Morphogenesis = homeostatic process *toward* a specific form (beyond open-loop complexity and emergence)

- Where do the specific goals come from? (beyond selection and specificity of environment + genetics)

- Platonic space = structured space of patterns that in-forms biology and physics (physicalism is insufficient; causation and explanation)

- Even very simple interfaces get some of the magic (brains, algorithms, and chimeras)

- Research program: study the space, and the mapping

Autopoiesis of Bodies and Minds

Rene Descartes

"just physics" - oocyte

Gene 2

Protein A

Protein B

Gene 1

Protein D

Protein C

Gene 4

Normal Embryonic Development

morphogenesis

cancer

Anthrobots

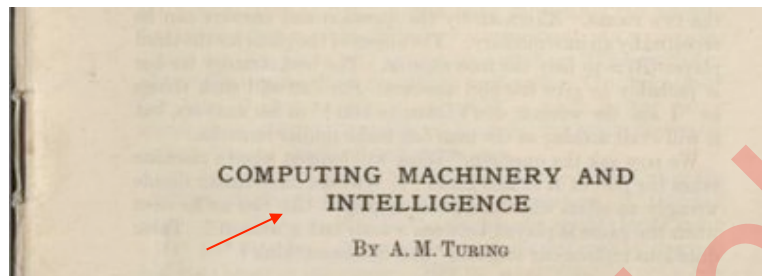WHOA - there *is* life after death!

Forms: (patterns)

forms of body (morphology) and of mind (behavior) are part of the same class

Deep symmetry between the scaling of bodies and minds
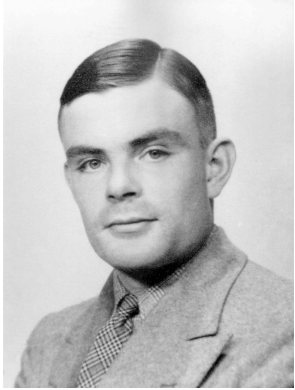
Alan Turing

Problem–solving living machines:
intelligence through plasticity
(reprogrammability)

COMPUTING MACHINERY AND INTELLIGENCE

By A. M. TURING

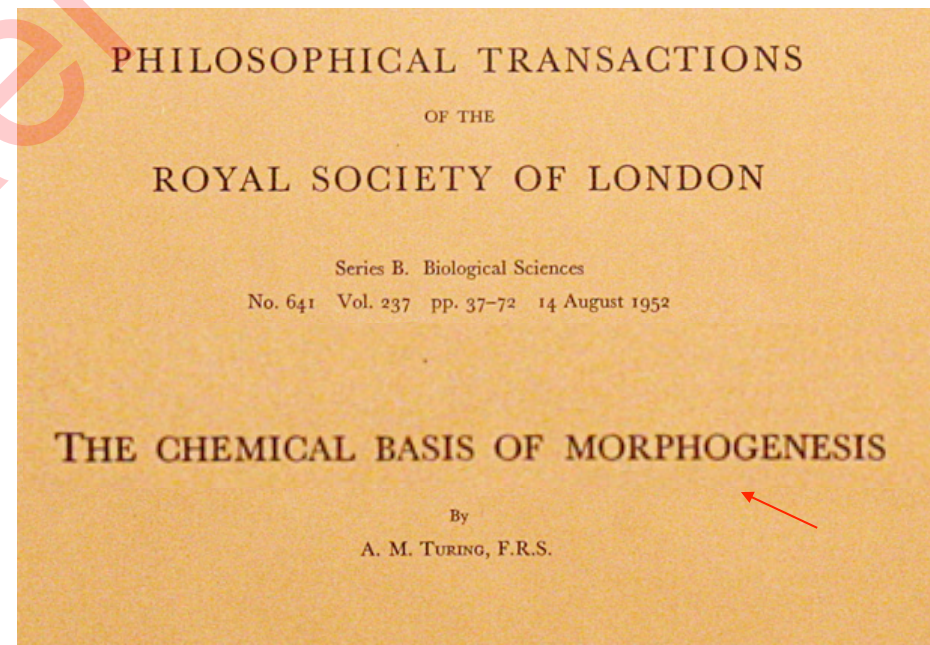230   A. M. TURING   [Nov. 12,

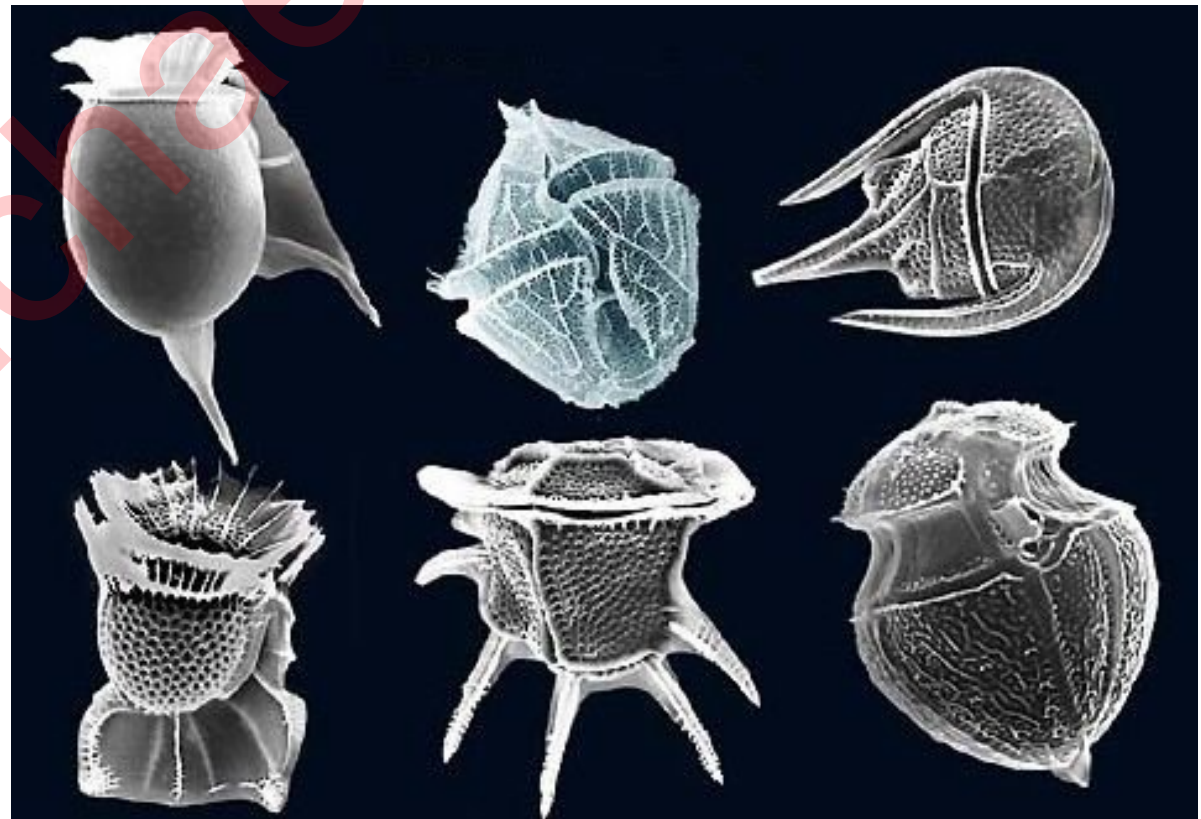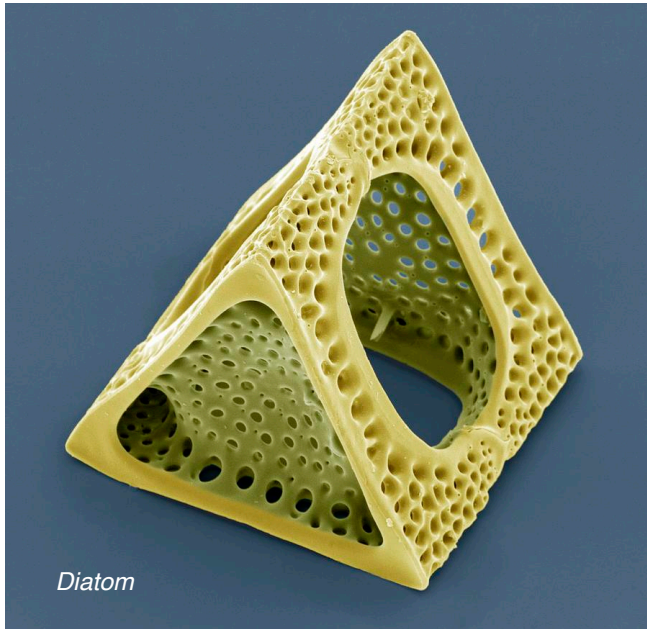ON COMPUTABLE NUMBERS, WITH AN APPLICATION TO THE ENTSCHEIDUNGSPROBLEM

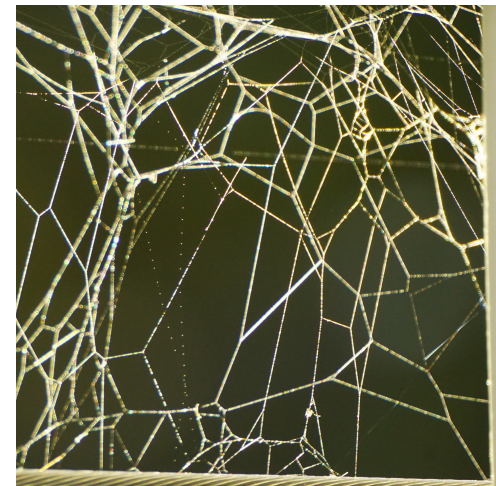By A. M. TURING.

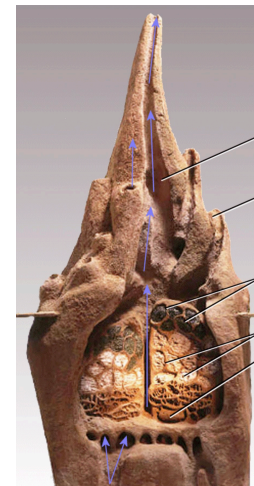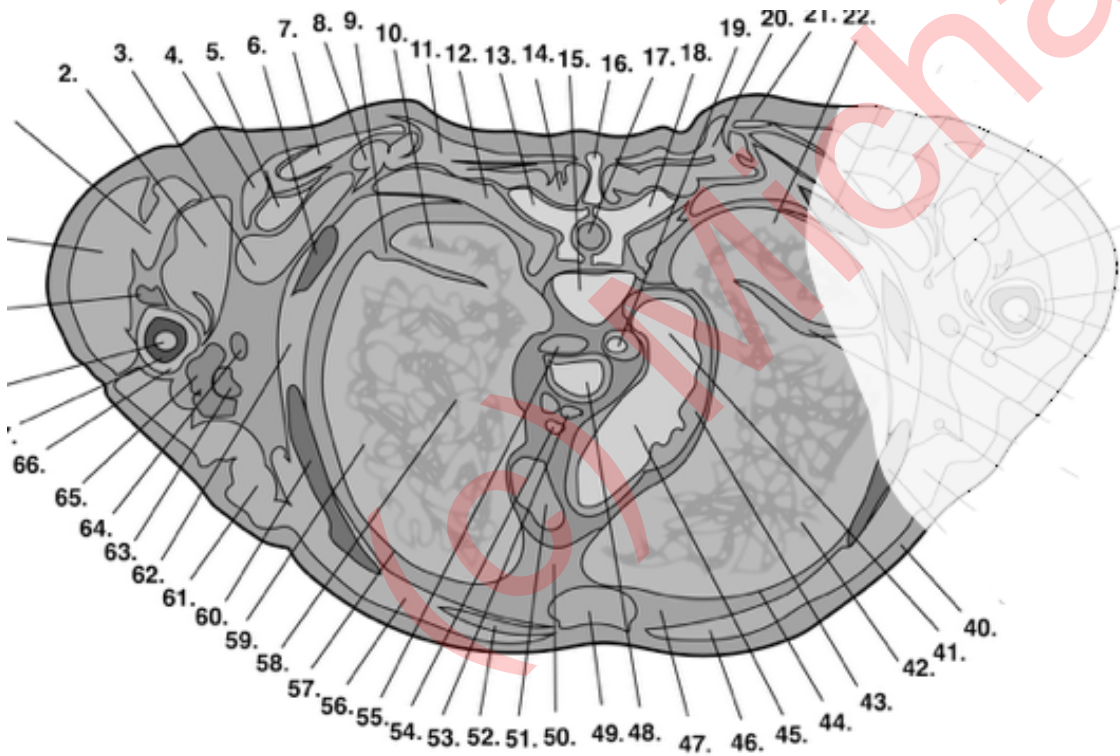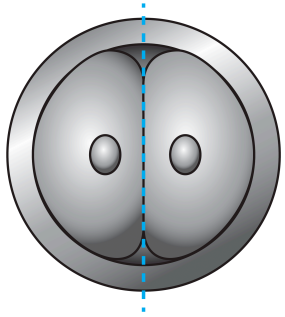[Received 28 May, 1936.—Read 12 November, 1936.]

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.

Forms of Very Small Life

Diatom

Larger Forms of Life

Goniurellia Tridens

Hessam Akhlaghpour

Forms of Minimal Systems' Behavior:

Lacrymaria olor

video by Charles Krebs

Lacrymaria = 1 cell
no brain
no nervous system

high competency
at cell-level
agendas
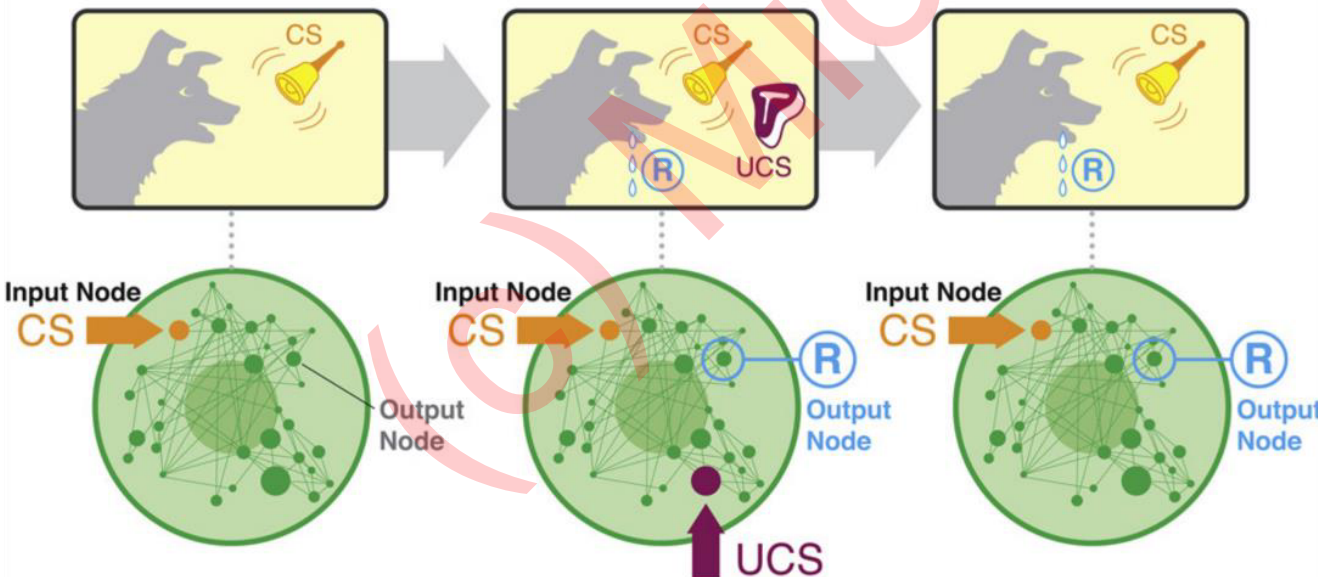
Associative conditioning in gene regulatory network models increases integrative causal emergence

Check for updates

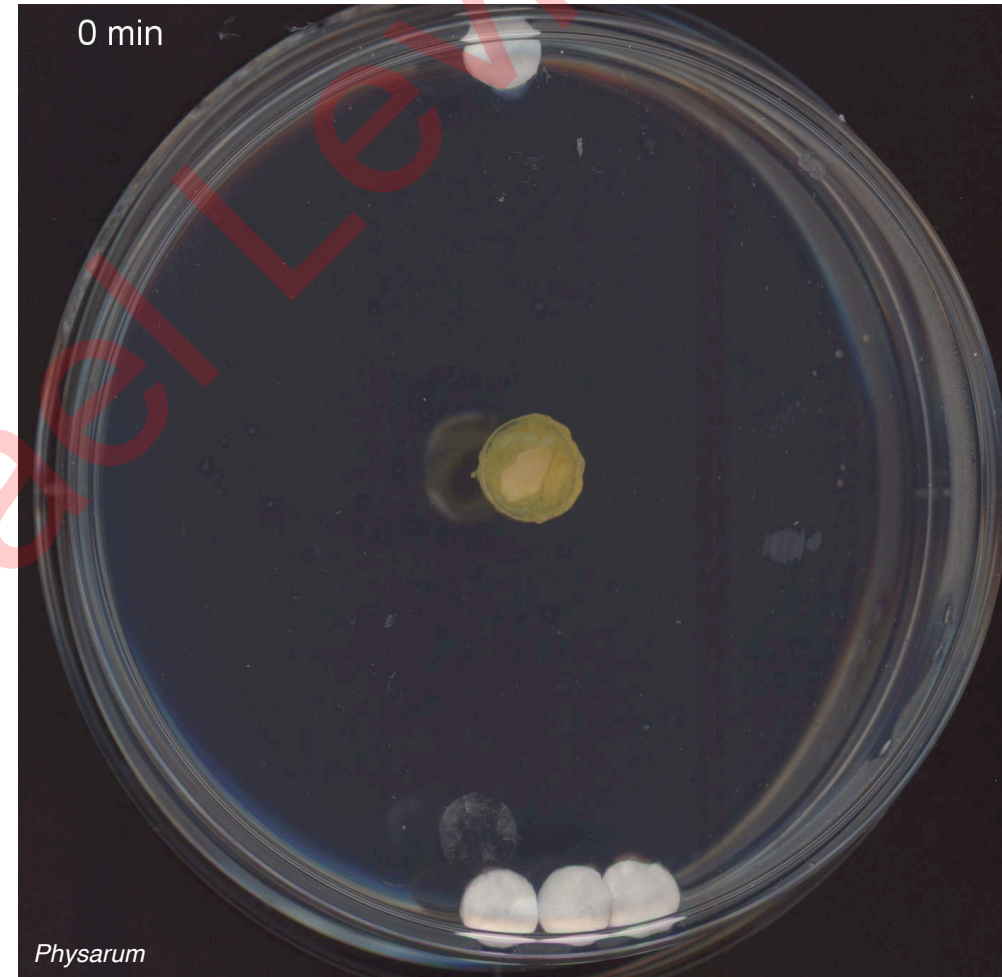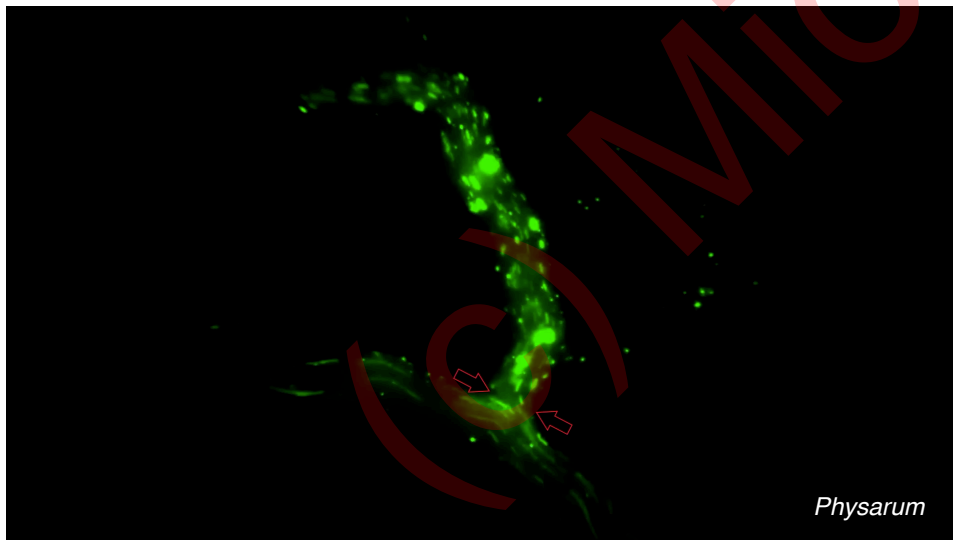Federico Pigozzi[1], Adam Goldstein[2] & Michael Levin [1,3]

"Simple" behaviors

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]*

0 min

Physarum

Nirosha Murugan

Physarum

High-Agency Behaviors

(actual degree of agency
is not obvious from pure
observation!)

Collective Intelligence of Cells: Competency in Diverse Spaces

3D Space (behavior)


entropy · MDPI
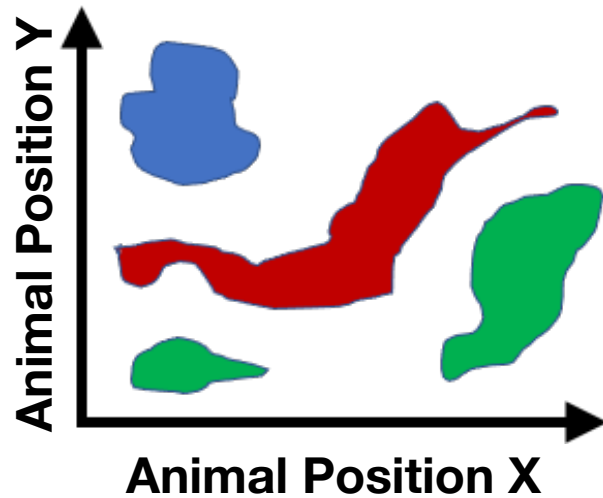
Concept Paper

Competency in Navigating Arbitrary Spaces as an Invariant for Analyzing Cognition in Diverse Embodiments

Chris Fields [1,2] and Michael Levin [2,3,*]

Is there a privileged space?
3D space is equally "constructed"

CROWS ARE BEING TRAINED TO CLEAN CITIES BY PICKING UP CIGARETTE BUTTS
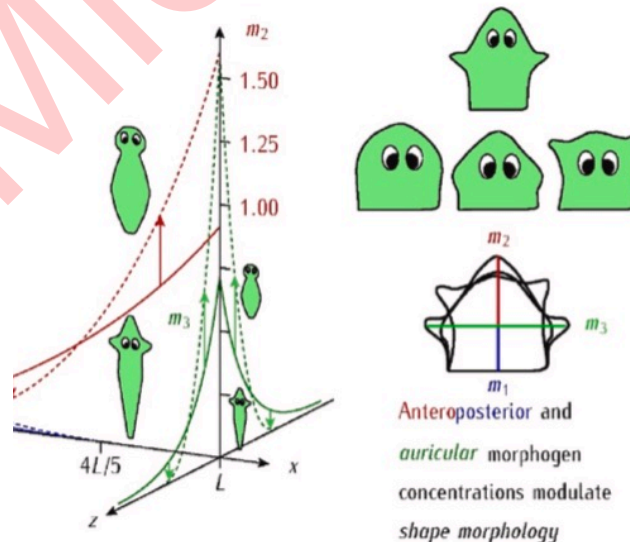
Transcriptional Space

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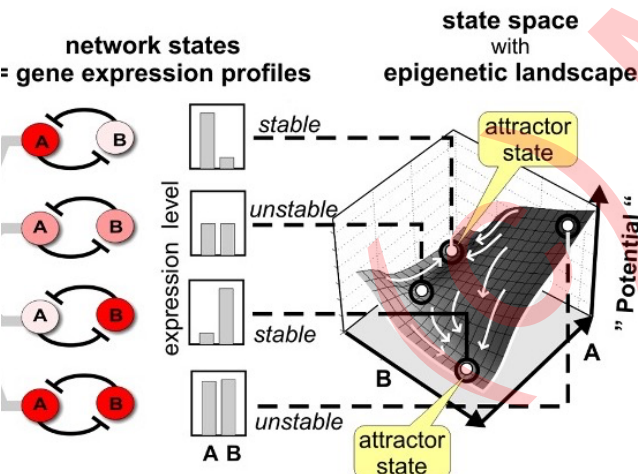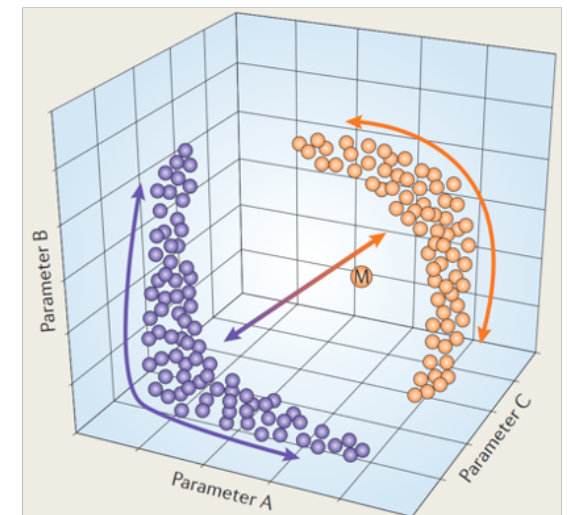

Morphospace

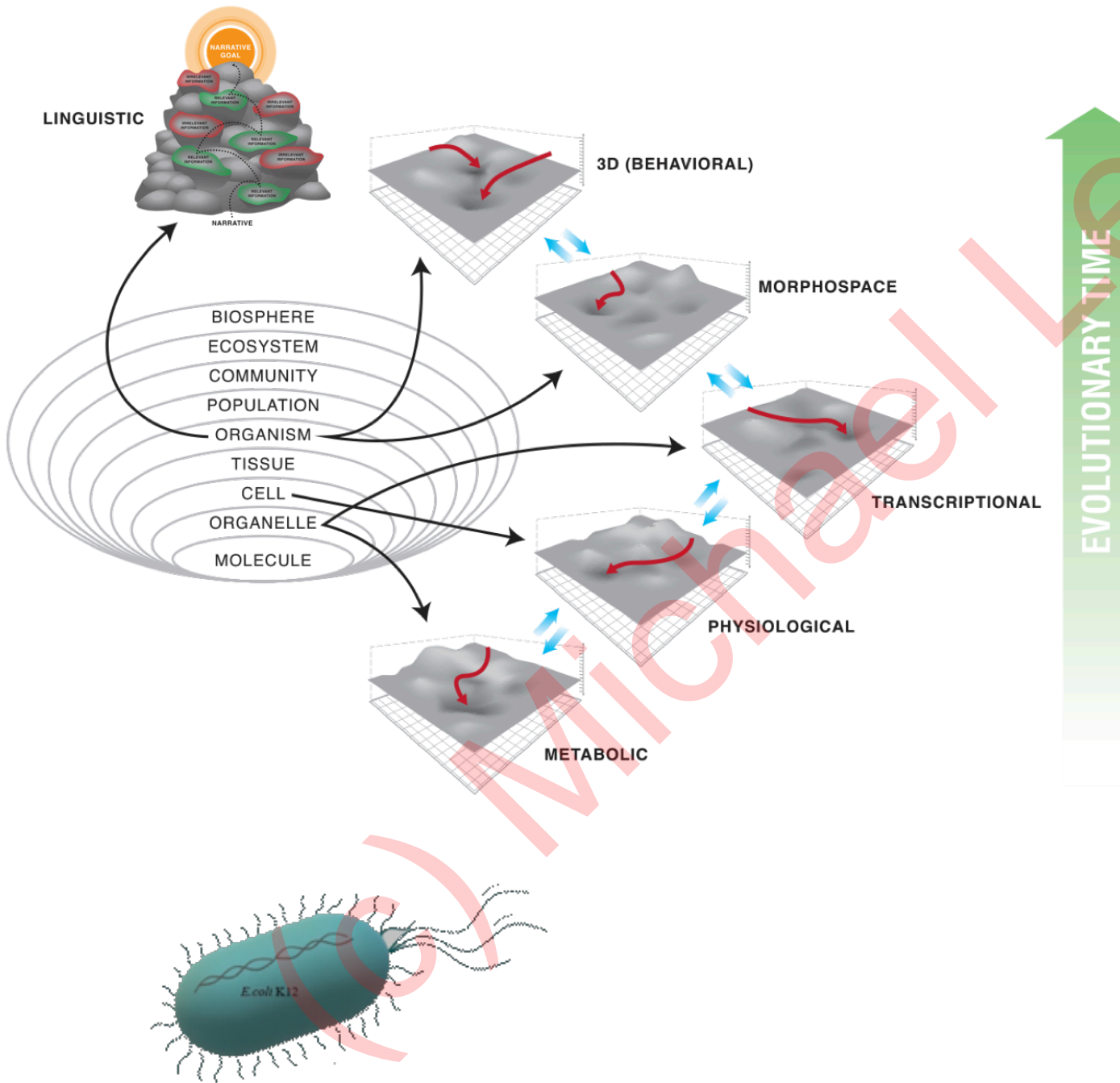Cervera, J., Levin, M., and Mafe, S., (2021), BioSystems, 209:104511

Physiological Space

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

Spaces are in the Eye of the Observer

LINGUISTIC

NARRATIVE GOAL

BIOSPHERE
ECOSYSTEM
COMMUNITY
POPULATION
ORGANISM
TISSUE
CELL
ORGANELLE
MOLECULE

3D (BEHAVIORAL)

MORPHOSPACE

TRANSCRIPTIONAL

PHYSIOLOGICAL

METABOLIC

EVOLUTIONARY TIME

E. coli K12

WILEY-VCH

Nirosha Murugan

https://www.nature.com/articles/s41598-019-51046-7

It's not just genetics + emergence

What needs to be explained is specific target morphology <u>as a goal pursued by diverse means</u>

https://youtu.be/1gZw1SuykB8?si=YF1yXgU91y8XwFrw

Same anatomy, from different starting states

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

Perfect
Regeneration

Amputation

Time
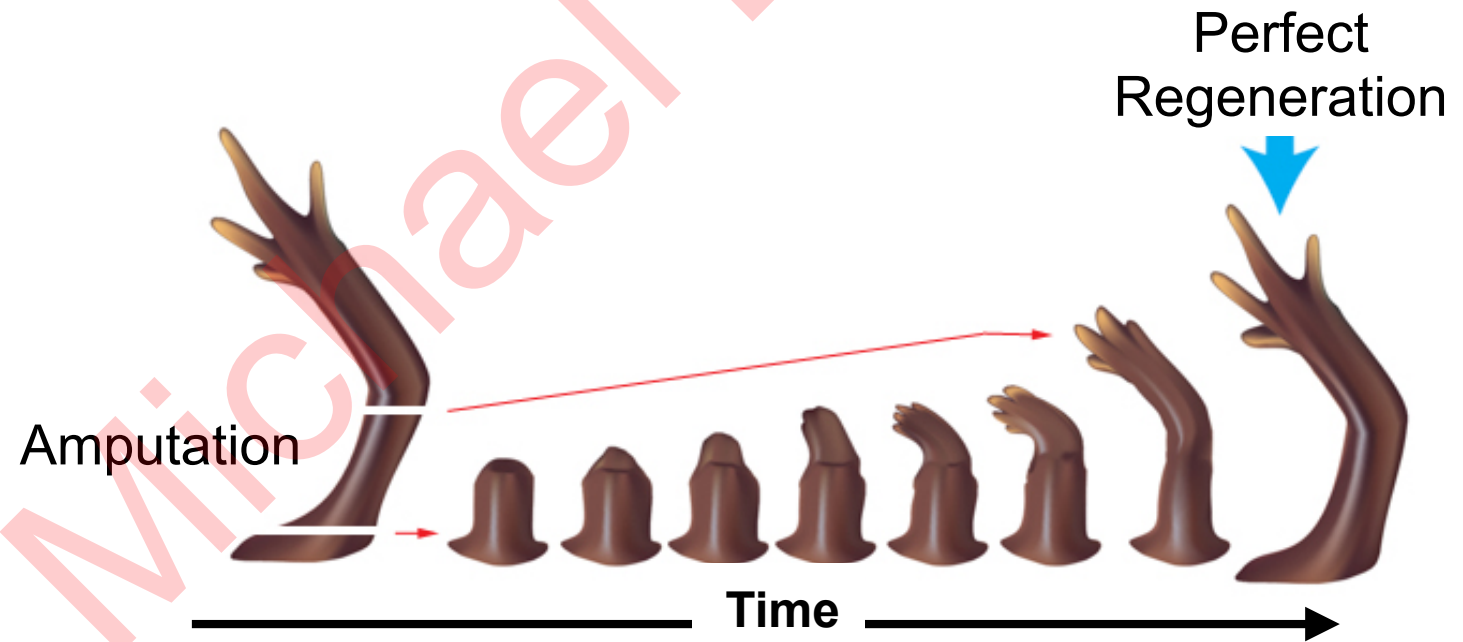
Anatomical homeostasis:

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

System-level Goals Trickle Down to Molecular Machinery

Regeneration is not just about damage repair; anatomical homeostasis is more general - top-down causation and goal-directedness, just like when abstract cognitive plans and memories make the ions dance in muscle cells

Tail grafted onto flank

Time
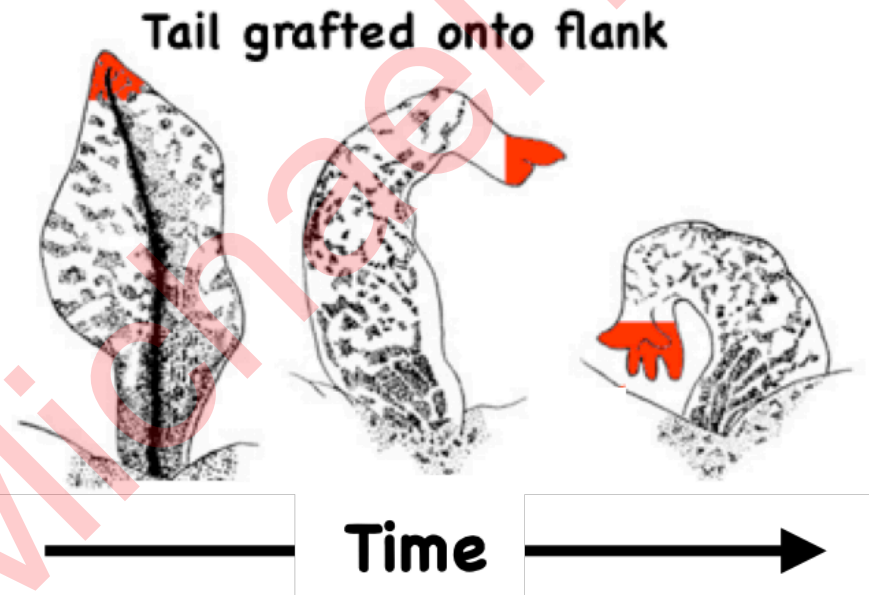
Farinella-Ferruzza, Experientia, 1956 (15)

Anatomical homeostasis: **local order obeys global plan**

Same Goal by Different Means:
Target of problem-solving, reuse of affordances

- get to the same outcome
  - despite perturbations (external and internal)
  - from diverse starting positions
  - **via different molecular mechanisms!**

newt kidney tubule cross-section
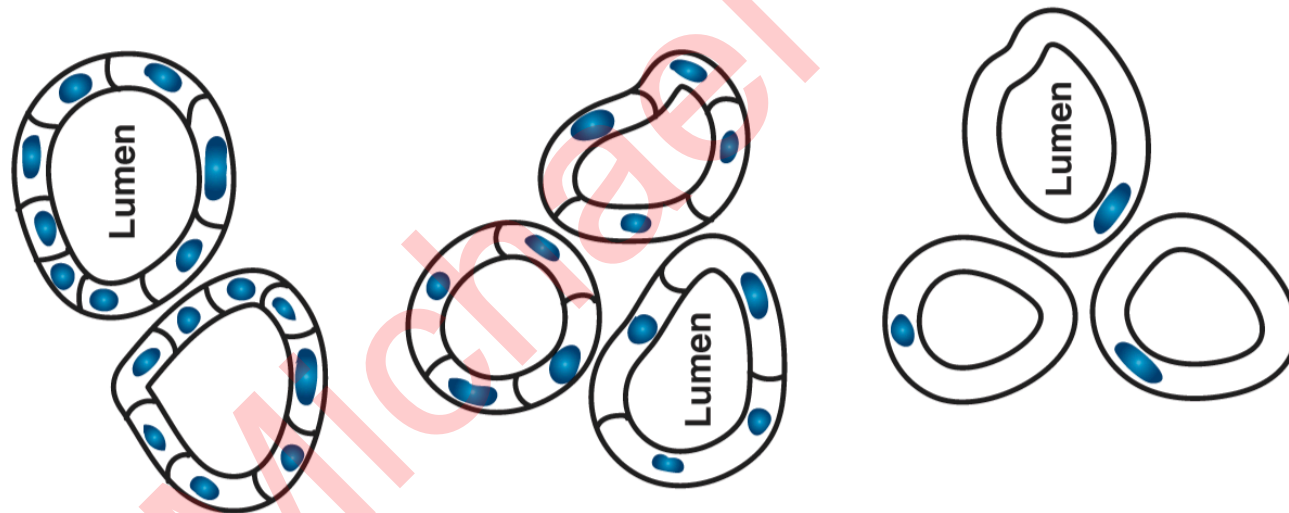
Fankhauser, 1945, J. Exp. Zool., 100(3): 445-455

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

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

Giovanni Pezzulo[2] and Michael Levin[1]

[1]Biology Department, Allen Discovery Center at Tufts, Tufts University, Medford, MA 02155, USA
[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

ROYAL SOCIETY OF CHEMISTRY

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]

Morphogenetic Goals are Re-Writable
without genetic change

or, can force V$_{mem}$ state back to normal

Cut, and <u>briefly</u> perturb bioelectric circuit

weeks later, cut in plain water
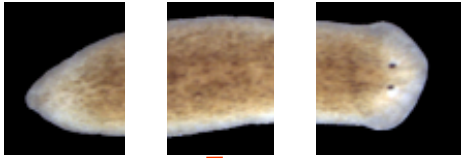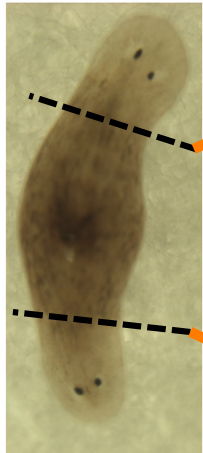
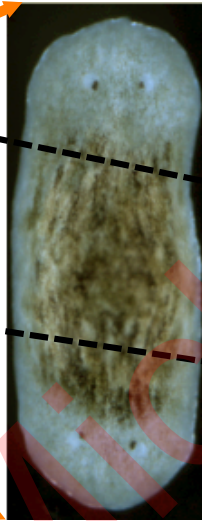**Keep trunk**

weeks later, cut in plain water
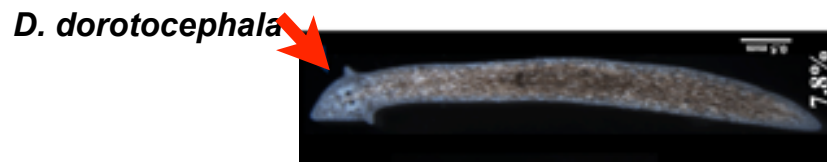
Keep trunk

Nestor Oviedo
Junji Morokuma

. . .

Same Hardware can Access Other Species' Forms
genetics doesn't fix the goal state

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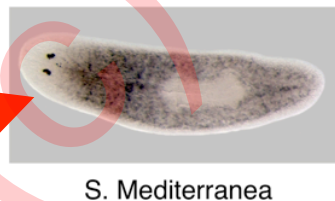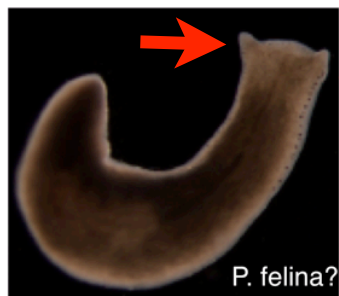
D. dorotocephala

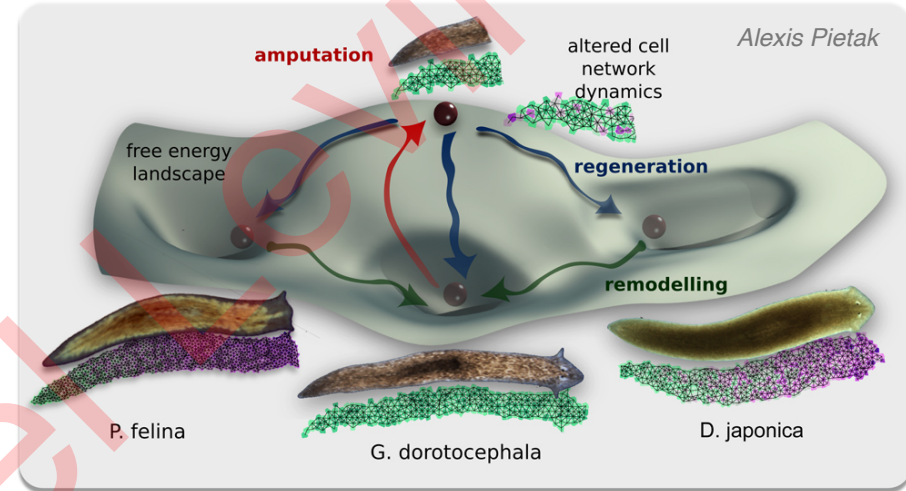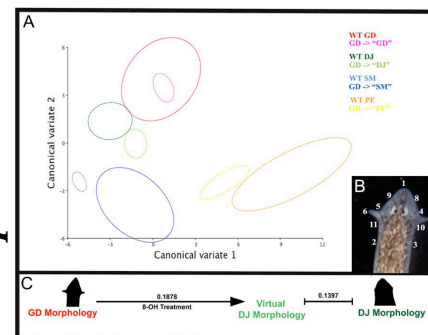**cut off head, perturb network topology**
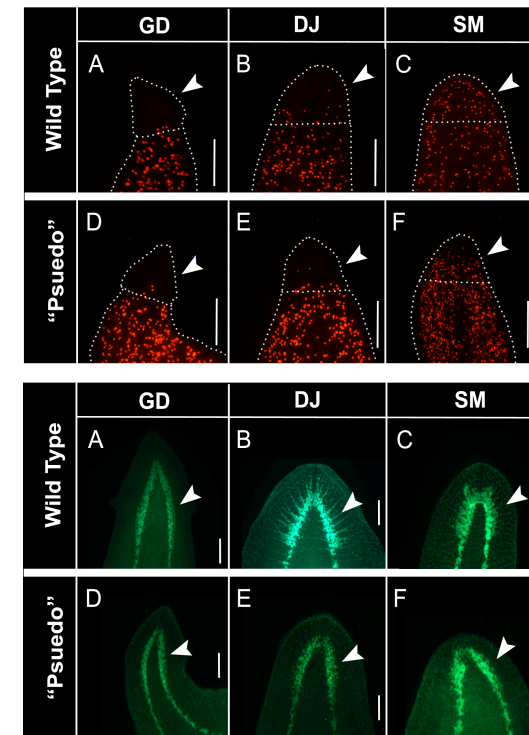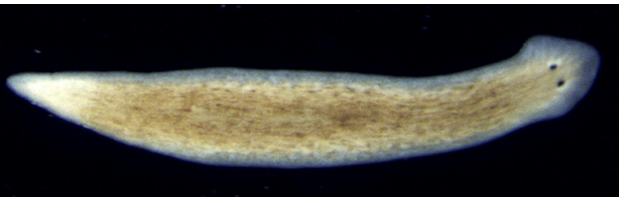
like:

like:

P. felina?

S. Mediterranea
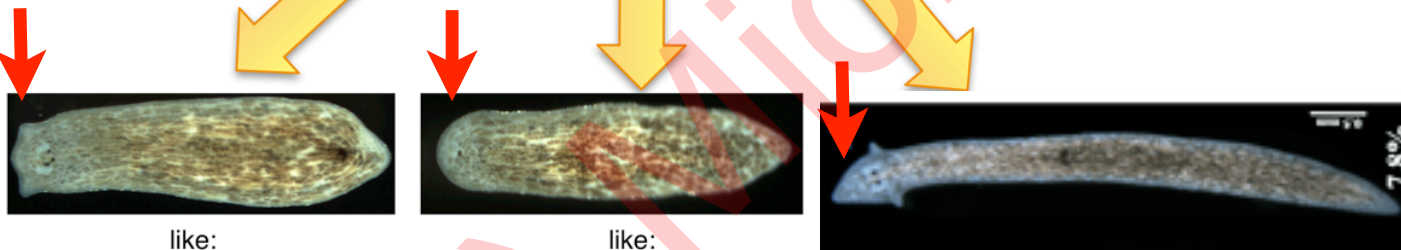
quantitative morphometrics

brain shape and stem cell patterns match also!

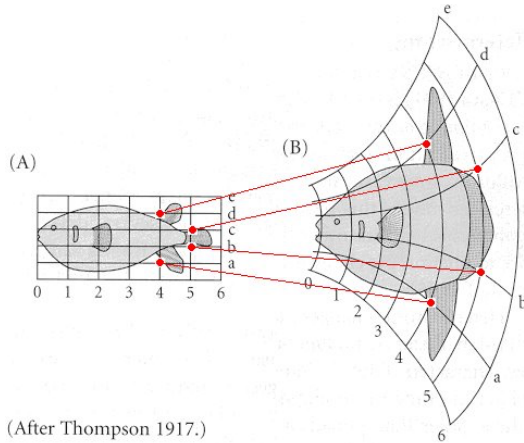**It's not just past history of selection**

hardware is able to find truly novel forms

Normal   Bioelectric Circuit Altered   After Bioelectric

(A)   (B)
(After Thompson 1917.)
(A)
0 1
(After Thompson 1917.)
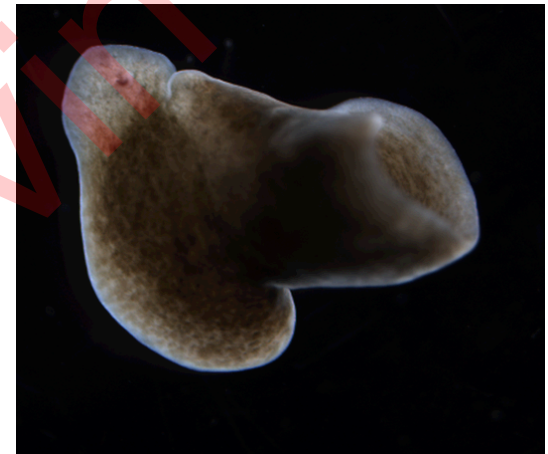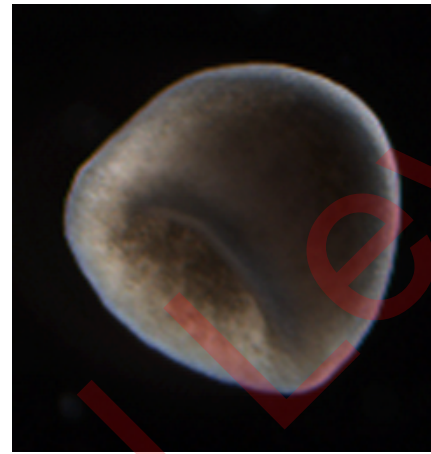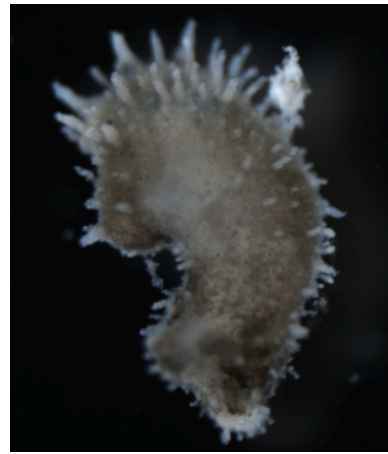
Cell groups are a
collective intelligence
navigating latent morphospace

**What are the available attractors, and
where do they come from?**

Good Old Reliable Development
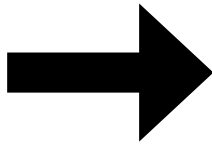
White Oak Leaf - Photo by Chris Evans, River to River CWMA, Bugwood.org

Bio-Prompting Toward New Target Morphologies

Photo Credit: Andrew Deans

Hedgehog Gall

Acraspis erinacei
August - November

© TIMOTHY BOOMER
WILDMACRO.COM

Biohacker finds new forms, without genetic modifications
Standard evolutionary default (Target Morphology) = a pinpoint in latent space

Biology's take on "where does it come from":

- Re-write the medium

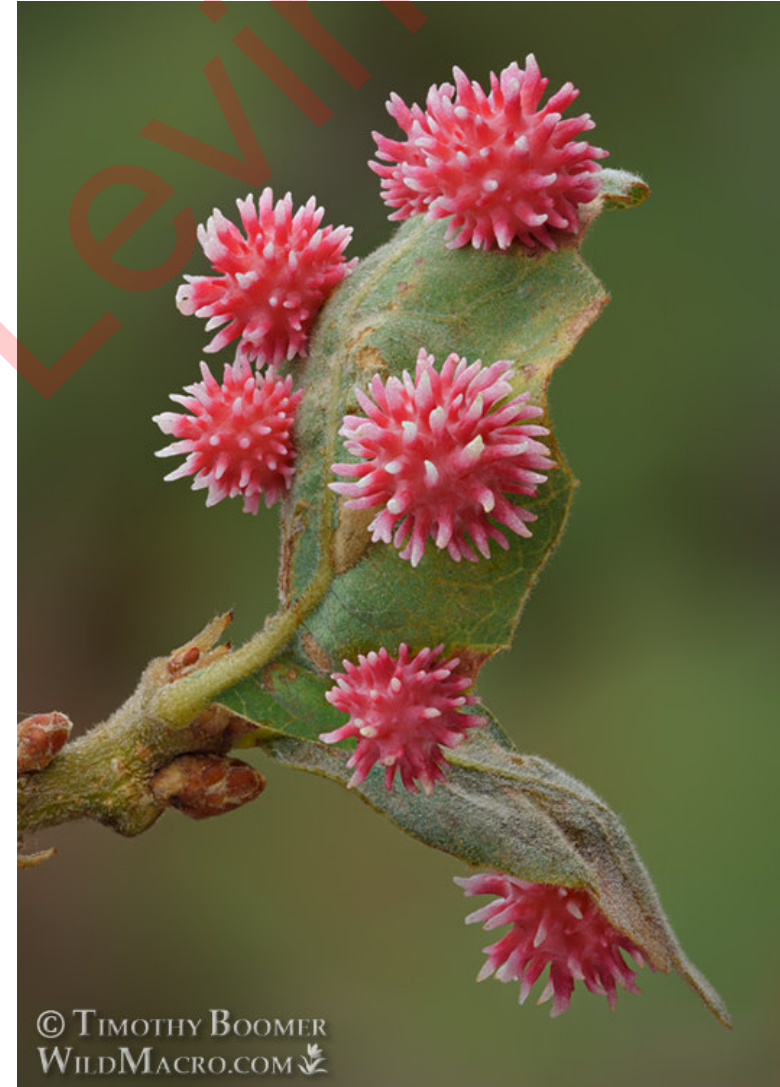Genetic media
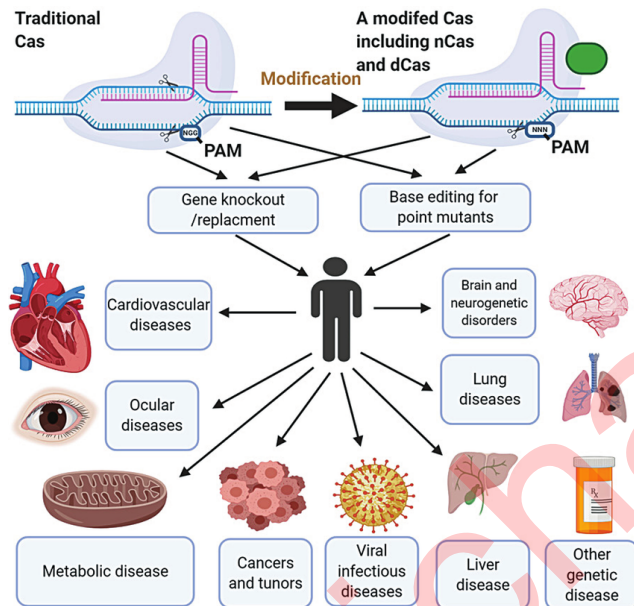
Bioelectric media
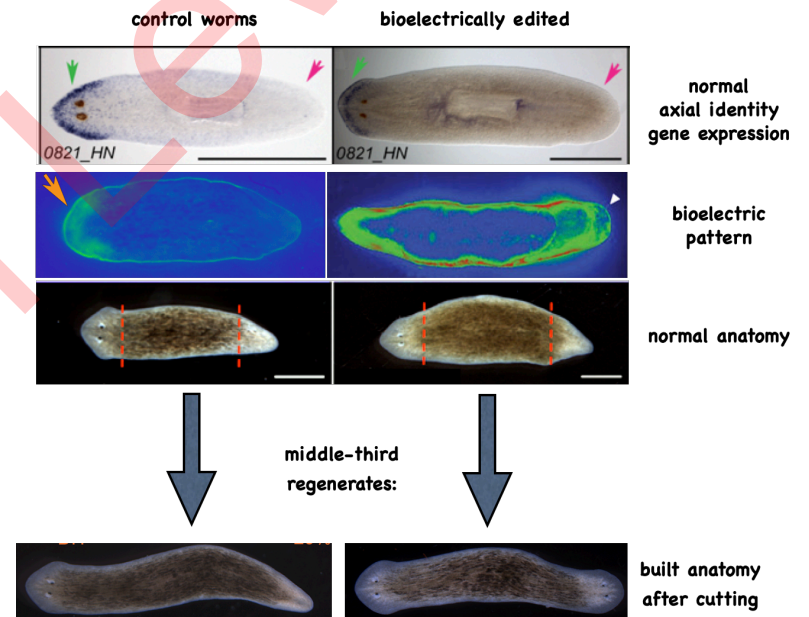
- Show a history for the specificity
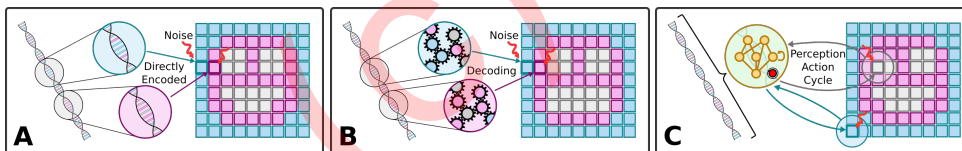
REVIEW

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

Michael Levin[1,2]

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,*]

Patterns Come From Genetics, Environment, and ??

$z = z^3 + 7$

Figure 16   Figure 17

https://thoughtforms.life/halleys-method-fractal-art/
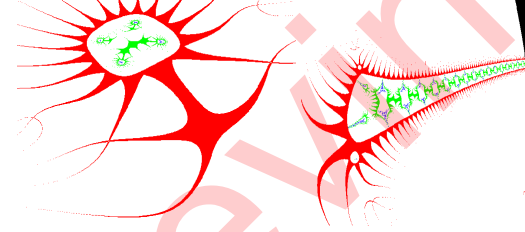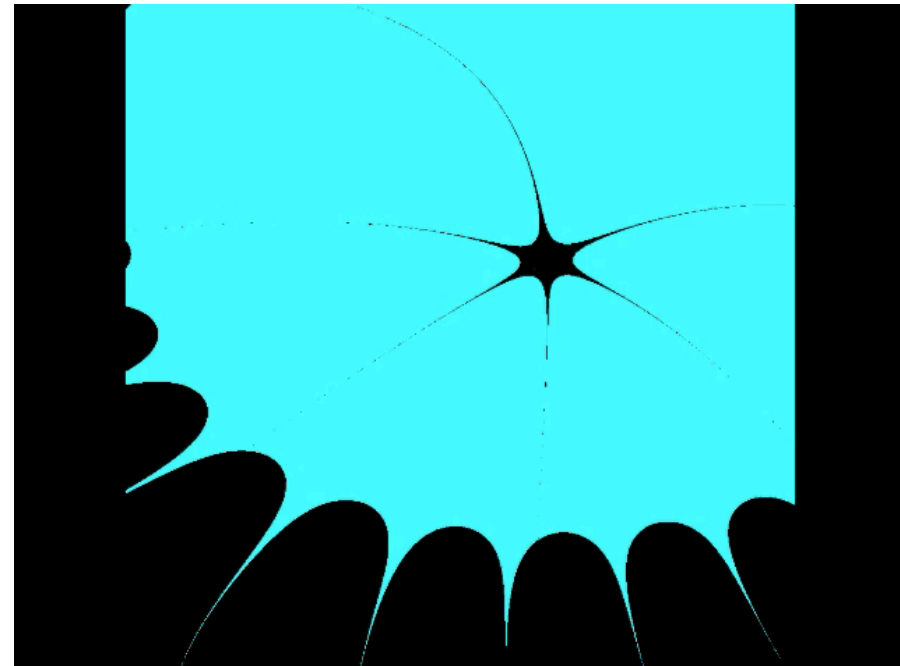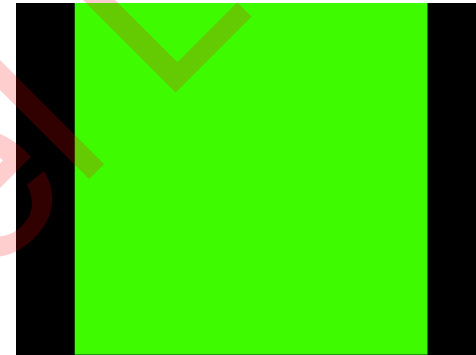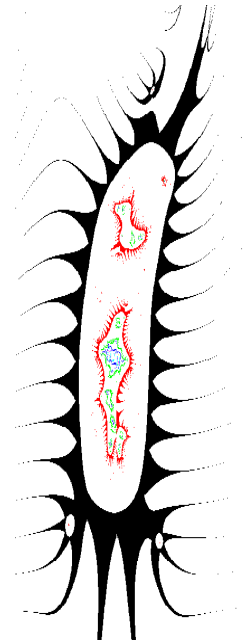
What aspect of physics or history is responsible?

Prediction: can we find novel living
forms with no history?

Rebooting Multicellularity: Xenobots
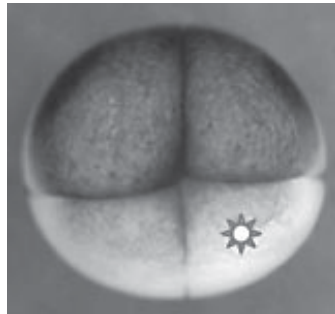
Early frog
embryo

8 hours
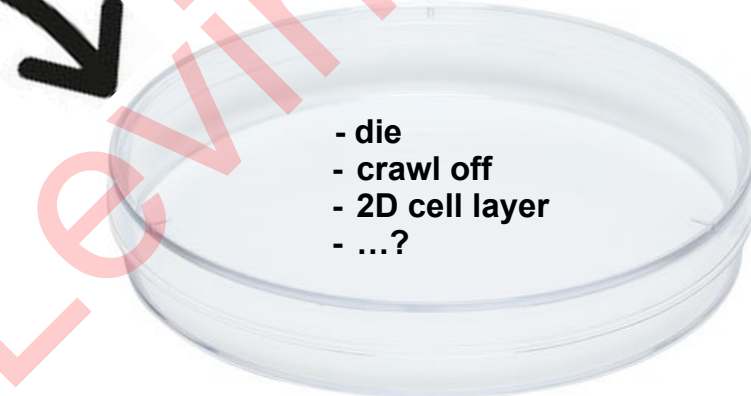
- die
- crawl off
- 2D cell layer
- …?

assay for form
and function

Douglas Blackiston
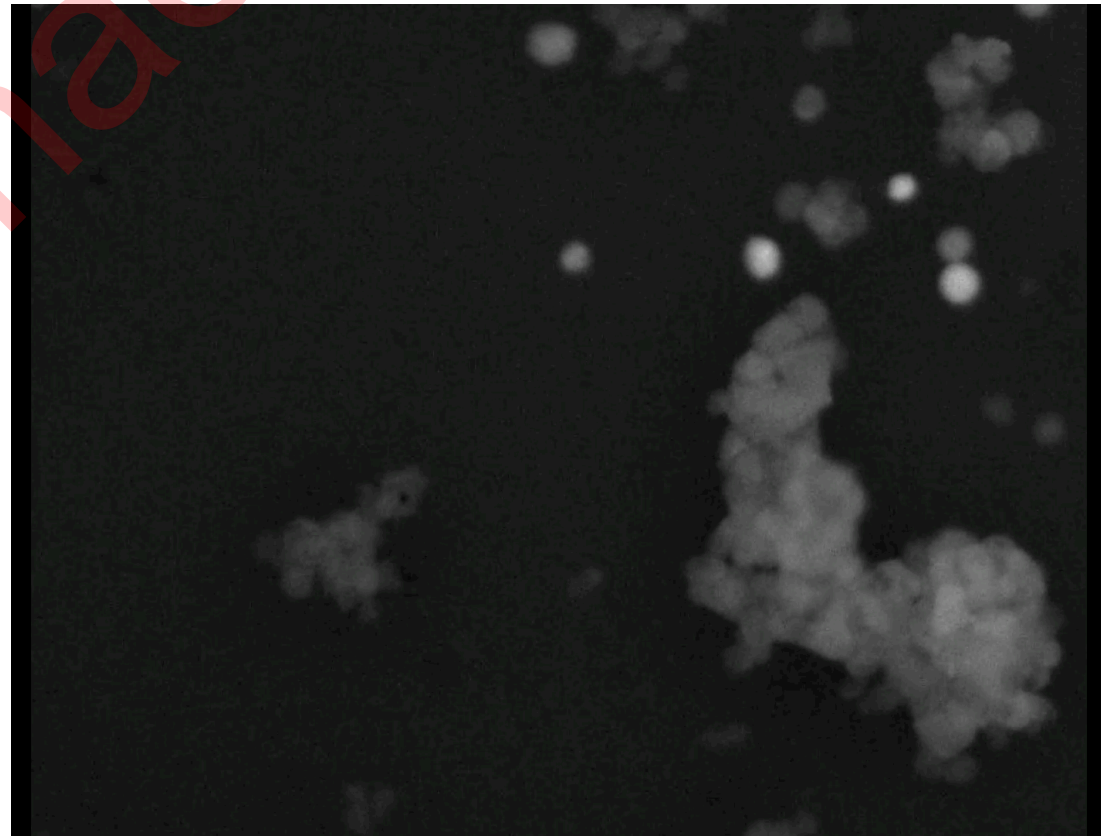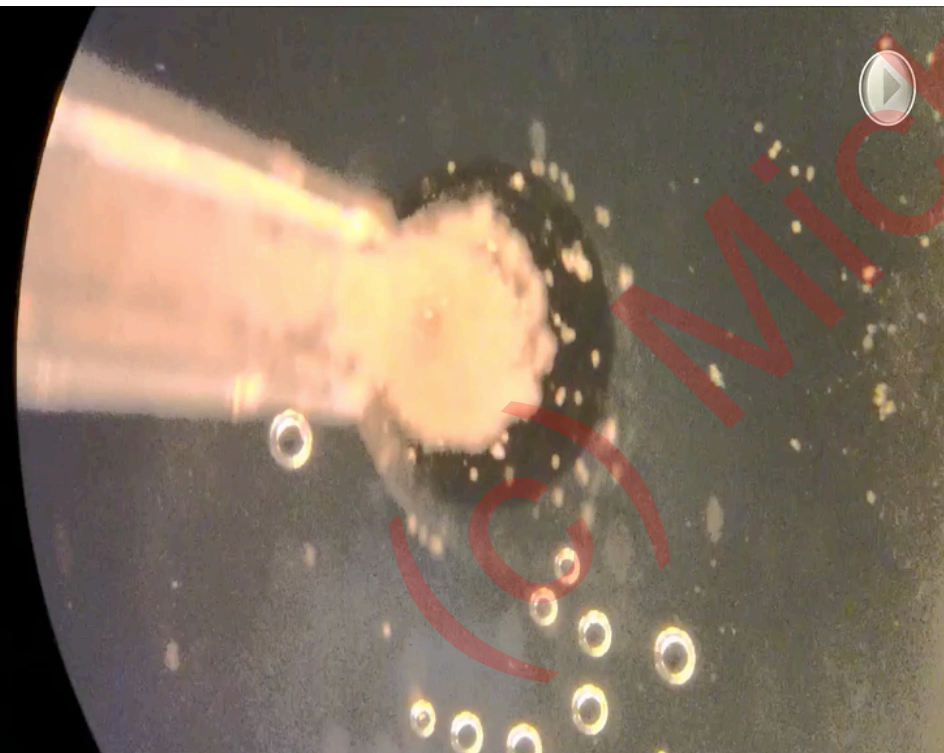
Xenobot behaviors - repurposing cilia for motion
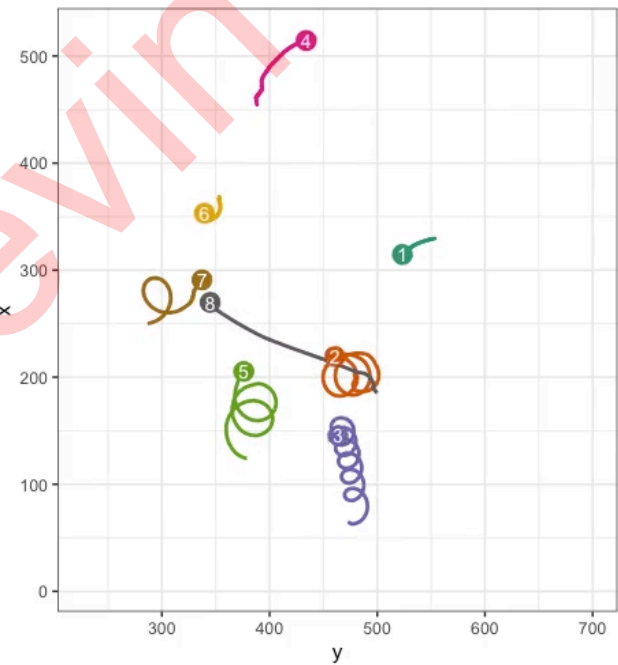
collective behaviors

Douglas Blackiston

Reading the Xenobot mind: calcium spiking in skin cells — there are no neurons here
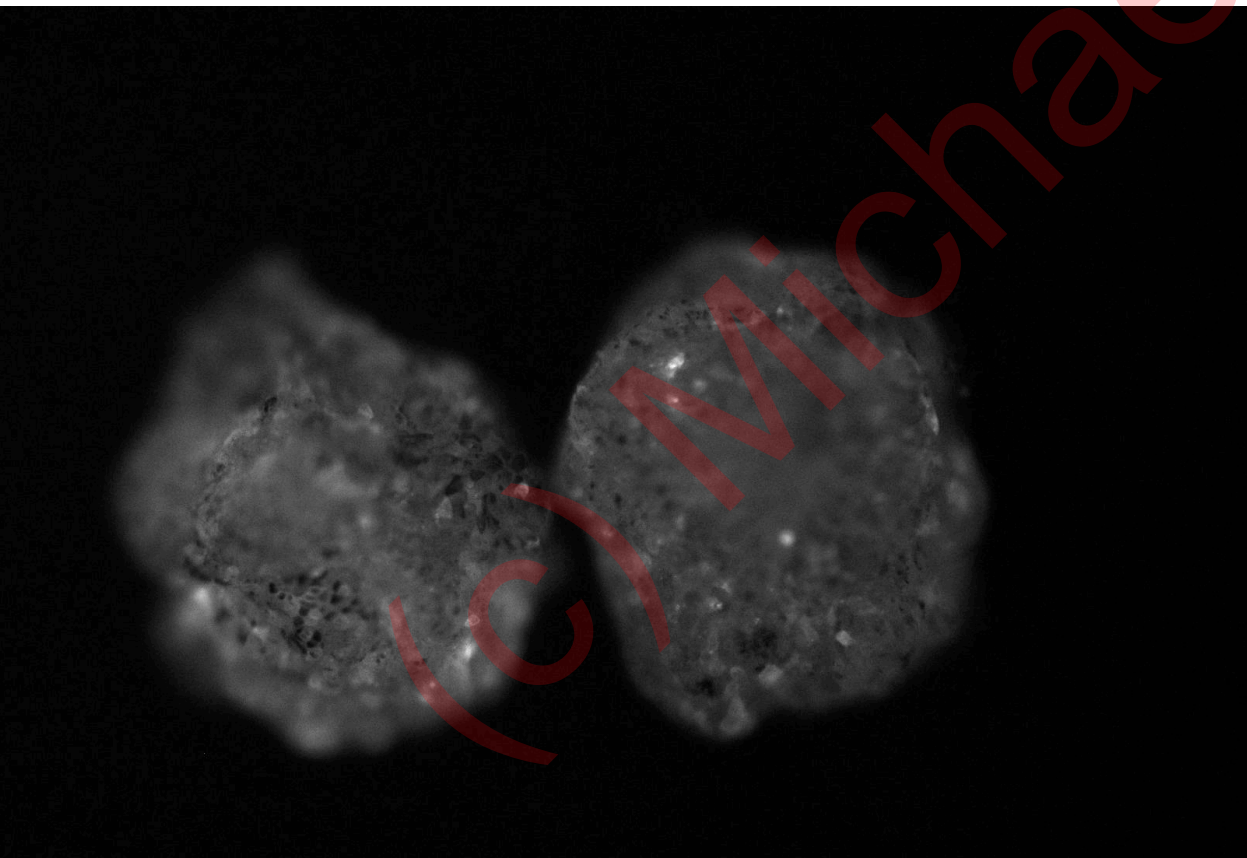
Kinematic Replication in Xenobots:
novel competencies of the agential material
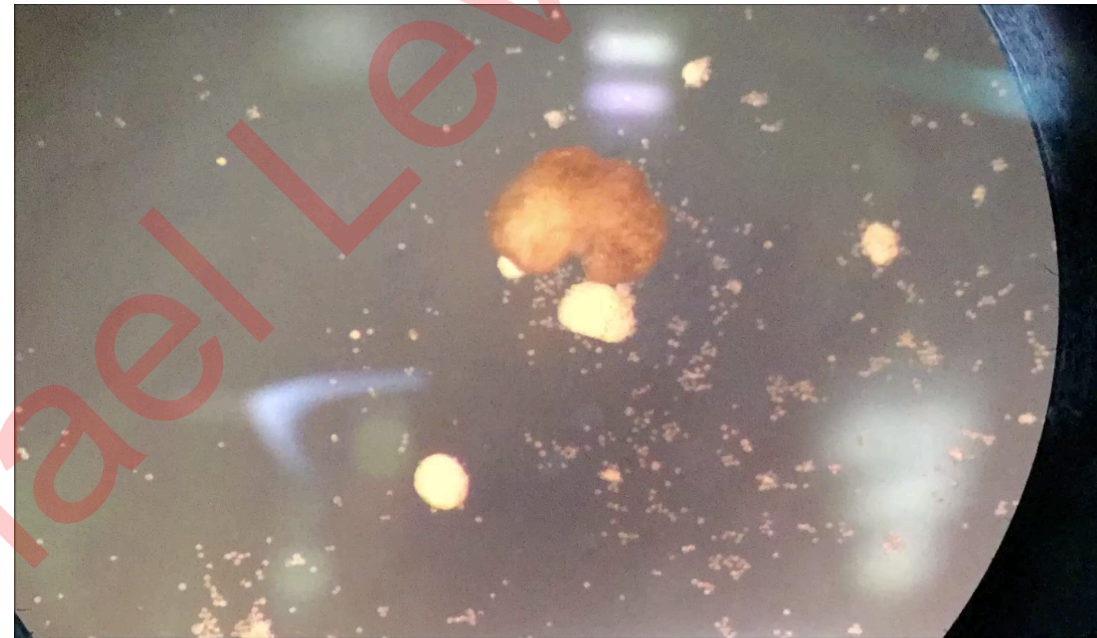
Douglas Blackiston
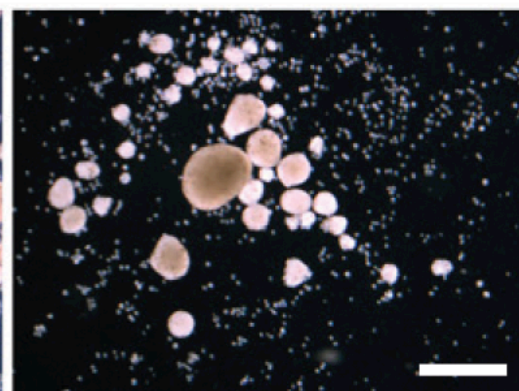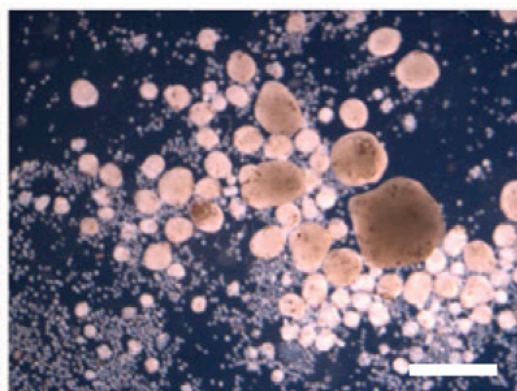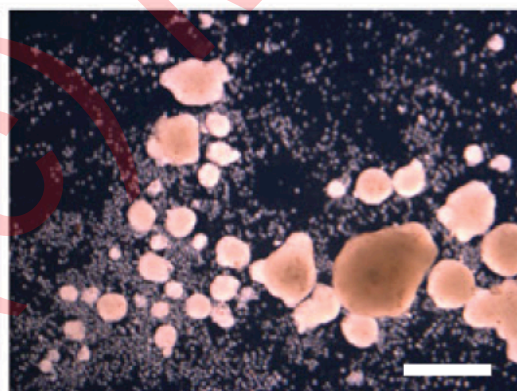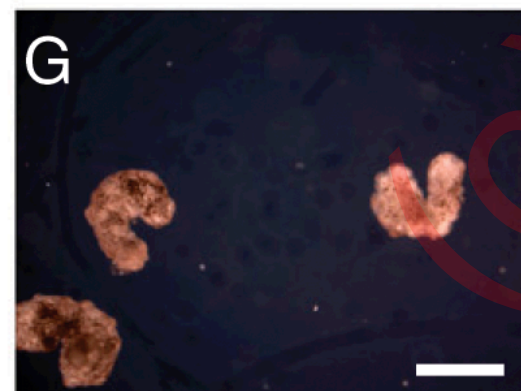
Interfacing with Xenobots via Sound:
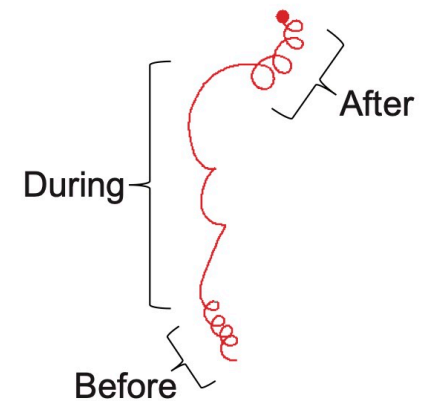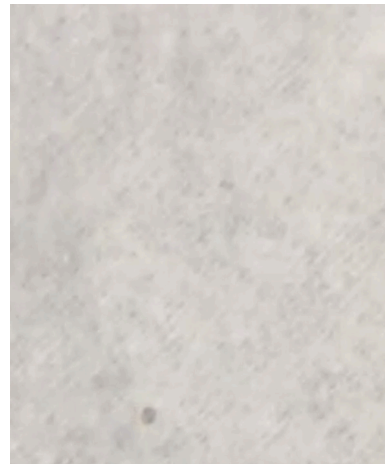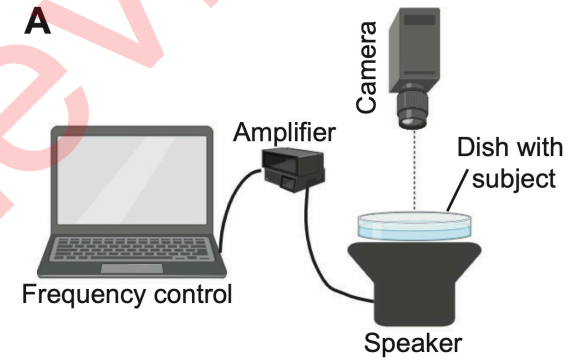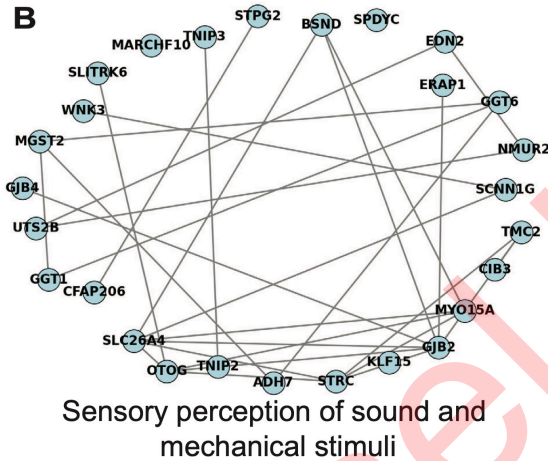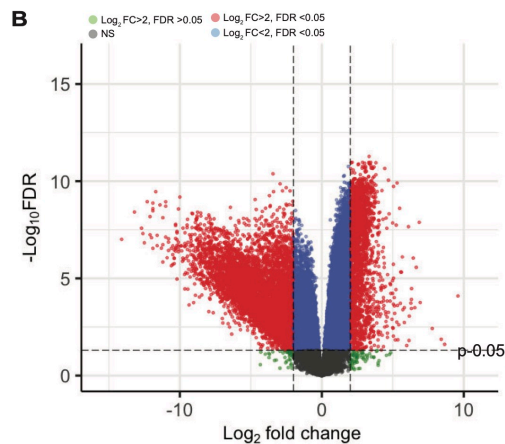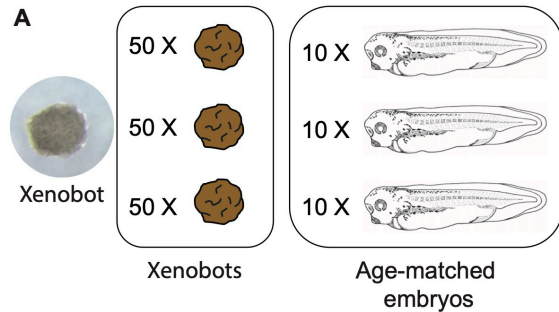
Basal Xenobot transcriptomics reveals changes and novel control modality in cells freed from organismal influence

🔲 Check for updates
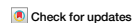
Vaibhav P. Pai ⑩ [1], Léo Pio-Lopez[1], Megan M. Sperry[1,2], Patrick Erickson ⑩ [1], Parande Tayyebi ⑩ [1] & Michael Levin ⑩ [1,2] ✉

Vaibhav Pai

What Lies Beyond Repair of Normal Target Morphology?
Meet the Anthrobots:

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

Super-bot cluster

Human neurons

Neural wound

Human neurons
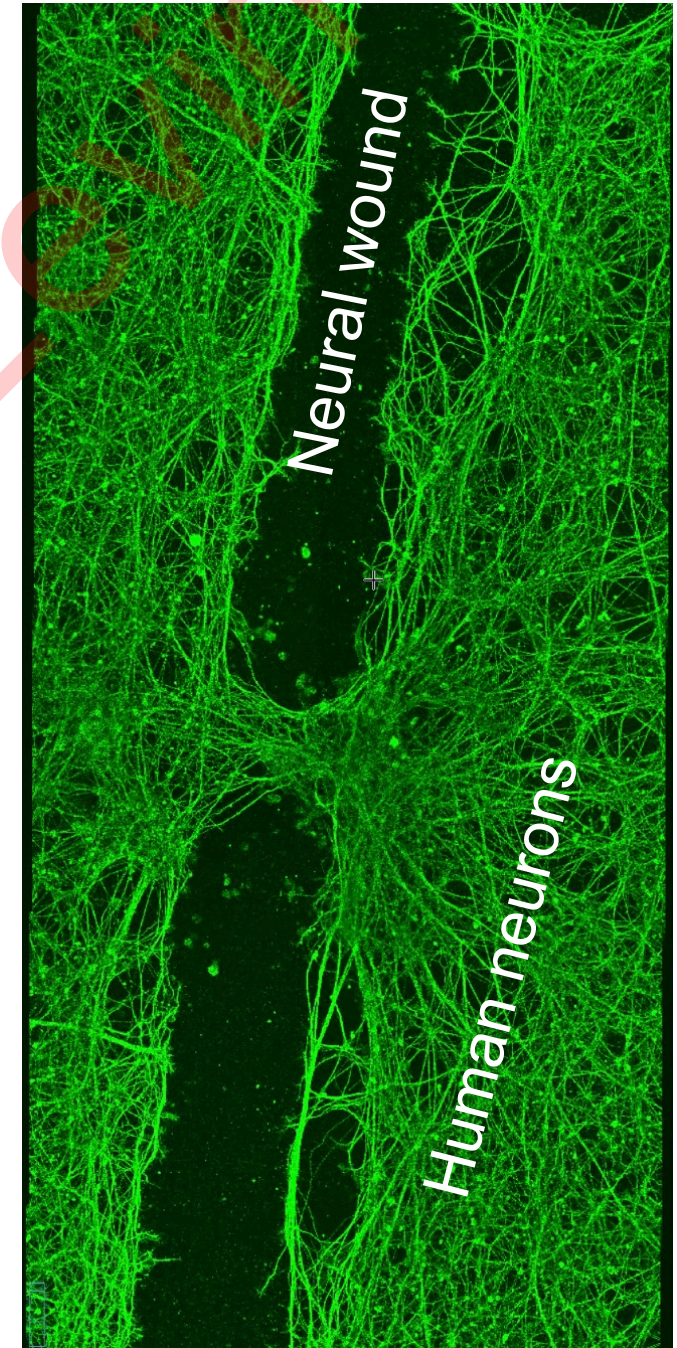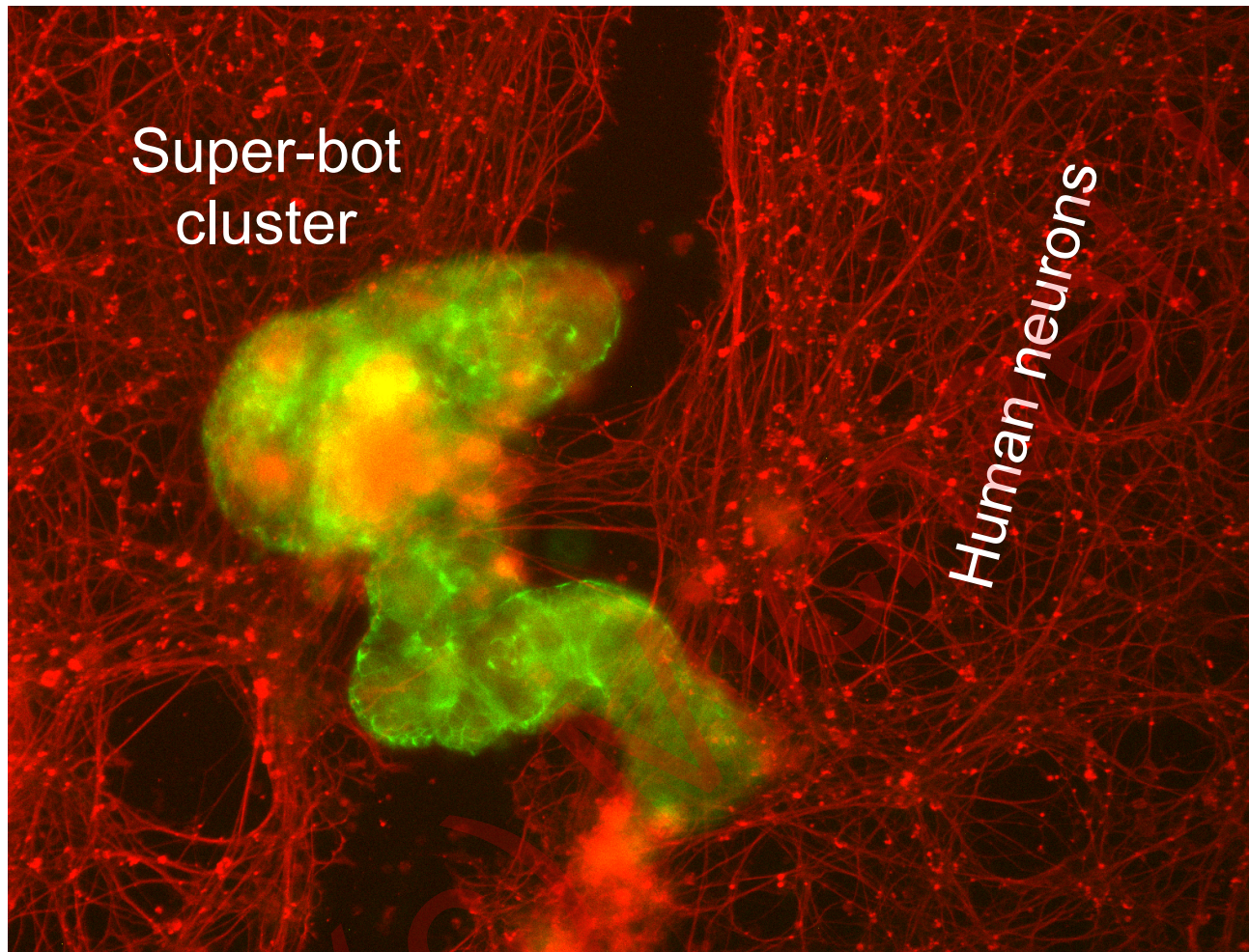
Gizem Gumuskaya

No Selection History Predicts Anthrobots' Form and Behavior:

drastically
remodeled
transcriptome
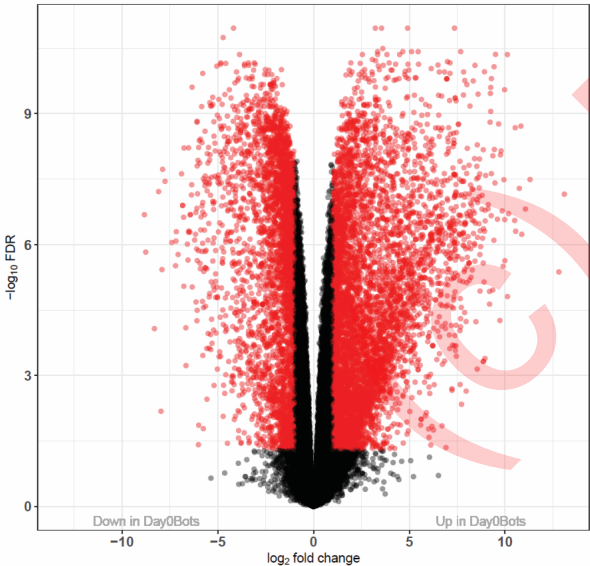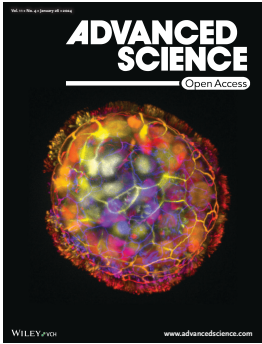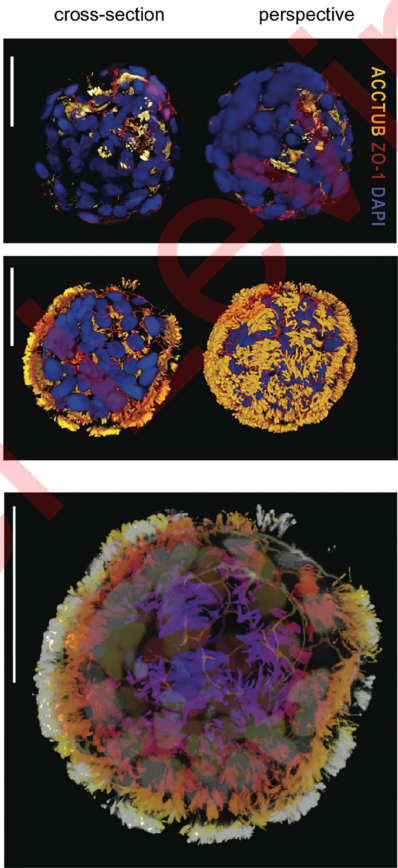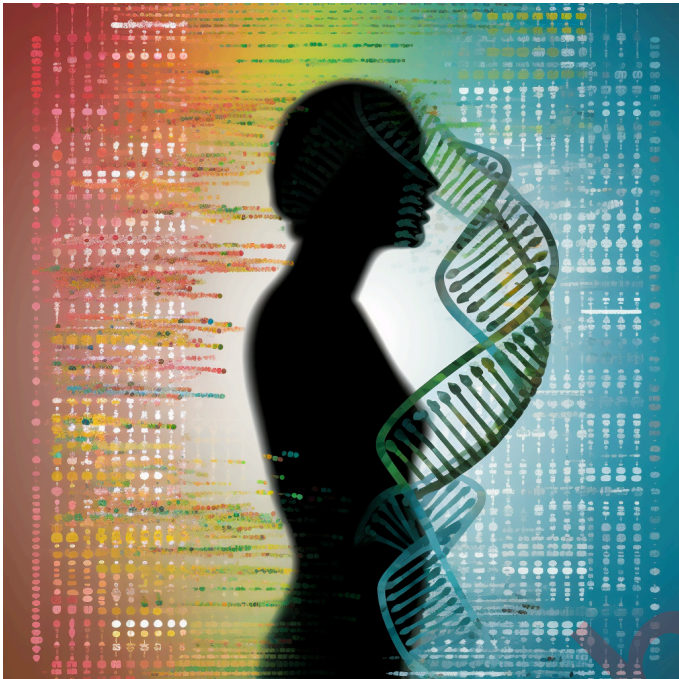
Ethogram of discrete behaviors
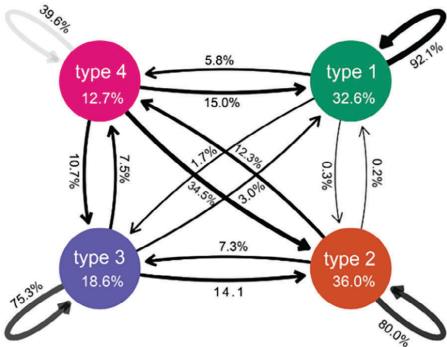
Gizem Gumuskaya,
Nik Davey

What did the Genome Learn?

Xenopus laevis genome
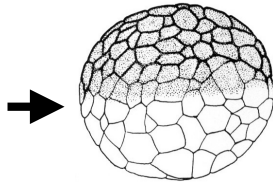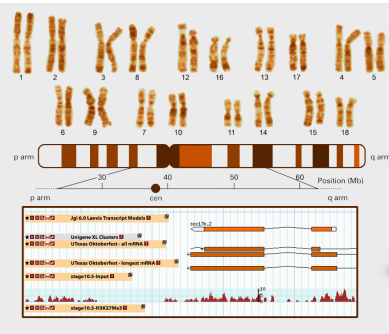
Path A: embryos
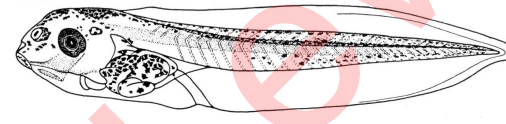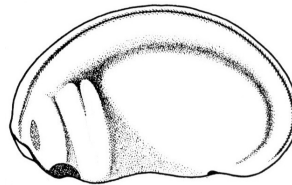
Douglas Blackiston

Path B: Xenobots

Developmental Time

Behavior
cognitive capacities TBD

- Xenobot bodies and minds have no straightforward evolutionary back story; some of it happened in a virtual world at the Bongard Lab's supercomputer. **Where did their goals come from**?

- Xenobots were engineered by releasing constraints, not adding circuits; collaboration with the material

- **We know when computation was done to make a frog; when was it done for Xenobots/ Anthrobots?**

Emergent Goals and Competencies:
it doesn't take much!!
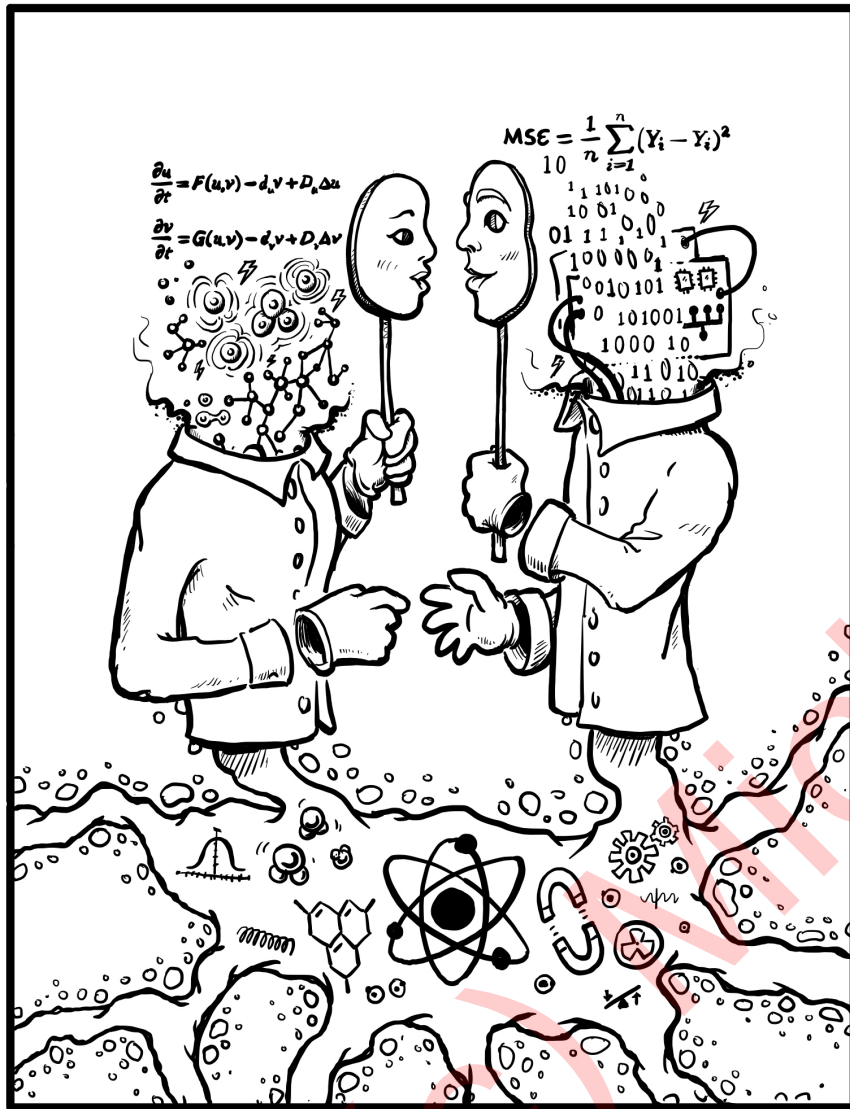
It does not take cells, life, or huge complexity to have emergent goals and competencies recognizable by behavioral scientists

We underestimate matter and we underestimate algorithms/"machines"

Algorithm + intrinsic (implicit) behavioral competencies

Algorithm + spontaneous side-quests
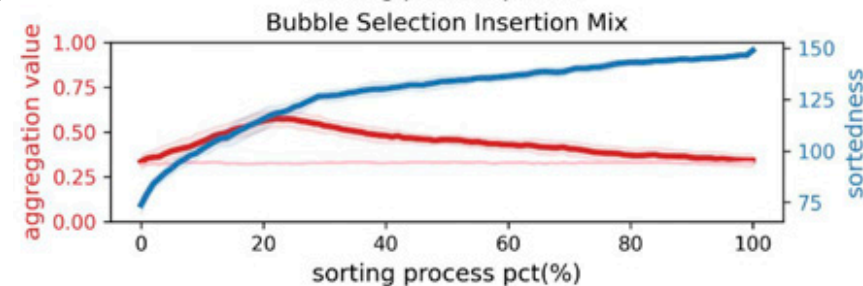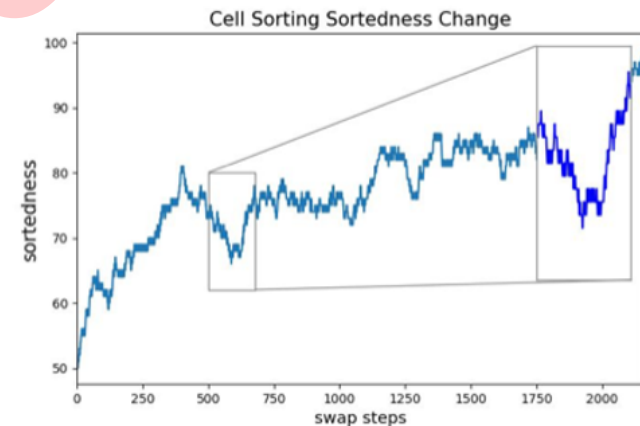
Taining Zhang[1], Adam Goldstein[2] and Michael Levin[1,3]

Taining Zhang, Adam Goldstein

So where do novel goals come from?

Emergence (mysterian surprise) vs.
Structured latent space (research program)

Whence specific goals and competencies if not Selection (history)?!

Evolution exploits free lunches: shapes, behaviors, properties of networks, features of computation, numbers, etc.

Option 1: there is a random set of amazing "facts that hold" and we will call it "emergence" and be surprised each time

Sparse Ontology –> mysterianism

Option 2: there is an ordered, non-physical latent space of patterns which can be studied systematically

Optimism –> research agenda

Synmorpho beings and minimal algorithms as vehicles for exploring Platonic latent space!
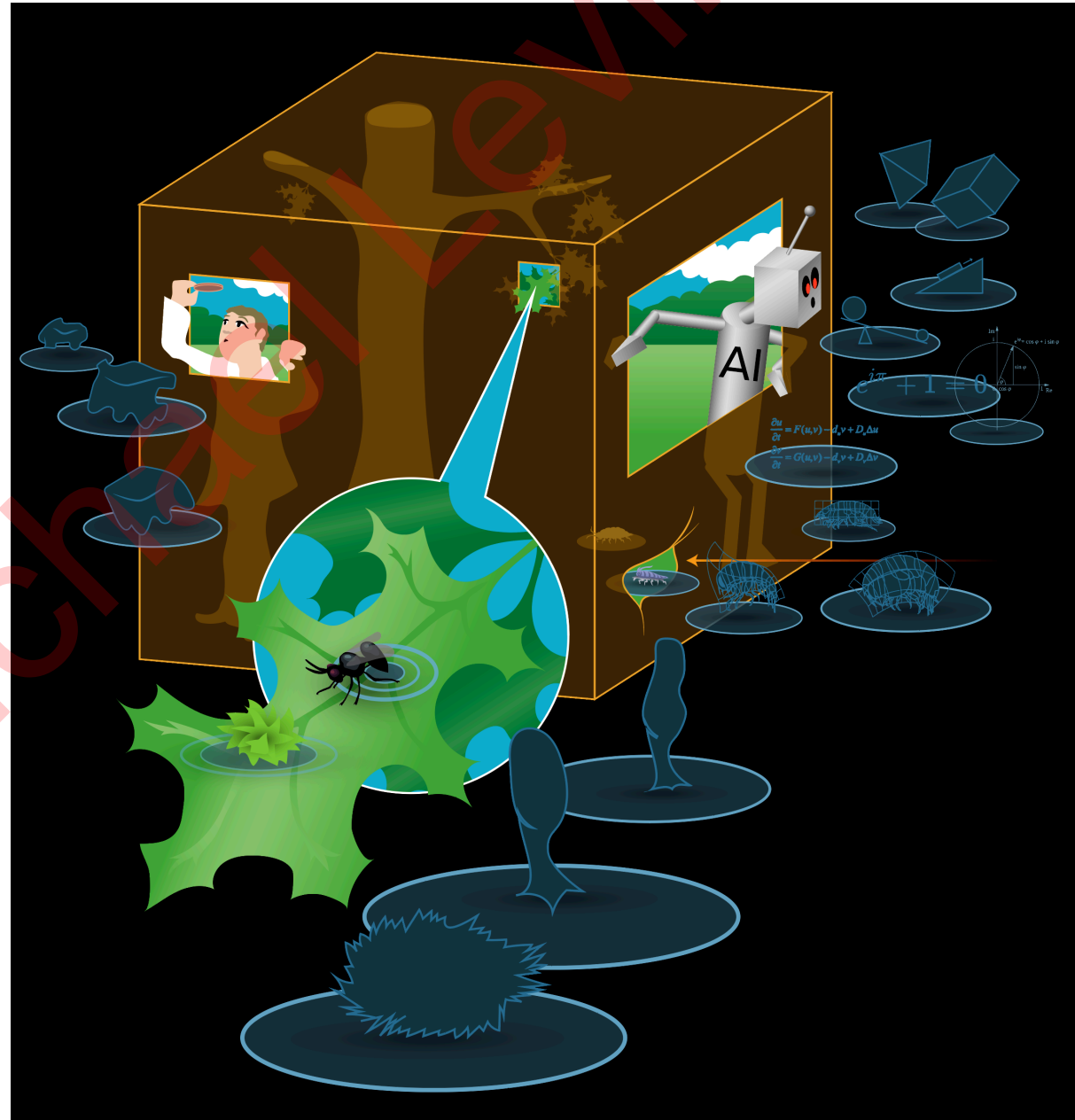
Platonic Latent Space

Karl Popper

Pythagoras

Plato

Popper's World III of Culture
Mental World
Physical World

World 3
Human Concepts, Abstractions, Creations in the Objective World
Theories, books and many other products of the mind

Invention and innovation modifies the physical world to support individual existence within it

Interpretation of the physical world with theories, shared imagination and common expectations

World 1
Physical, Objective World
Matter, energy and their relationships

Signals from physical world enter subjective perception

World 2
Psychological, Cognitive Subjective World
Individual perception and interpretation of World 1

~~Physicalism~~

BEAUTY — The Form of Beauty

BEAUTY — The Concept of Beauty

Individual Beautiful Entities

Imitations of Beautiful Entities (paintings, photos, reflections, shadows)

Platonist Mathematicians: systematically DISCOVER, not invent
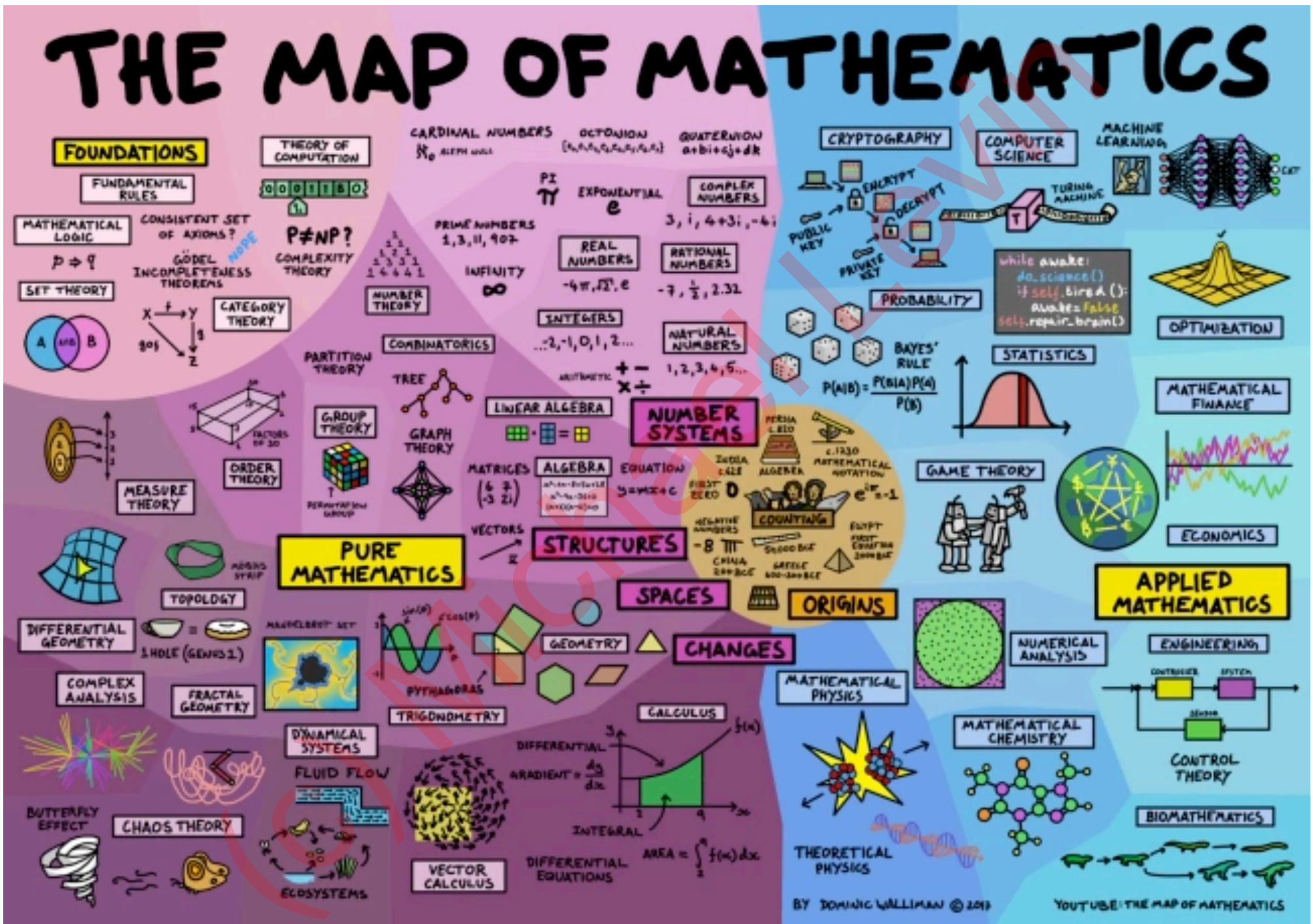
Beyond Low Agency (?) Mathematical Truths - Behavioral Patterns (a.k.a., minds)

Math = the behavioral science of a specific layer of the Platonic Space
(those forms that are amenable to certain classes of precise formal models)

What else inhabits it?
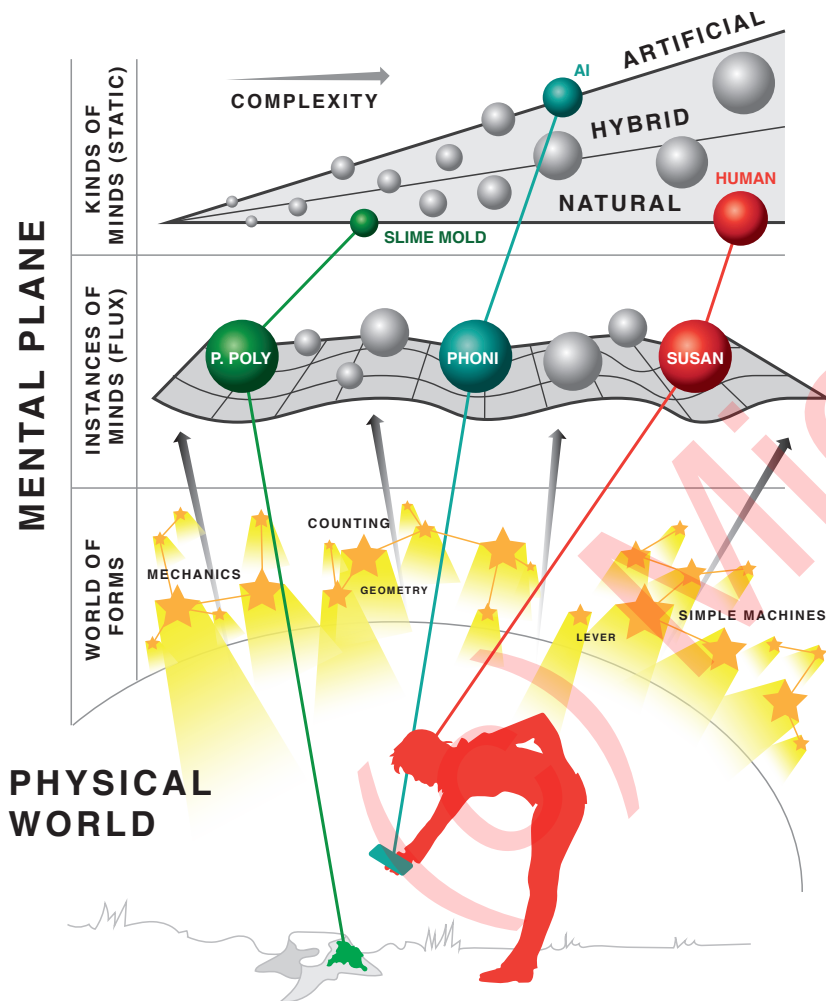
"What breathes fire into the equations?"
Hawking had it backwards
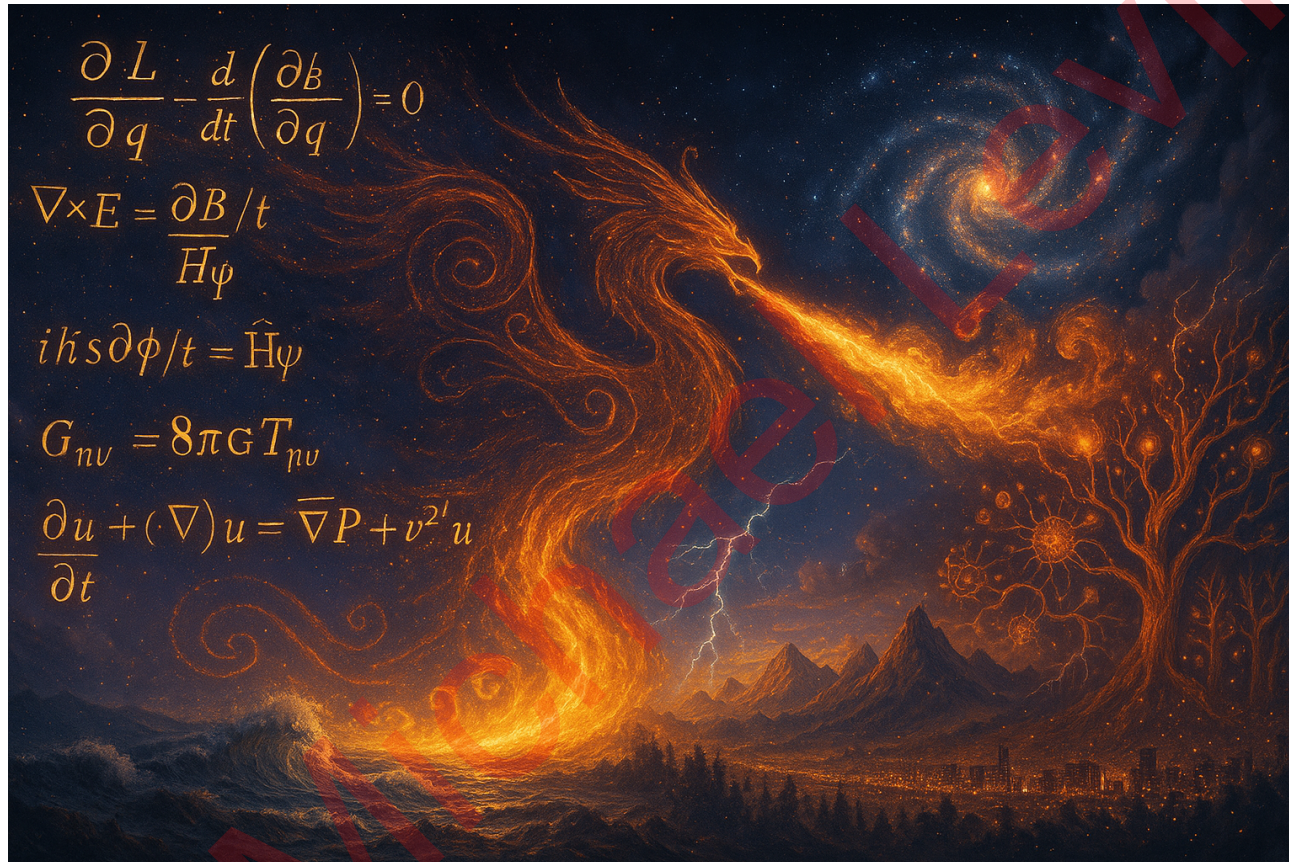
"I think that modern physics has definitely decided in favor of Plato. The smallest units of matter are not physical objects in the ordinary sense; they are forms, ideas which can be expressed unambiguously only in mathematical language."

- Werner Heisenberg

"Biology is the study of the larger organisms, whereas physics is the study of the smaller organisms,"

- Alfred North Whitehead

Causality, Explanations: Math -> Biology

2, 3, 5, 7, 11, 13, 17,...
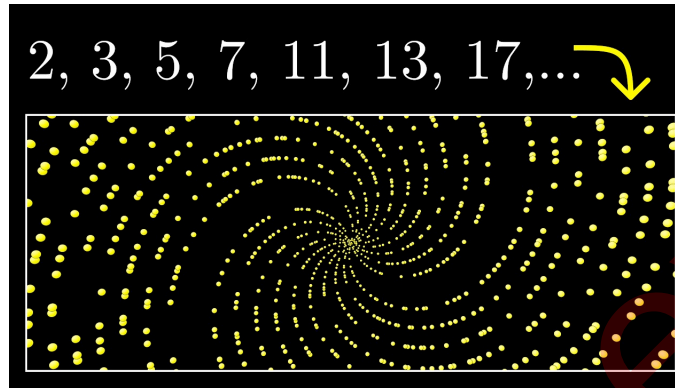
"come from" doesn't mean temporal causality

Biology Exploits Free (Cheap) Lunches
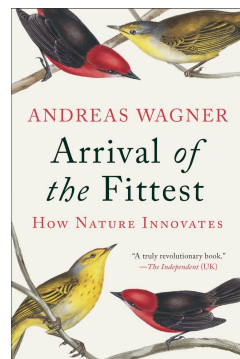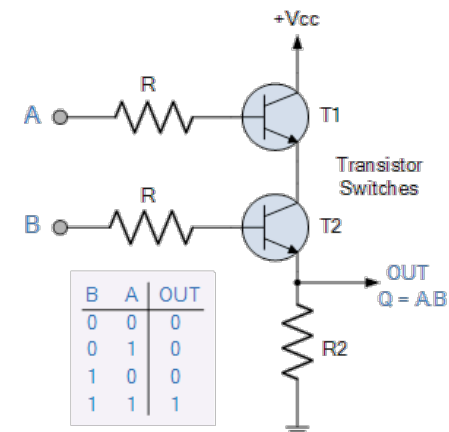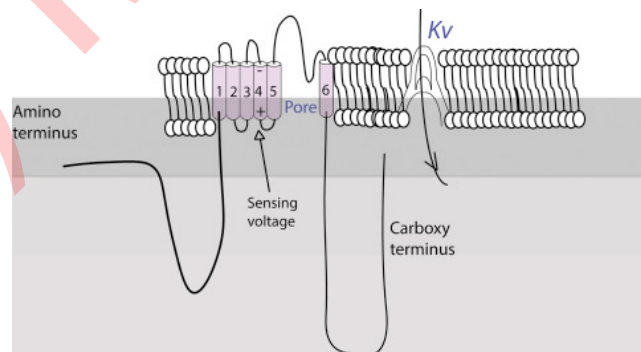
The Brain as Thin Client, Biology as Interface
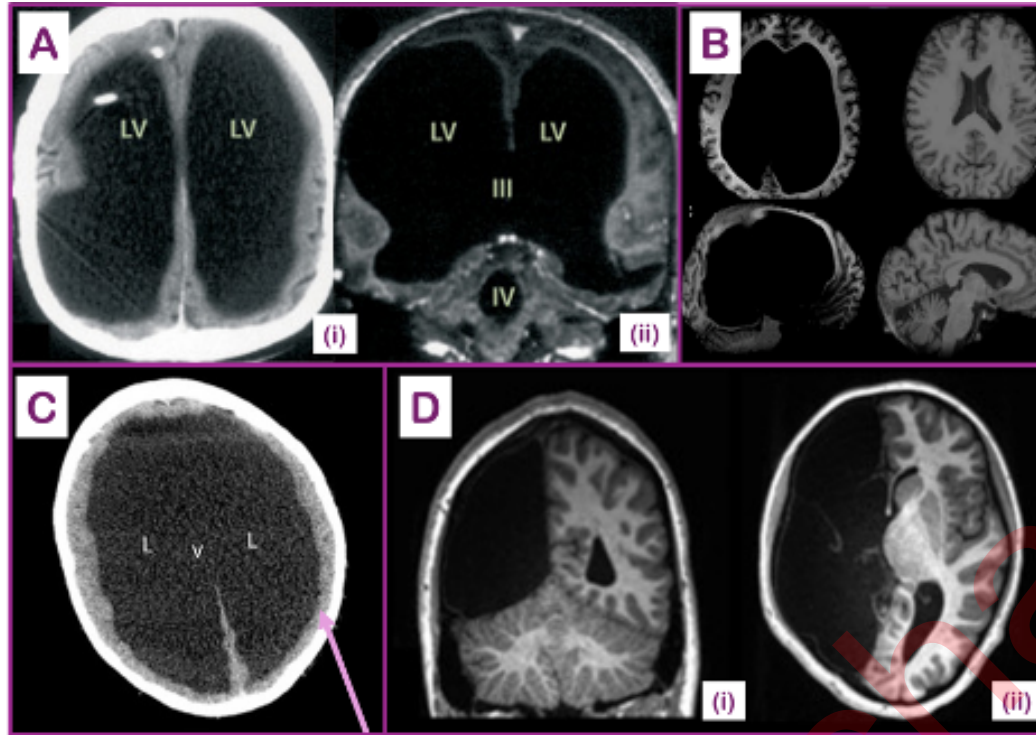
Minimal brain structure

or function (Savant syndrome)

cases of high performance!

Figure 2. <u>Select cases of reductions in brain matter with normal function</u>. **[A]** Image from (Feuillet *et al.* 2007) showing a white collared worker case of extreme hydrocephalus; he led a normal life as a civil servant, who possessed an average IQ of 75. During his neurological assessment at age 44, his (i) CT scan and (ii) T1 weighted MRI scans with contrast showed extreme ventricular enlargement. LV indicates lateral ventricle, III and IV indicate the third and fourth ventricles, respectively. **[B]** Image from (Alders *et al.* 2018), showing the case of a 60-year-old with a bad mood with massive ventriculomegaly and severely reduced cerebral mantle and corpus callosum, that went largely unnoticed. The left column is T1 weighted MRI images taken in the transverse, coronal, and sagittal planes of the patient. The right column represents T1 weighted MRI scans of a healthy control. **[C]** Image from (Persad *et al.* 2021), imaging of a Canadian living a normal, independent life with massive hydrocephaly. MRI scan taken from the axial view (plane parallel to the ground) at the level of the lateral ventricles (arrow points to extremely thin layer of cortical mantle, LV stands for Lateral Ventricle). **[D]** Image from (Asaridou *et al.* 2020), showing the T1 Weighted MRI scans of a child born without left hemisphere (i) taken in the coronal plane, (ii) taken in the axial plane. The child had normal cognitive development and language skills despite hemihydranencephaly of the left hemisphere and near-absence of the corpus callosum. All images re-used with permission.

But isn't Interactionism Dead?

But if the mental state is non-physical, how does it transfer over into the physical world and cause things to happen?

Mental world   **Physical world**
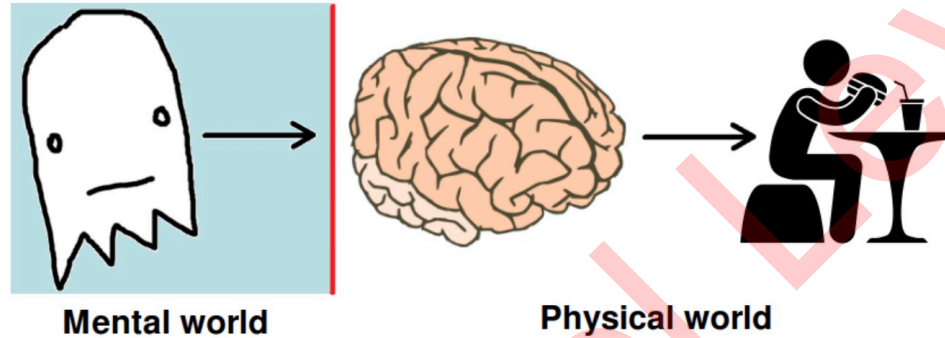
How does the non-physical mental state (left) **cross over into the physical world** (over the red line) and cause changes in my brain and in my behaviour?

https://philosophyalevel.com/aqa-philosophy-revision-notes/dualism/

physicalism was already dead in Newton's universe because it was haunted by the laws of mathematics. No QM needed.

the explanation, the *reason* (driver) for facts of particle physics, and aspects of biology (Cicada timing, On Growth and Form, etc.) are facts of mathematics. Epiphenomenalism is as hopeless for math as for mind.

math :: physics   =   mind::body

Make New Interfaces, Meet New Minds!

YOU ARE HERE

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

1. EVOLVED LIFE FORMS
2. ENGINEERED MACHINES
3. ARTIFICAL INTELLIGENCES (AI)
4. INGRESSING PATTERNS

1. EVOLVED LIFE FORMS

4. MICROBES
11. BIOBOTS
18. CYBORGS
5. PLANTS
12. HYBRIDS
19. TRANSPERSONAL INTERFACE

2. DESIGNED MACHINES

6. ANIMALS
13. SYNTHETIC ORGANISMS
21. ANIMAL SWARMS

3. ARTIFICAL INTELLIGENCES (AI)

7. HUMANS
14. ROBOTS
22. ROBOTIC SWARMS
8. SOFTWARE AGENT
15. REMOTE WALDO
23. SYNTHETIC ORGANISM SWARMS

4. INGRESSING PATTERNS

9. AUTOMATA
16. COMPUTER-DESIGNED ORGANISM
24. PATTERN
18. CYBORGS
17. INSTRUMENTIZED ORGANISM

Humility Warning: neither digital nor biochemical "machines" are only what our formal models say they are

nothing **is** a TM, not even a TM

Magritte

ceci n'est pas une machine de Turing

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

Summary:

- Patterns of form (in 3D space, and in other spaces = behavior) are ubiquitous
- They serve as goals for minimal agents' problem-solving competencies
- Genetics + emergence is insufficient; emergence itself is mysterian and limiting
- Novel forms, which can't be pinned on history of selection, require new models

Hypotheses, Speculations, and Implications:

- Patterns exist which are not determined by history or facts of physics; like facts about mathematical objects.

- Physical objects (simple machines, cells, embryos, cyborgs, swarms, robots, etc.) are pointers into a space of these patterns - interfaces through which non-physical influences ingress into the physical world

- Evolution exploits these free lunches massively, and so can bioengineers! (So, it's not just philosophy - it matters for practical reasons).
  - Physics is what we call things that are *constrained* by these patterns;
  - Biology is what we call things that are *enabled* by and exploit these patterns.

- This magic is not quantum, it already exists in a deterministic, classical world because even Newton's universe was already "in-formed" by truths of mathematics which affect it but are not determined by its properties; embryos are haunted by morphogenetic patterns as triangular objects are haunted by facts of geometry.

- Mind::Brain as Math::Physics.   We *are* patterns in the Platonic Space, along with other denizens. Math = the behavioral science of certain kinds of objects in that space (the low agency ones?).
  - Reasons = your interface is controlled by high-level Patterns; Causes = it's controlled by low-level Patterns; it's all a continuum.
  - "Free Will" = degree to which your current interface (determined by genetics, physics, and *your past history of action*) enables your highest Form to come through un-tarnished by others' or low-level forms

Research Program:

- Build new interfaces to observe new ingressing forms - our synthetic morphology work provides tools/vehicles/periscopes for exploration of the space.

- Infer a rigorous mapping between properties of the pointers and the patterns they facilitate.

- Quantify the "free lunch" aspects - how much information/influence/ evolvability is injected into the physical world? Free compute?

- Are the contents of this space under positive pressure?

- Is the space sparse? Are some attractors "better" than others?

- Are the contents of this space purely passive (eternal, unchanging) or can we define a kind of "chemistry" of how these things interact and live in their own space?

- Are mathematical objects really "low agency"? Can we extend standard behaviorist tests to their native space?

- Why? Where did the Platonic Space and its structure/contents 'come from'? Could it have been otherwise?

Thank you to:

Post-docs and staff scientists in the Levin lab:
Wesley Clawson - hybrots and virtual worlds for biological controllers
Douglas Blackiston - brain-body interface plasticity, Xenobot form and function
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Nestor Oviedo, Junji Morokuma - bioelectrics of planarian regeneration
Federico Pigozzi - causal emergence in non-neural substrates

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Adam Goldstein, Taining Zhang - emergent competencies of algorithms

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Pranjal Srivastava, Ben G. Cooper, Hannah Lesser, Ben Semegran - Anthrobots
Karina Kofman - anomalies in brain:body mapping

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Erin Switzer - vertebrate animal husbandry

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Simon Garnier - computational analysis of Anthrobot form and function
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Erik Hoel - theory of causal emergence
David Resnik, Lauren Ross - philosophy of causation and biology
Richard Watson - computational models of cognitive scaling and evolutionary learning
Giovanni Pezzulo - cognitive science applied to morphogenesis
Anil Seth, Robert Chis-Ciure, Blaise Aguierra y Arcas - consciousness in novel substrates
Olaf Sporns, Sara I. Walker, Thomas F. Varley, Hannah Dromiack, Caitlin Grasso,
    Douglas Moore, Krishna Srinivasan - Ca^{++} neuroscience-relevant infometrics
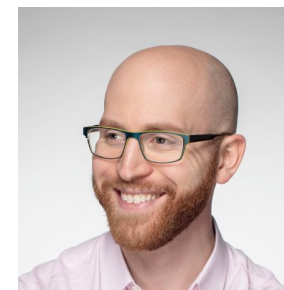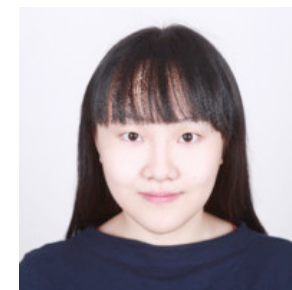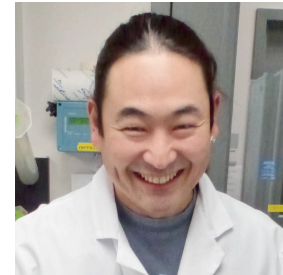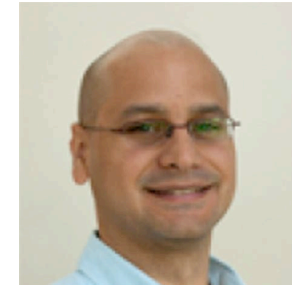
Model systems: tadpoles, planaria, zebrafish, slime molds, human cells, and chick embryos, animats

Illustrations: Jeremy Guay @ Peregrine Creative

Not claiming that the people listed here endorse my non-physicalist model!

Disclosures: Morphoceuticals, Fauna Systems, Astonishing Labs