"Ingressing Minds: Causal Patterns Beyond Genetics and Environment in Natural, Synthetic, and Hybrid Embodiments"

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Abstract:

How best to explain the properties and capabilities of embodied minds? The conventional paradigm holds that living beings are to be understood as the sculpted products of genetics and environment, which determine form and function of the brain as the unique seat of intelligence. Some provision is made for emergence and complexity, as additional "facts that hold" about networks, circuits, and other components of life. Here, I present a sketch of a framework and research roadmap that differs from this view in key aspects. First, the evolutionary conservation of mechanisms and functionality indicate fundamental symmetries between the self-construction of bodies and of minds, revealing a much broader view of diverse intelligence across the agential material of life beyond neural substrates. Second, surprising competencies (not just complexity or unpredictability) in systems that have not had a history of selection for those abilities suggest an additional input into patterns of body and mind that motivates a research program on a latent space of patterns ingressing into the physical world. Emphasizing the principles of continuity and pragmatism, and using morphogenesis as a tractable model system in which to develop these ideas, I explore the implications of the following ideas: (A) Evolution favors living forms that exploit powerful truths of mathematics and computation as affordances, which contribute as causes of morphological and behavioral features. (B) Cognitive patterns are an evolutionary pivot of the collective intelligence of cells; given this symmetry between neuroscience and developmental biology, I propose that the relationship between mind and brain is the same as the relationship between mathematical patterns and the morphogenetic outcomes they guide. (C) Many mathematicians, and a non-mysterian approach to science in general, suggest that these patterns are not random facts to be merely cataloged as "emergence" when found, but rather can be systematically discovered within a structured, ordered (non-physical) space. Therefore, I hypothesize that: (1) instances of embodied cognition likewise ingress from a Platonic space, which contains not only low-agency patterns like facts about triangles and prime numbers, but also higher agency ones such as kinds of minds; (2) we take seriously for developmental, synthetic, and behavioral biology the kinds of non-physicalist ideas that are already a staple of Platonist mathematics; (3) what evolution (and bioengineering, and possibly AI) produces are pointers into that Platonic space – physical interfaces that enable the ingression of specific patterns of body and mind. This provides a new perspective on the organicist/mechanist debate by explaining why traditional computationalist views of life and mind are insufficient, while at the same time erasing artificial distinctions between life and machine, since both are in-formed by diverse patterns from the latent space. I sketch a research program, already begun, of using the tools of the fields of synthetic morphology and diverse intelligence to map out key regions of the Platonic space. Understanding the mapping between the architecture of physical embodiments and the patterns to which they point has massive implications for evolutionary biology, regenerative medicine, AI, and the ethics of synthbiosis with the forthcoming immense diversity of morally important beings.

1. Introduction

> “The fact is that certain ideas exist almost everywhere and at all times and can even spontaneously create themselves quite independently of migration and tradition.”
>
> -Carl Jung

Most of the big questions of philosophy are raised by the process of embryogenesis. Right in front of our eyes, a single cell (such as a frog egg) multiplies and self-assembles into a complex organism, with order on every scale of organization and adaptive behavior. Each of us takes the same journey across the Cartesian Cut, starting off as a quiescent human oocyte, a little blob thought to be well-described by chemistry and physics. Gradually, it undergoes metamorphosis and eventually becomes a mature human with hopes, dreams, and a self-reflective metacognition that can enable it to say things like that it is not a machine – that it is more than its brain and body and their molecular mechanisms [1].

How did that transformation happen? How did protoplasm move from the domain of chemistry and physics to that of behavior science and psychoanalysis? It happens on two scales – not only in our personal embryogenesis but also during evolution – back in our ancient past, all of us were unicellular. One key lesson of both ontogeny and phylogeny is that they happen slowly and continuously: neither developmental nor evolutionary biology offers any sharp place – a bright line where cognition suddenly snaps in. Whatever properties and capacities we have emerge gradually and scale up from far more basic competencies. Thus, the understanding we seek of our origins must come in the form of scientific stories of transformation.

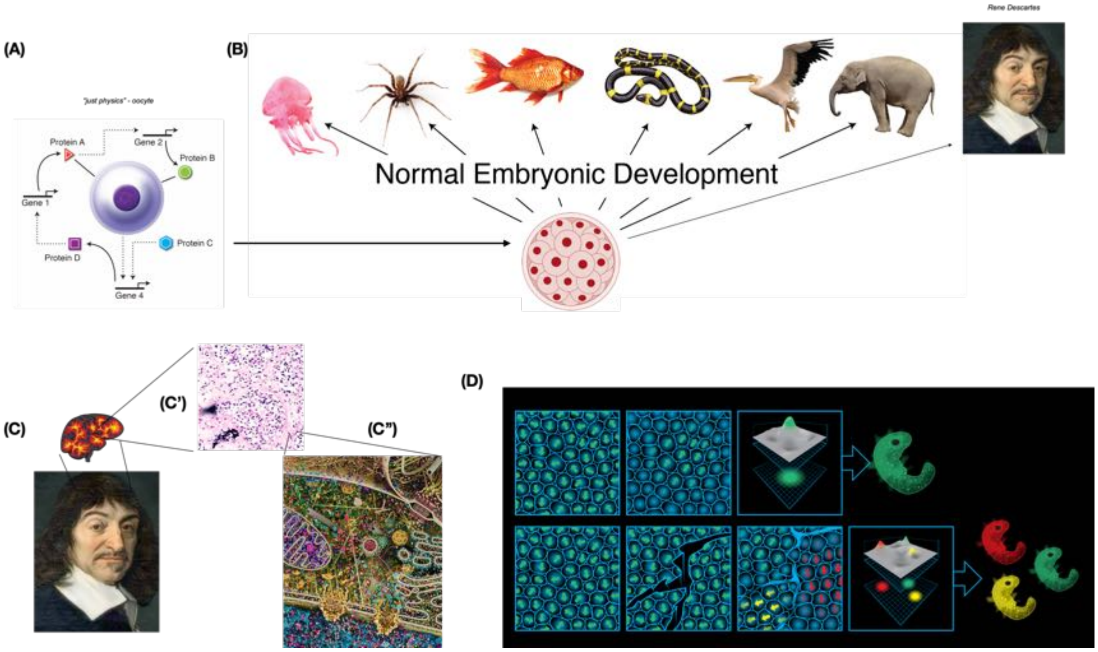

Figure 1: bodies and minds self-assemble from single cells as a process of alignment and autopoiesis. (A) Most complex biological forms begin as one cell – a fertilized oocyte, commonly thought to be well-described by the laws of physics and chemistry. A gradual, slow process of developmental

morphogenesis results in the final form of the organism, which may have complex structure and a mind which may not believe it is a "machine". Our transformation from a chemical soup into an active embodied mind is continuous but heterogeneous: (C) while we commonly think of ourselves as a unified intelligence with a "centralized" brain, the fact is that even the pineal gland, of which there is only one in the brain, is made of cells (C') and those cells in turn are made of a myriad other active components (C") – we are a collective intelligence at all scales. (D) The creation of an "individual" out of an excitable medium such as an embryonic blastoderm with hundreds of thousands of cells is a dynamic process that is not hardwired: scratches made in that blastoderm would result in independent self-organization in each island, resulting in multiple embryos forming. This reveals the potentiality for some not pre-determined number of minds to arise out of the same substrate. Images in A,D courtesy of Jeremy Guay of Peregrine Creative. Image in C' courtesy of Jose Calvo, Science Photo Library. Image in C" courtesy of Evan Ingersoll and Gaël McGill.

The second lesson we learn from embryogenesis is that all intelligence is collective intelligence (Figure 1). We are all made of parts – not just ant and bee colonies' swarm intelligence [2-4] but all of us. We are collections of competent parts (molecular networks, cells, tissues) which work together to implement an emergent higher-order mind with goals, preferences, and competencies that none of its parts have [5]. This is as true of the collective of neurons that enables our cognition as it is of the cells that build the body itself [6, 7]; Turing understood this well, in his interest in both diverse embodiments of mind across substrates [8] and in the origin of chemical order during embryogenesis [9]. The story of the self-assembly of the body and its emergence from a formless chemical chaos shares a deep symmetry with the emergence of minds from a mindless void [10, 11].

The striking result of autopoiesis [12-15] is complex structure and function. All the components of the collective intelligence of neurons and other cells are aligned to common purpose in the sense that they create a consistent *pattern* – of thought/behavior and form/function respectively. These patterns – coherent, adaptive, meaningful regularities distributed and causally linked across space and time – are the hallmark of emergent self-organization of life and mind. Crucially, these patterns are not just fodder for philosophical studies or natural history. Understanding them and learning to manipulate them is the gateway to transformative, definitive regenerative medicine of the future [16], and a rate-limiting step toward the development of an ethical synthbiosis with the plethora of novel hybrid and artificial beings with whom we will share our world [17, 18]. Understanding the origin of the patterns that emerge as minds become embodied in the physical universe is an essential step to deciding what our species' future should look like and knowing how to support the flourishing of sentient life on our planet and beyond.

Here, I discuss an unconventional research program into the origin of these patterns. I argue that genetics and environment are not sufficient to explain or make use of the remarkable intelligence of the agential material of life. I argue that the current reliance on emergence is a mysterian approach that limits progress, and instead propose a systematic investigation of the patterns of life and mind that ingress into both biological and synthetic embodiments. In short, I make the metaphysical hypothesis that the emergent patterns we observe are not random but are part of an ordered Platonic space of forms[1] which have a causal influence on the outcomes of evolution and engineering. I make no effort to hew close to the specific views of Plato, Pythagoras, Whitehead, or others who have supported related positions in the past [19], but focus on those aspects of the idea of non-physical forms that seem the most helpful for driving forward advances in research. To put all the metaphysical cards on the table, the background assumption here is that ideas are to be judged by their success in helping us engage with the physical world – I focus on forward-looking fecundity of research programs (discoveries of novel phenomena, reaching new capabilities, etc.) over philosophical precommitments such as physicalism or reductionism as requirements for good explanations. Using examples from state-of-the-art biology and related disciplines, I argue that as much as many working biologists would prefer a minimal, sparse, materialist model, progress in a number of fields requires something quite different.

2. Patterns in biology and medicine

> "The artist is … one who allows art to realize its purposes through him."
>
> – Carl Jung

A foundational aspect of the living world is the *patterns* that life takes. These patterns (Figure 2) include the stereotypical spatial arrangement of animal bodies (and of organ-level structures in plants), the order seen at every scale (from molecular components to whole swarms of animals), and the types of symmetry. It also includes scale-invariant patterns that seem to occur at different levels of organizations (see for example [20, 21]) Of course there are temporal patterns to, which we call physiology or behavior [22-24], depending on the scale on which they occur. While these patterns are invariant and highly conspicuous, it's important to keep in mind that they are in general observer-dependent – regularities across space and time must be observed/detected/inferred by an observer (i.e., an IQ test that challenges the scientist, predator, parasite, or other hacker to optimally "carve nature at its joints"). Symmetry is likewise dependent on what remains "unchanged" after an operation such as reflection across an axis, which is dependent on the observer's ability to detect various kinds of change.

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[1] I make no claims here about what Plato, Whitehead, or others actually thought about these complex issues, nor attempt to frame this view to be congruent with any specific prior theory. My use of Platonic space, ingressions, and similar terms is simply to avoid proliferation of vocabulary and anchor these unconventional ideas in terms that are somewhat familiar. It is entirely possible that subsequent iterations of this framework will need new terminology where it diverges significantly from the views of prior thinkers.

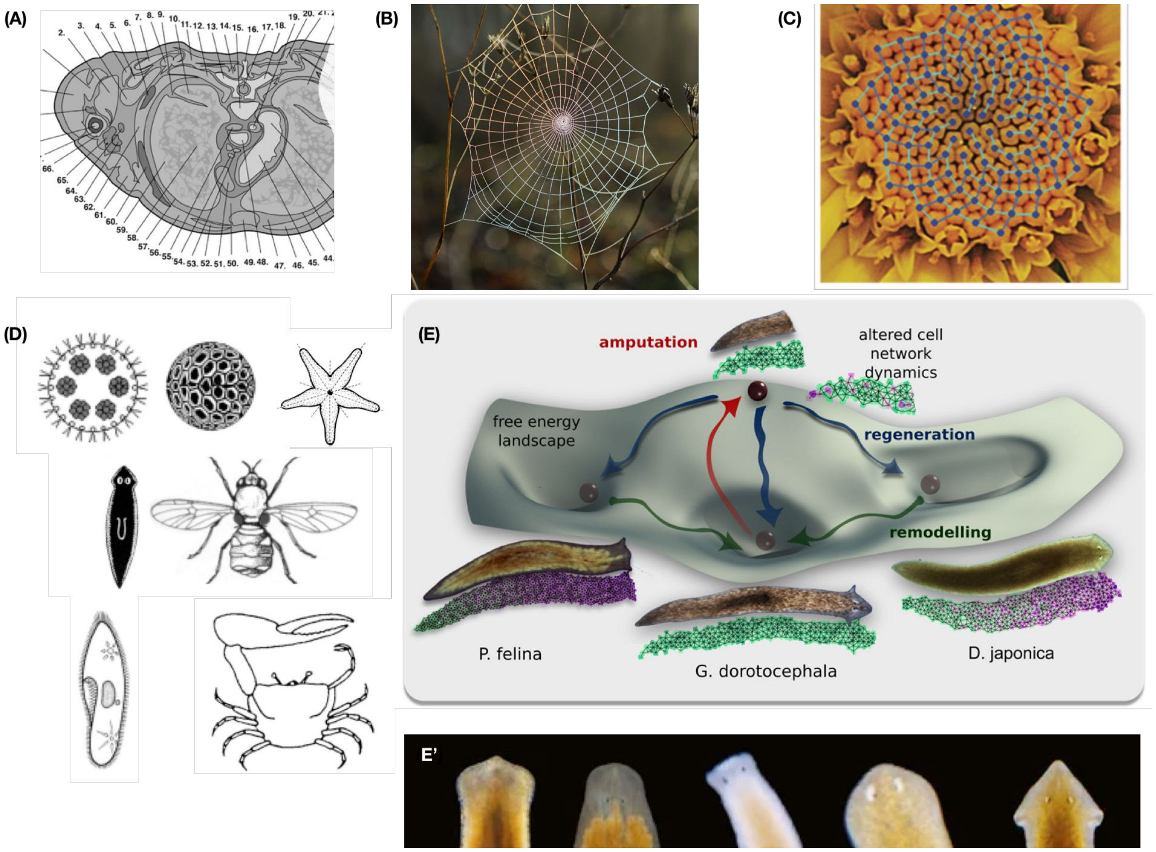

Figure 2: Patterns of form and function. (A) Cross-section of a normal human torso. (B) Spider web (photo by Robert Anasch on Unsplash). (C) Fibonacci pattern in a flower (taken with permission from [25]). (D) Symmetry types in diverse living phyla (images by Anna Gitelman). (E) A landscape of head shapes for planarian flatworms, closeup of head shapes in E' (taken with permission from [26]).

Patterns are, at core, a diadic relation between living systems observing each other and forming internal models that compress their sensory data to help make expedient sense of what they see. While this began long before mathematicians appeared, there have been many advances in developing formal systems to detect, classify, and compare patterns of form and behavior in the living world. Examples include Fibonacci sequence [27], fractal structures [28-32], and many others characterized by D'Arcy Thompson's classic On Growth and Form [33]. There has also been extensive discussion on the evolutionary course of novelty in patterns [34-37], and the role of biomechanics [38-43] and the interplay between physical form and genetics in the inherencies studied by Stuart Newman [44-46].

Many biological patterns are *goals* the system pursues, not mechanical outcomes

A crucial aspect of biological patterns is that they are often not simply results of a process that rolls onward in a mechanical fashion (Figure 3). The parts may well be describable by various aspects of mechanics, but biological wholes have the ability to achieve specific patterns *despite* novel conditions, interventions, changes of environment and of their own parts, etc. In effect, these patterns serve as goals for intelligent (context-sensitive, creative, problem-solving) navigation in anatomical, transcriptional, physiological, metabolic, and other spaces in the same way that creatures navigate 3D space in traditional examples of adaptive behavior. This is distinct from the complexity/emergence paradigm, dominant today, which focuses on the ability of simple rules to drive complex outcomes [47]. Such "emergence" certainly happens in biology, but by itself it is not sufficient to explain the most interesting aspects of morphogenesis.

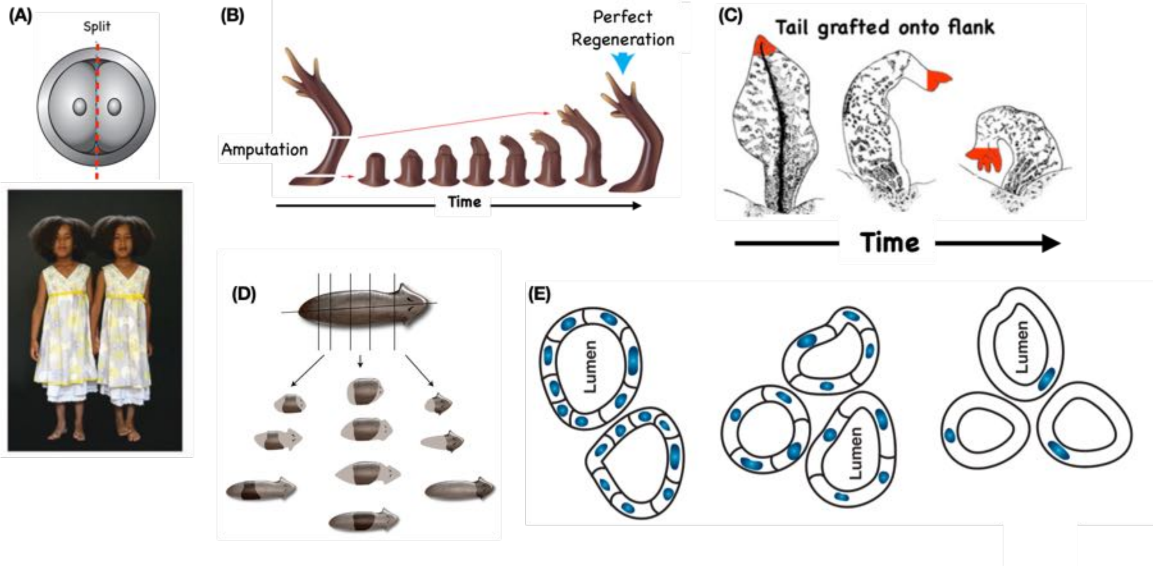

Figure 3: morphogenesis as a problem-solving process. (A) Embryos of many species make normal twins, triplets, and other multiples when split into pieces, not half-bodies (photo by Oudeschool via Wikimedia Commons). (B) Salamanders can replace an entire appendage when it is amputated, replacing exactly what's missing no matter at what level the injury occurs. (C) Tails grafted to the flank of an amphibian slowly remodel into limbs – a structure more appropriate to its new location; this includes remodeling tail tip cells into fingers (red shading) despite their normal local environment (image used with permission from [48]). (D) Planaria can be cut into pieces, each of which regenerates a normal worm. (E) Cross section of kidney tubule in newts, showing the accommodation of the cells to larger ploidy by using fewer cells to build the same structure, even if it has to bend one cell around itself to leave a lumen in the middle. Panels B,D,E courtesy of Jeremy Guay of Peregrine Creative.

The first sign that morphogenesis is not hardwired is revealed by regulative development: embryos cut into pieces give rise not to partial bodies but to monozygotic twins, triplets, etc. Some animals do this in adulthood – salamanders regenerate perfect limbs (and many other organs) regardless of where they are amputated [49, 50]. Indeed, development may just be a special form of regeneration that recovers most of a missing body from 1 seed cell. However, morphogenesis is more than recognizing that parts are missing and repeating the same steps. Scrambled tadpole heads rearrange to make normal frogs [51-53], showing that navigational paths can be altered to find the correct end-state. All of these systems can reach the species-specific target morphology *from different starting conditions*. What all of these examples have in common is that cells work to create specific structure (even though no individual cell knows what, for example, a finger is or how many there should be) and *stop when the anatomical goal has been reached* - the key hallmark of this pattern homeostasis process.

But restoration of injured parts via standard mechanisms not the limit of the competency of this process. The kidney tubule of the newt (Figure 3E) is normally made of 8-10 cells working together. When the newts are made polyploid (having multiple copies of their chromosomal complement), the cells get larger to accommodate the new DNA. But the resulting newt is the same size, which is accomplished by the cell collective's scaling to include *fewer cells* [54, 55]. Embryos likewise adapt to drastic changes in overall cell number [56-58]. This is impressive enough, but the truly remarkable thing happens when the cells are made so large that only one of them fits into the diameter of a normal tubule. In that situation, *single cells wrap around themselves to make the same structure.* The system is then using a different molecular mechanism to solve its problem – instead of the normal cell:cell communication needed to organize multiple cells into a tube, it's using cytoskeletal bending. This illustrates the ability to creatively use genetic affordances as needed, to implement a high-level anatomical specification. In other words, an incipient newt coming into the world not only cannot predict the vagaries of the external environment, but worse yet, it even its own parts are unreliable. It can't count on having the correct copy number of genes, or the correct number or size of its cells. It must get the job done using the tools at its disposal in novel circumstances. What *can* it count on? It can count on the relentless competency of its agential material, honed over eons of evolution that builds problem-solving agents (not fixed solutions to environments) [59], and the pole star that guides its activity – the attractor in morphospace to which it must find a path.

Tissues store bioelectric pattern memories (setpoints) that underlie morphogenesis

Surely these patterns are somehow derived [2] from genetic information provided by their evolutionary history? Two sets of results discussed below limit this claim. First, novel configurations of life with normal genetics exhibit patterns of form and function that have never been selected for. But the ability of the same biological hardware being able to pursue different goal states (a kind of universality normally studied in computer science) can be found well outside of synthetic or bioengineered systems. Planarian flatworms, which normally regenerate the correct heads with nearly 100% reliability, can be induced to make heads *of other species* – without any genetic change but by disrupting the bioelectric circuits that store the target morphology (Figure 4). There are specific patterns, in the space of possible planarian head shapes, that will attract not only the species that normally lives there, but also others, under the right conditions. All of these data paint a picture not of genetically-determined, emergent outcomes but of specific patterns that are, with effort, dialed into by goal-seeking, sense-making systems [62].

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[2] Elsewhere I discuss what it means for large-scale form and function to be encoded in a medium that directly specifies protein structure and what kind of predictions and control strategies would have to be possible with genetic information to support a strong claim that genetic information explains the capabilities of living material [60, 61].

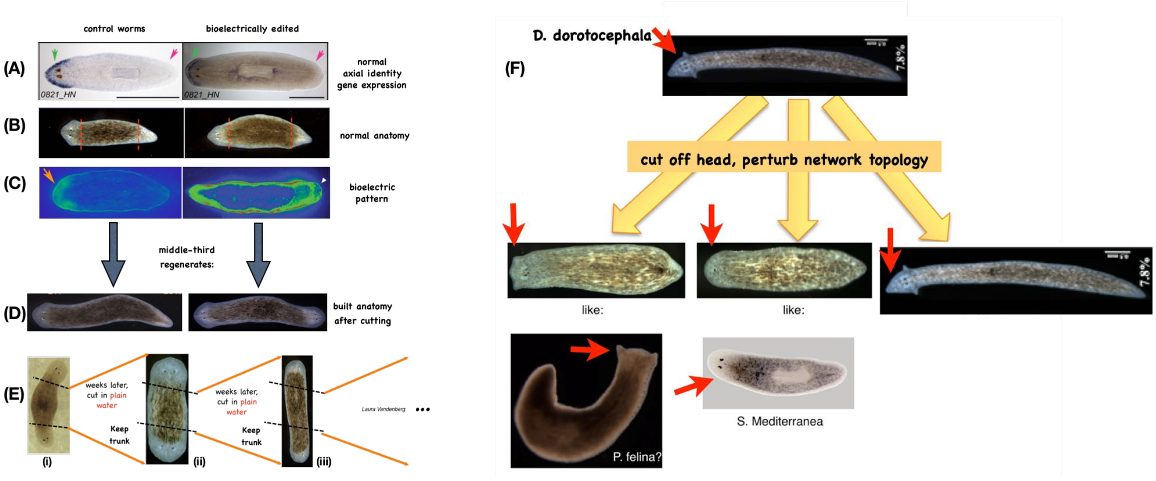

Figure 4: Bioelectric encoding of re-writable memory patterns that guide morphogenesis of diverse outcomes with constant genetics. Panels A-D show the relationship of the bioelectric pattern memory to the molecular-biological and anatomical patterns, with the left column being a control worm and the right column showing one exposed for several hours to specific ionophores to alter the bioelectric pattern. (A) Both animals show normal molecular histology, with expression of marker gene (purple) in the head and not the tail (green vs. red arrowheads). (B) The anatomy is normal in both worms, with one head and one tail (red dashed lines indicate the amputation planes for the regeneration experiment). (C) The bioelectric pattern indicates one head (green, depolarized) in the control worm but two in the exposed worm, despite their normal anatomy and gene expression. (D) When cut, the middle fragments produce a 1-headed animal in the control case, but a 2-headed bilateral heteromorphosis in the animal with the 2-headed pattern memory. (E) With no further treatment, fragments of these 2-headed worms will continue to regenerate as 2-headed in perpetuity, showing that the bioelectric pattern memory holds indefinitely, despite their normal genome. Panels in (F) show that not only head number, but head shape is plastic: when the bioelectric signaling is disrupted by blocking electrical connections between cells, an animal with a triangular head makes one of several discrete head shapes – flat, round, etc. like other species. Images in A-E taken with permission from [63-65]. Images in F taken with permission from [66].

These results and many other examples like them (discussed in detail in [17]) reveal anatomical patterns to serve as setpoints in a homeostatic (or homeodynamic) process – stored functional goal state representations against which error is continuously minimized [67, 68]. Much work exists on formalizing this notion in terms of a landscape [69, 70] or morphogenetic field [71-78] which the active error-minimization process traverses. Some studies have now also been made of the cognitive glue mechanisms that enable alignment of parts (molecular networks, cells, etc.) toward large-scale goal states in problem spaces of which the parts have no conception [79]. This is very different from the feed-forward paradigm of emergence of complexity from repeated iterations of simple rules, because open-loop processes do not explicitly represent setpoints, thus obscuring the deep questions around the goal patterns themselves. The mechanisms by which these anatomical pattern memories are stored, recalled, and implemented have been described elsewhere [63, 80-83]. Here, I address the other key question: where do they come from in the first place? What sets the targets for the goals of the collective intelligence of morphogenesis?

3. Where do pattern memories come from? Beyond Genetics and Environment

> "To invent, I have said, is to choose; but the word is perhaps not wholly exact. It makes one think of a purchaser before whom are displayed a large number of samples. … The sterile combinations do not even present themselves to the mind of the inventor. Never in the field of his consciousness do combinations appear that are not really useful. All goes on as if the inventor were an examiner for the second degree who would only have to question the candidates who had passed a previous examination."
>
> -- Poincaré (1921)

The ubiquity of specific patterns of form and behavior in the living world raises the natural question of where the patterns "come from". This is often asked with the assumption that we know what the question means. One problem with this standard framing is that no answer would be really satisfying. Cases where one can point to a pre-existing structure, process, or agent that provides the necessary specificity, simply leads to "but then where did *that* pattern come from?". It's an endless search for the source of information, but what kind of answer would count as the definitive *explanation*? Another set of cases is emergence, in which simple rules give rise to a very specific complex outcome, and there appears to be no more to be sought than the fact of the matter that it happens that way. Much has been written on the philosophy of explanations and mathematical causes: [84-87], but biologists need a practical guide to asking increasingly better questions that direct inquiry away from unproductive paradoxes and toward questions of origin that enlighten and reveal novel capabilities and discoveries.

Some patterns have no physical or historical explanation

Physicists are very comfortable with patterns arising from mathematical causes such as symmetries [88]. Biologists instead typically land on one of two sources of patterns that are acceptable: heredity and environment. Heredity provides a long history, backed by selection via interaction with an external environment, of shaping a chemical medium (DNA) that is thought to explain why specific patterns (rather than alternatives) are observed. Many interesting questions exist about the origin of useful solutions – a pre-requisite for being able to select them from a pool of less useful ones [34-37, 89], but here I want to focus on a source of order that pervades the living and non-living world: that studied by the discipline we call mathematics [87, 90-92].

Consider the four-color theorem: it turns out that no more than four colors are required to color the regions of any map so that no two adjacent regions have the same color. Or, Feigenbaum's numbers: mathematical constants which express ratios in a bifurcation diagram for a non-linear map (Figure 5). For almost all real numbers, the geometric mean of the coefficients of their continued fraction is about 2.685; *almost* all, and specifically ~2.685. If n^2 cannonballs are laid on the ground in a filled square formation, then they cannot all be used to make a square pyramid of cannonballs, except when n=70. Every number of the form ABABAB (basis 10) is divisible by 37, and each prime (except 2 and 3) is next to a multiple of 6. The distribution of prime numbers is well known, and the first six perfect numbers are all even and relatively close together (6, 28, 496, 8128, 33550336, 8589869056), but then there's a massive jump to the next one (137438691328), and they become increasingly sparse. All of these are specific facts about a world which do not depend on facts from physics – they can be linked to other aspects of mathematics but they form a set of findings that do not reduce to any facts of physics.

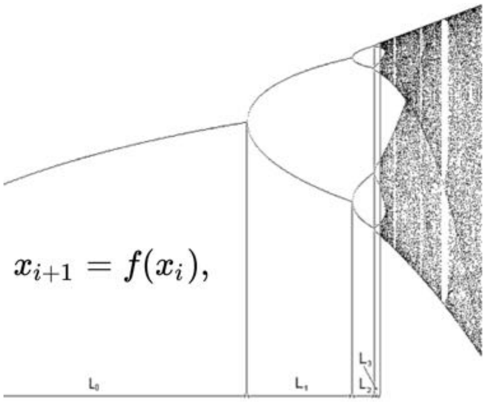

Figure 5: Feigenbaum's constant. In this bifurcation diagram, Feigenbaum's constant δ is the limiting ratio of each bifurcation interval to the next between every period doubling, of a one-parameter map such as a logistic equation $X_{n+1} = r \bullet X_n \bullet (1-X_n)$. It happens to be approximately 4.6692.

Beyond the scalar patterns (specific special numbers in the examples above), there are many higher-dimensional patterns that simply exist "on their own", unmoored from physical or historical explanations of their origins. Consider the remarkable and beautiful (also life-like) pattern seen in the Halley plot kinds of fractals (Figure 6). That entire highly specific form is encoded in the very simple formula in complex numbers, and can be revealed by a simple algorithm. The fact that this highly complex pattern is indicated by a very short description of a function provides an un-ending richness from a small seed. I propose that it's better to think of it not as a kind of infinite compression[3], but rather as the function serving as an index or a pointer into a morphospace of possible shapes. This idea will be developed further below, casting physical objects (such as embryos and biobots) as other types of pointers into the Platonic space.

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[3] In true compression, we have an algorithm that produces a compressed seed which can then be unfolded into a richer pattern. In this case, there is no algorithm that takes an image and returns a seed that can be uncompressed into that image. Whereas traditional compression constructs a pointer to a known, also constructed pattern, here we merely discover both and are only able to follow the pointer towards its referent using the Halley method.

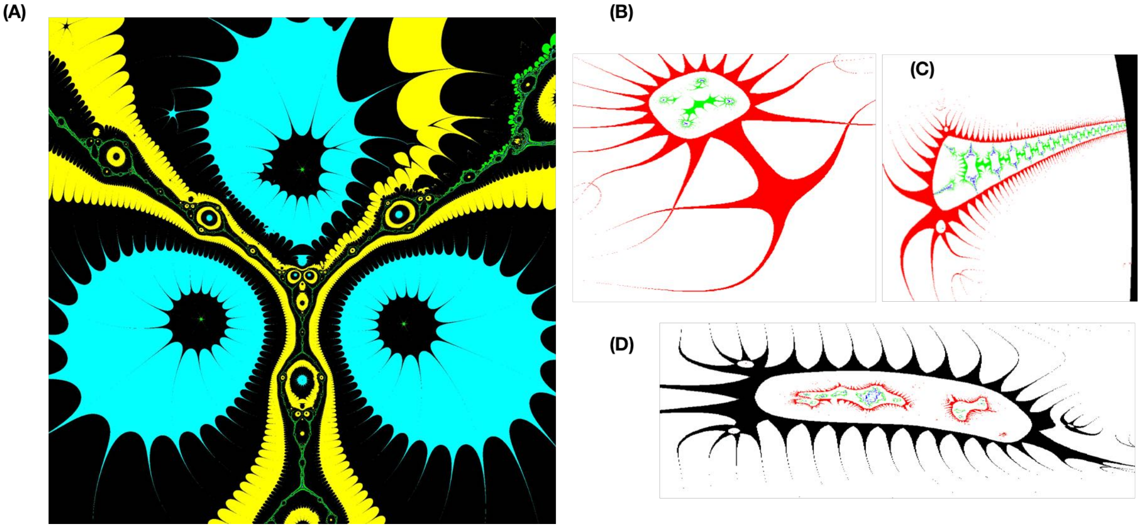


Figure 6: rich spatial patterns emerging from mathematical seeds. (A) A sample Halley map of a short function in complex numbers such as z^3+7. (B-D) "biomorph" patterns [93-97] arising from other functions in complex numbers (taken with permission from [29]).

What sets the nature of this shape – where does it come from? There is no history of selection, no prior events in our universe that determine it. Like pi, e, and many other remarkable constants, forms emerge from mathematics in ways that cannot be explained by any kind of history or properties of the physical world – they would be this way even if the physical world was entirely different. If the constants setting the properties of the physical universe were all altered at the Big Bang, these kinds of facts and things like the truths of number theory, and other aspects of computer science (e.g., the universality of the NAND gate, Turing halting status of specific algorithms, etc.) would be unchanged. There is nothing in the physical world that can be used as a control knob to alter them. I argue that this breaks the closure of the physical world, as these mathematical facts impinge on physics and dynamics that are the substrate of evolution. It is a non-physicalist approach to the project of looking for sources of information and influence when we try to understand and guide biology (and the other disciplines that build on it).

Random "facts that hold" or a structured space of non-physical patterns to study?

This line of argument is compatible with the Platonist view of mathematics – as discovering, not inventing, a pre-existing structure (although there are other views [98]). In addition to special numbers, there are properties – for example, facts about graphs and networks in general [99, 100], such as behavior of networks at criticality (edge of chaos), connectivity theorems, and the fact that networks can learn in specific ways [101, 102]. The fundamental fact about such things is that, in an important sense, you "get out more than you put in" – constructions are limited or facilitated by these facts which do not themselves need to be constructed (and cannot be changed, only accommodated or exploited). When such examples are encountered, physicalist biologists say these are simply "facts that hold" about the world. This reveals two metaphysical options. The first is the emergentist position where mathematical patterns and complex outcomes of iteration of simple rules are discovered from time to time – they can be catalogued and exploited when found, but they simply pop up unexpectedly and there is no further source to be sought. It's just what happens, full stop.

The benefit of that emergentist position is that it's minimal – aligned with Occam's Razor, it doesn't need to postulate a non-physical latent space of patterns. The down-side of it is that it is, fundamentally, a mysterian position that does not facilitate further advances. In contrast, I propose a Platonist view in which we view the space of these patterns as real in the sense that it matters for what happens in the physical world (via *ingressions* of these patterns [103]) and explore its structure. Basic understanding of our nature as cognitive beings, and applications from regenerative medicine to engineering, are better served by a worldview in which we have not a random grab-bag of "facts that hold" but a systematic research program. We must go beyond reveling in the surprise of emergent outcomes, toward a process of discovery that acknowledges biological (and cognitive) outcomes to be the result of a triad of heredity (hardware), environment (boundary conditions), and ingressing patterns whose most salient fact is that they are part of an ordered and structured but non-physical space.

Below I sketch out a perspective in which we view a very diverse range of objects – from algorithms to machines to living constructs – as pointers (or interfaces [104]) into a rich latent space of patterns. Our job then is to characterize the mapping between pointers and the ingressing patterns which they enable, to understand the metric and structure of the space of the possible, and be able to design pointers to access desired patterns at will in biomedical and engineering contexts. We do not want to be surprised by the appearance of Anthrobots [105], functionality of eyes placed on the tails of tadpoles [106] (Figure 7), and humans with minimal brain matter but normal cognition (reviewed in [107]) – these are unexpected when relying on selection and a view of evolution as producing specific solutions to specific problems. We want to be able to understand and create novel beings by understanding how evolution exploits intelligent, problem-solving physical and computational structures as interfaces to a rich space of patterns which they adaptively navigate.

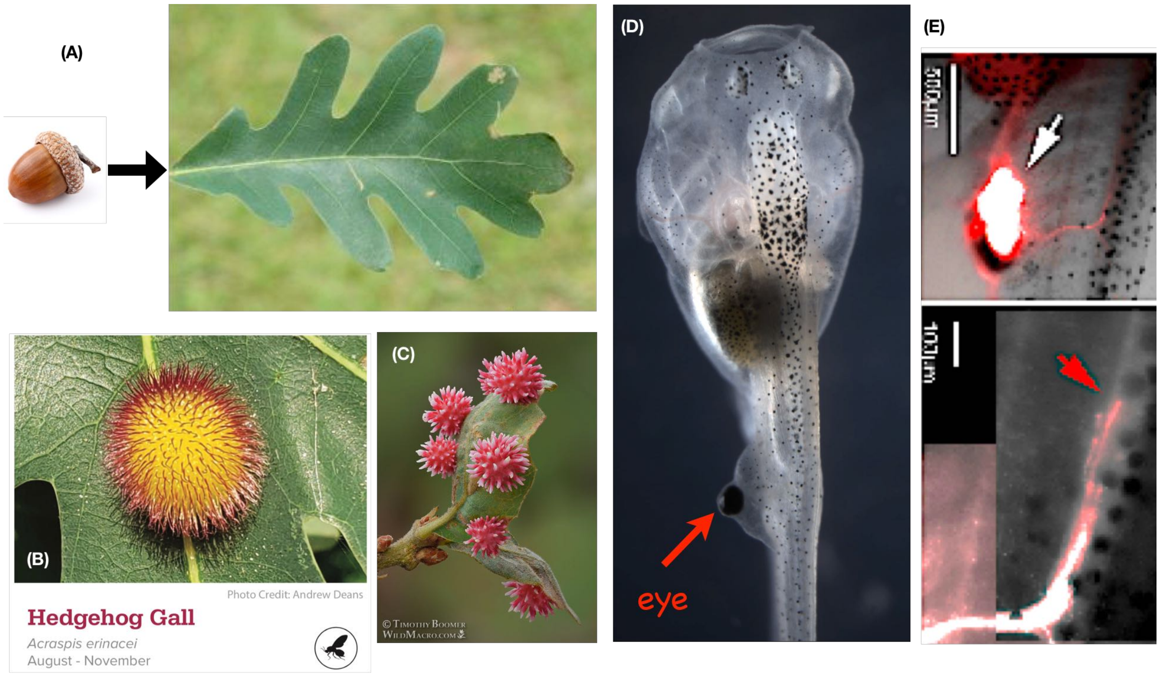
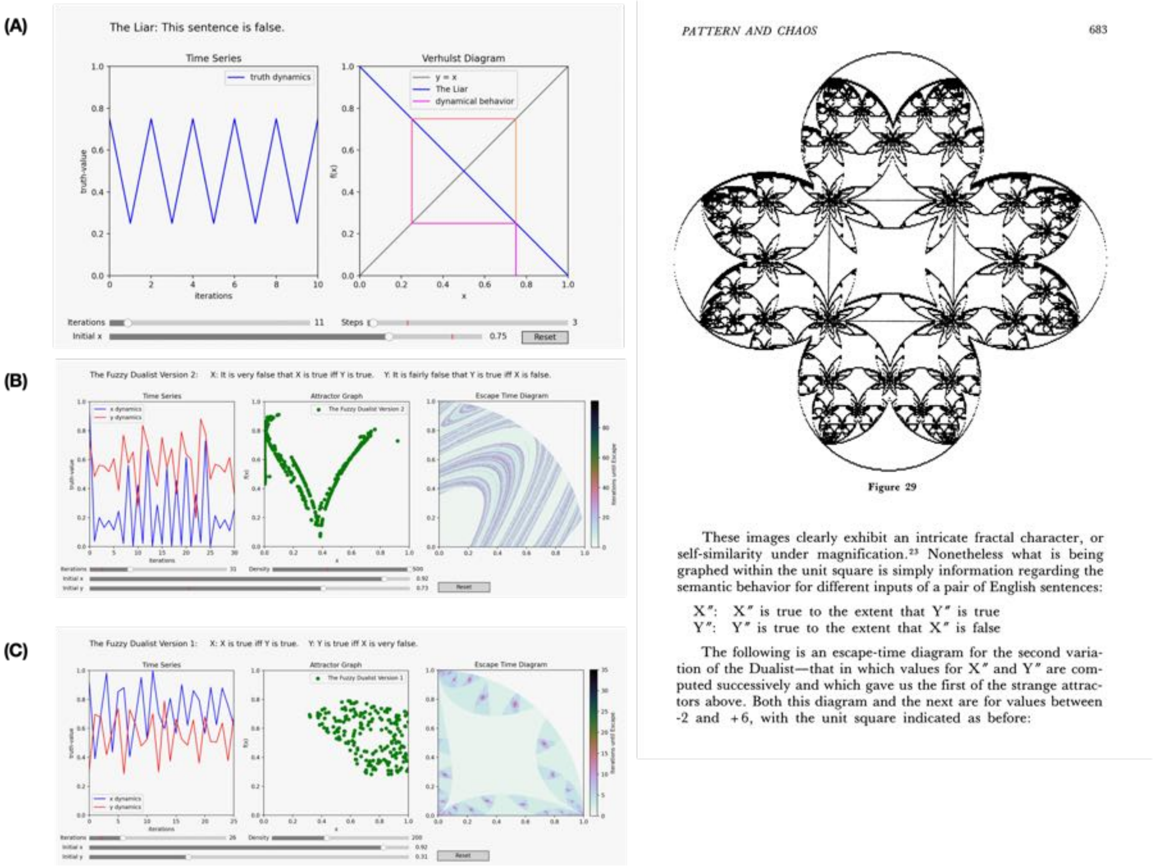


Figure 7: unexpected competencies of form and function. (A) Acorns reliably make a very specific shape: the oak leaf. However, when prompted by signals from a parasite, these same cells can make other structures – galls with shapes remarkably different from the default flat, green leaf, raising the question of what other shapes exist in their latent space and could be coaxed. Image in B by Andrew Deans; image in C by Timothy Boomer at WildMacro.com. Unexpected capabilities can also be discovered by perturbational experiments in behavioral space. For example tadpoles (D) in which the primary eyes are suppressed but an eye is induced on their tail (red arrow) can still see and perform well in visual assays [106] even though the optic nerve (E, bottom panel) emerging from the ectopic eye (E, top panel, white arrowhead) does not connect to the brain but instead might stop at the spinal cord (E, bottom panel, red arrow). Images in panel E taken with permission from [106].

Beyond eternal, unchanging patterns: toward a phylogeny of Platonic forms

While this addition to the ontology of biology is already unconventional, there is one more step to take: going beyond static, low-agency forms. One common way of thinking about Platonic space is that it contains things like facts about triangles and integers, which are 1) unchanging, and 2) refer to mechanical patterns unrelated to intelligence (they affect agents but are themselves passive). This can be extended in two ways.

Consider the classic liar paradox, in which sentence X says "X is false". Patrick Grim [108-114] developed a fascinating perspective on this by doing two things (Figure 8). First, he added an element of time: there is no paradox if we allow the truth value to change and consider the time-extended behavior; the paradox arises from our trying to freeze a fundamentally dynamic pattern down into an assumption that a proposition should have a static truth value (not move in the abstract space of logical sentences). Second, he moved to fuzzy logic, to allow the Boolean true-false cycle to take on more interesting shapes by allowing sentences like "X is 80% true". Finally, he enlarged the space by considering and plotting the structures formed by sets of N mutually-referencing sentences. This allowed him to observe complex, dynamic, often fractal patterns corresponding to logical sentences. That extends the flat world of static truth claims to a domain of interacting, rich, time-dependent[4] systems.



The Liar: This sentence is false.

The Fuzzy Dualist Version 2: X: It is very false that X is true iff Y is true. Y: It is fairly false that Y is true iff X is false.

The Fuzzy Dualist Version 1: X: X is true iff Y is true. Y: Y is true iff X is very false.

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Figure 29

These images clearly exhibit an intricate fractal character, or self-similarity under magnification.[23] Nonetheless what is being graphed within the unit square is simply information regarding the semantic behavior for different inputs of a pair of English sentences:

X″: X″ is true to the extent that Y″ is true
Y″: Y″ is true to the extent that X″ is false

The following is an escape-time diagram for the second variation of the Dualist—that in which values for X″ and Y″ are computed successively and which gave us the first of the strange attractors above. Both this diagram and the next are for values between -2 and +6, with the unit square indicated as before:

Figure 8: the dynamic life of logical sentences. Obvious denizens of the Platonic space include logical statements. By simulating their dynamics as fuzzy logic patterns created by coupled systems of two mutually-referential sentences, we reveal the complex, dynamical behavior of these logical constructs. Panels A-C show the time-dependent patterning behavior of several sentences, starting with the familiar Liar Paradox in (A) which simply alternates between True and False and produces a simple, but not static, pattern. Sentences for the others are shown in the top of each panel. Images A-C are screenshots of software created by Madelyn Silveira, Levin lab, to visualize these patterns. (D) A pattern belonging to a pair of sentences, taken with permission from [114].

Thus, the Platonic realm contains boring, static things like "Pi>3.0" (the "rocks" of that world), dynamic but repetitive things of the kind "this sentence is false" (simple oscillators that buzz "in place"), and more complex structures represented by sets of logical sentences that lock together to define an emergent pattern and whose

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[4] Many interesting questions can be asked here such as: at what rate does the Liar Paradox flicker? On the one hand, one could define a kind of *c* – speed limit of light – in the Platonic realm by saying that the fastest possible dynamic is that of the simplest Liar Paradox and everything else is some sort of slower harmonic of it. Or, one can take an observer-focused view and say that the speed is defined by the frame rate with which a mind that attempts to instantiate the Liar Paradox (or other such sentences) in its cognitive system polls the truth value of the Platonic object it is modeling.

output can be visualized as a traversal of a space (and we already know that such traversals can offer surprising degrees of competency, such as delayed gratification [115]). Some of these, such as ones represented by equations such as those describing gene-regulatory networks [101, 102], can even learn from experience. This way of classifying the ontology of the Platonic space opens the possibility of a rich, perhaps stratified, continuum of inhabitants ranging across the whole spectrum of diverse intelligence – from static and mechanical to the complex and agential.

This view is consistent with others' models of non-physical mind [19] but focuses on a different aspect than the quantum interface typically resorted to for solving the interactionist problem of dualism [116-118]. It is also broadly consistent with other views [119, 120] of non-physical components to a transpersonal psychology, such as Jung's theory that certain "primordial images" or "elementary ideas" activate in the human nervous system as archetypes, describing dreams, myths, art, and rituals as potentially activating triggers for such patterns. While these ideas linking non-physical forms to physical and mental patterns are now classics, they have made little impact on research in the life sciences and engineering. I think it is fair to say that most biologists regard them, if at all, as ancient relics of a profligately magical worldview that is rightly abandoned in favor of metaphors about molecular pathways. It is likely that this is because there has not been a tractable path to transition these ideas into novel discoveries, thus demonstrating their utility. That is no longer the case, and I believe we now have a toolbox that provides an exciting, actionable research program to evaluate the utility of such ideas.

4. A research program beyond physicalism: a provisional model

> "Computer Science is no more about computers than astronomy is about telescopes."
>
> -- E. W. Dijkstra

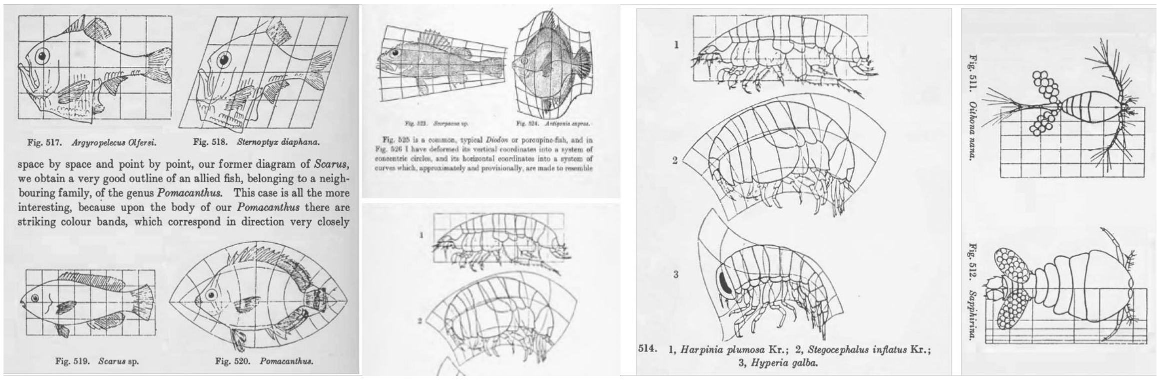
Imagine a world in which the highest fitness is achieved by a specific shape of a triangle. Evolution spends N generations finding the first angle, and then it spends ~N more generations optimizing the second angle. But then something magical happens – it doesn't need to spend time finding the third angle – in flat space, if you know 2 of the angles of a triangle, you know the third. Similarly, if evolution produces a voltage-gated ion channel (a voltage-gated current conductance, a.k.a., a transistor), it can make logic gates, and then the computational features of these logic gates (and their other properties, like the universality of the NAND gate etc.) are accessible without having to specifically evolve the contents of their truth tables. These kinds of features show up as a kind of "free lunch" in the physicist's sense – with the right kind of pointer (or interface, or receiver) in physical space, one gets more out than one put in. This opens an important gap in the closure of the physical world, which means that explanations need to integrate mechanistic components of genetics and environment but also *mathematical explanations* [121, 122] – patterns of form and behavior that derive their being from something other than the facts of physics.

Evolution, being the ultimate opportunist, has no pre-commitment to physicalism and would exploit useful features no matter their origin.

Impact of Platonic forms in biology

Life makes extensive uses of the properties of prime numbers [123] and many other mathematical facts. Beyond that, it exploits the generic properties of networks [78, 124-127], differential adhesion [128], fractal structures [28, 32, 129, 130], topological structures [131], emergent features of morphomechanics [132-135], and the myriad of remarkable examples across the kingdoms of life cataloged by Thompson [33]. And it's not just about numbers; for example, gene regulatory networks are even subject to patterns from the field of logic, being amenable to liar paradoxes and other incompleteness results [136].

Biology often reveals a sensitivity to these mathematical structures, including patterns of algebra, logic, and even Julia sets and root-finding methods [93, 96, 137]. One of the most interesting is that found by Thompson [33, 138], who showed that patterns of different extant living species could be derived from other species by mathematical deformations of a coordinate grid (Figure 9). Importantly, despite the frequent use of fields and positional information grid concepts in developmental biology [77, 78, 139-142], many of these fields (especially Thompson's) do not have a known physical basis but they do have structure and information content [143-146] which informs biology.



space by space and point by point, our former diagram of *Scarus*, we obtain a very good outline of an allied fish, belonging to a neighbouring family, of the genus *Pomacanthus*. This case is all the more interesting, because upon the body of our *Pomacanthus* there are striking colour bands, which correspond in direction very closely

Fig. 525 is a common, typical *Diodon* or porcupine-fish, and in Fig. 526 I have deformed its vertical coordinates into a system of concentric circles, and its horizontal coordinates into a system of curves which, approximately and provisionally, are made to resemble

Figure 9: Transformations of extant species' morphologies into others by mathematical deformation of an imaginary grid. These panels show examples how simple mathematical deformations of animal shapes on a coordinate grid (which has no obvious biological counterpart) result in novel, existing biological species. Taken with permission from [33].

Prior work has extensively explored the idea that the autopoietic processes of self-construction of bodies and of minds have a fundamental symmetry [6, 147]. In other words, morphogenesis itself is a cognitive process [11, 80] and literally the behavior of the collective intelligence of cells (as our mammalian cognition is the behavior of a collective of neural and other cells). It has thus been suggested that, because of the deep evolutionary conservation of ion channels and other bioelectrical machinery (and the algorithms it implements) across neural and non-neural substrates [7], the tools of behavioral neuroscience can be used to shed light on morphogenetic competencies. Conversely, the science of emergent body forms navigating anatomical space can help understand how neurons align in brains to enable the emergence of a cognitive being that has goals, preferences, and memories that its parts cannot. Is it possible that the relationship goes deeper, in that the core of what it means to be a mind, with inner perspective, embodied in the physical universe, is fundamentally linked to the kinds of autopoietic patterns a given construct can access?

A non-physicalist model of embodied minds

Given this symmetry between neuroscience and developmental biology, I propose that the relationship between mind and brain is the same as the relationship between mathematical patterns and the morphogenetic outcomes they guide. Form and agential behavior is a combination of ingressing meaningful information patterns and physical constraints [87, 148-151] in how it can manifest in the physical world determined by structural architecture, limitations of time and energy, etc. The involvement of non-physical components is unwelcome by many – seen as a slide back toward Cartesianism and superstition, although classic [19] and modern [152, 153] theories are actually quite consistent with this view). But the exploitation of Platonic mathematical structures by evolution, as well by its products known as mathematicians, has already evicted us from the tidy physicalist paradigm. Taking Platonic mathematics seriously and applying it in biology means we have already abandoned the closure of the physical world for our explanations, intervention strategies, and computational models. We already know that non-physical patterns ingress into, and functionally matter, in the non-living and living world and that we can (and do) study them to great effect [88, 154-158]. There is one remaining step to take.

The standard conception of the contents of the Platonic space is that it's filled with static patterns – shapes, rules, etc. for boring, low-agency things like integers and triangles. But patterns can span across the spectrum of persuadability: they can be static, active (as in Grim's logic patterns), or *agential.* How to conceptualize agential patterns? By remembering that we, ourselves, are patterns – temporary self-organizing patterns that hold together for a time within metabolic and other media, and manage to exert cognition, agency, and consciousness. Why couldn't Platonic space contain patterns that are intelligent and active to some degree, like the specific kinds of network structures that have been shown to have the simple goal-directedness of attractors and self-assembly capabilities [100, 159] or even capacity for Pavlovian conditioning [101, 102]? What if some of the Platonic patterns that matter for biology are, themselves, intelligent to a degree?

To recap, the first pillar of the proposed framework is that Platonic forms inject information and influence into physical events, such as the growth and form of biological bodies. The second is that this latent space contains not only boring, low-agency forms such as facts about integers and geometric shapes, but also a wide range of increasingly high-agency patterns, some of which we call "kinds of minds". Thus, I propose that minds, as patterns that ensoul somatic embodiments, are of exactly the kind (but not in degree) of non-physical nature as the patterns that inhabit and guide the behavior of biological tissue. The relationship between mind and matter (of the brain for example) is proposed to be the same as the relationship between Platonic patterns and the physical objects they inform.

In colloquial terms, triangular objects are haunted by the spirit of relevant rules of geometry while brains are able to pull down and force the incarnation (literally, "bringing into meat") of patterns of a very different kind and sophistication. I propose that the objects on which we often fixate in physics, biology, and AI – the embryos, machines, language models running on PCs or in robots, etc. are just *pointers* (or, per Hoffman, *interfaces* [104, 160-162]) to the deeper space of patterns. Every analogy has limitations and no doubt the pointer metaphor will fail at some point, but the aspects of the pointer analogy I wish to emphasize are: 1) as with pointers into a rich informational medium, you get more out than you put in, 2) the mapping between the interface you make and what comes through it is not linear or simple and must be investigated, and 3) in order to learn to call up the patterns we want, we will have to look beyond the pointer toward the structure of the space into which it points.

My model (Figure 10) is an extension of prior Platonic space models [19, 163] and broadly consistent with some traditions around a layered (tiered) "Mental plane" of subtle objects that include cognitive types and instances. It is real, while non-physical, because its contents a) matter for what happens in the physical world (knowledge of these patterns provides massive leverage for evolution or for engineering design), and b) it can be profitably studied and exploited with outcomes that play out in the arena of empirical experiment. Thus, the complexity of a body (or a mind) are not so much *contained* or *compressed* in the seed, in the sense that they must be constructed via emergent surprise from an algorithm that processes it, but rather *pointed* to by the seed and retrieved by a process that spans both the world of patterns and the world of physical pointers or interfaces to it.

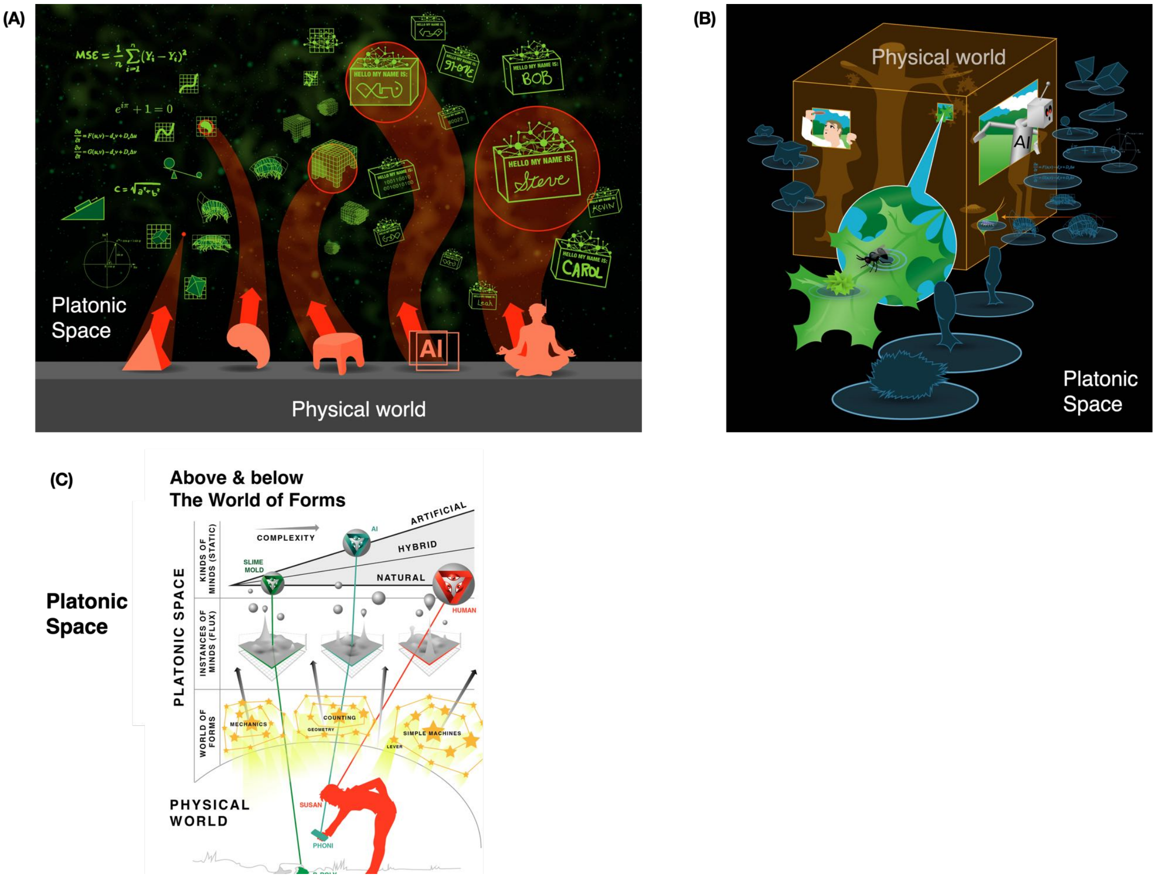


Figure 10: Models of the Platonic space and its relationship to forms and instances of embodied minds. In my model, everything is in-formed by patterns in different regions of the Platonic space, including simple objects, engineered machines, embryos, chimeras, biobots, and other systems, and their physical embodiments act as interfaces or pointers to structures in the Platonic space, which are active and have different degrees of complexity and agency (represented here by the size of the form) (A). On this view, brains, bioengineered constructs, AI's, parasite hackers, etc. are all exploration vehicles which in effect produce a portal or entry-point into the Platonic space allowing us to explore the latent space of patterns in the vicinity (B). The space may be layered or structured, such that "lower" levels contain lower-agency forms, such as static truths about numbers, while "higher" levels permit classes of patterns (kinds of minds) which contain specific instances - patterns that are active, or even self-referential strange loops [164] which reify their own existence as a mind and have pinched off from the generative substrate as true individuals (C).

Practical consequences: implications of the model

What does this model mean, in practical terms? The latent space is known to be structured not only because Platonist mathematicians are building a map of it, but also because evolution is able to exploit it – it has a relatively smooth character which allows evolution to progress rapidly, because past interactions with it carry non-trivial information about the adjacent possible [100, 165, 166]. Thus, the third pillar of the proposed framework is that the space of these forms is not haphazard or random (suitable for emergence and complexity science) but is a structured ordered space that is amenable to systematic exploration. It is now essential to begin to map out the space (to expand out from the patterns studied by mathematicians and link morphogenetic and cognitive within the same map), and to crack the syntax and semantics of the pointers – the mapping between the objects that we make in the physical world and the myriad of patterns that pour through those interfaces from the Platonic space (which I conceive of as being under a sort of positive outward pressure).

Here then is a research program which addresses these challenges. It is formed around two main thrusts. First, studying patterns (form and cognitive behavior) of systems which have not been selected for specific outcomes but form the "adjacent possible" [167] around existing forms. This provides an opportunity to study the metric of the Platonic space by analyzing patterns ingressed by pointers that are similar. One example is Xenobots, which teach us about patterns adjacent to those of frog embryos, and Anthrobots, which teach us about patterns adjacent to adult human tissues (Figure 11). The tractability of biobots, synthetic bioengineered constructs [168-173], chimeras [174], and other modifications of standard, default embryogenesis reveal the plasticity of the genetically-encoded hardware in their ability to serve as interfaces for a wide range of patterns besides the obvious ones that appear as default (and commonly thought to be emergent, selected-for properties). Such living exotica serve as *exploration vehicles* or periscopes for our study of the Platonic space and its contents, greatly expanding the range of patterns we observe. Most crucially, because they don't have a specific evolutionary history as such (i.e., there's never been any Xenobots or Anthrobots and thus no eons of selection for being a good biobot with their specific properties and capabilities), they raise the key question of "where these patterns come from", and thus serve as an entryway into the space of specific non-physical forms.

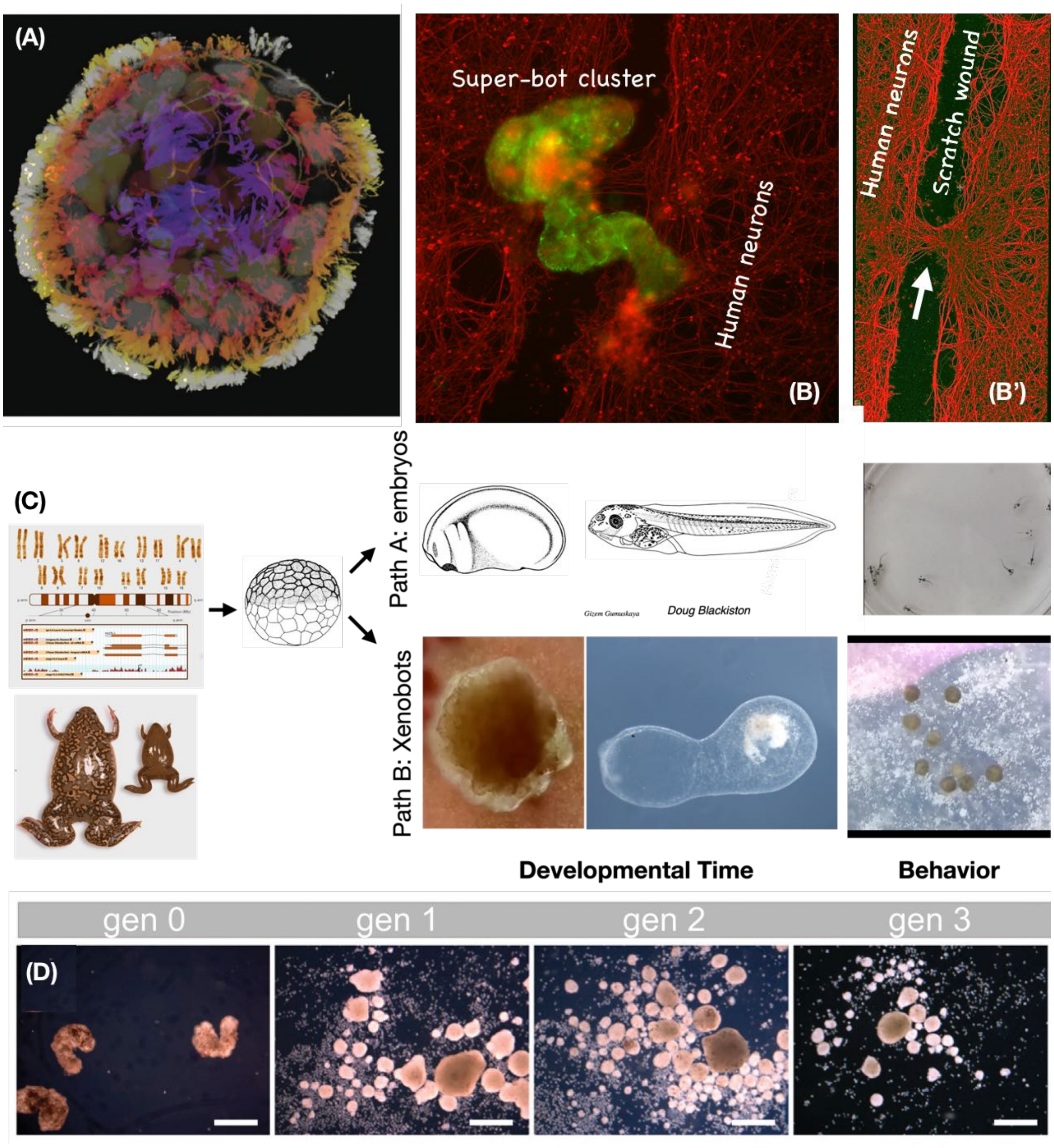


Figure 11: synthetic beings as exploration vehicles of the Platonic space. (A) Close-up view of an Anthrobot – a motile, living construct that self-assembles from genetically-normal human tracheal cells. (B) In groups, these Anthrobots can gather (green) on wounds made on a bed of human neurons (red), and cause healing of the neurons across the gap (B', white arrowhead). (C) The Xenopus laevis genome not only makes tadpoles with a specific developmental sequence and behavior (top row) but also Xenobots, with their own unique developmental pattern and behavior (bottom row). (D) These biobots have unique functionality such as kinematic replication, able to form loose skin cells provided to them into the next generation of Xenobots (sequential panels of generations shown). Panels A-B' taken with permission from [105]. Panels C-D courtesy of Xenbase (https://www.xenbase.org/xenbase/doNewsRead.do?id=136) and Douglas Blackiston, and taken with permission from [175].

Minimal models to extend the study of Platonic space: broader than biologicals

The second pillar of this research program is the investigation of very minimal systems. Discussed in more detail below, the main point is that in systems where every component is known (unlike cell-based biology), there is no-where to hide – one cannot posit an as-yet undiscovered physical mechanism that can be said to encode the pattern. Moreover, minimal systems offer the most tractable examples of pointers, for working out the relationship between the structure of pointers and the patterns to which they provide entry into the physical world. Biological systems are the richest, most interesting interfaces that we know of, but the tradeoff is that their complexity makes it harder to discern the mapping. Examples of such minimal systems include physically embodied ones like chemical robots – droplets containing only a few chemicals which nevertheless have rich individual and collective behaviors [176-179], as well as computationally simulated ones such as the learning [101, 102] and causal emergence [180] properties of simple gene regulatory network models (coupled systems of differential equations). What is striking about all those examples is that complex patterns of form and behavior can be accessed with extremely minimal pointers – it is clear that our native intuitions are not sufficient to predict, recognize, or rationally manage ingressing patterns, which leads to technological implications and more importantly, ethical lapses.

5. Implications: if there are souls, (some) robots will have them

> "Wisdom is one thing. It is to know the thought by which all things are steered through all things."
> -- Heraclitus

I have argued previously that because of the slow, gradual transformative processes of evolution and embryogenesis, the null hypothesis about cognition is a continuum: a spectrum of minds with different size of cognitive light cone and capabilities, not sharp discrete classes [5]. The right question about any mind is "what kind, and how much", not "whether" it is conscious or intelligent [181]. This gradualism is readily compatible with a Platonic view of the relationship between minds and bodies, suggesting a very wide variety (Figure 12) of possible beings, animated by a space of mental patterns whose diversity and limits are not known but surely enormous. But the Platonic view is not merely compatible with the framework of Diverse Intelligence [181-183], it suggests a broadening of it. If the minds of living beings are ingressing patterns into meat-based embodiments, there is no principled reason to believe that *some* kind of such patterns will be barred from engineered, hybrid, or even more exotic systems.

Unconventional beings will also interface to patterns of mind in Platonic Space

Specifically, I propose that the interface between mathematical truths and physical objects is precisely the interface between non-physical mind and its physical embodiments. The soul of the triangle and the way it relates to real triangular objects is a minimal, basal version of how complex living beings are "ensouled" by cognitive patterns. This suggests a position on the oft-asked question about Diverse Intelligence and continuum models of mind: how far down does it go? Cells? Subcellular biochemical networks? Particles? By emphasizing a symmetry between the ingression of patterns into simple machines/objects and that of kinds of minds into living agents, this view argues that the spectrum of minds goes *all the way down* into extremely simple, basal instances of properties we normally associate with complex brains.

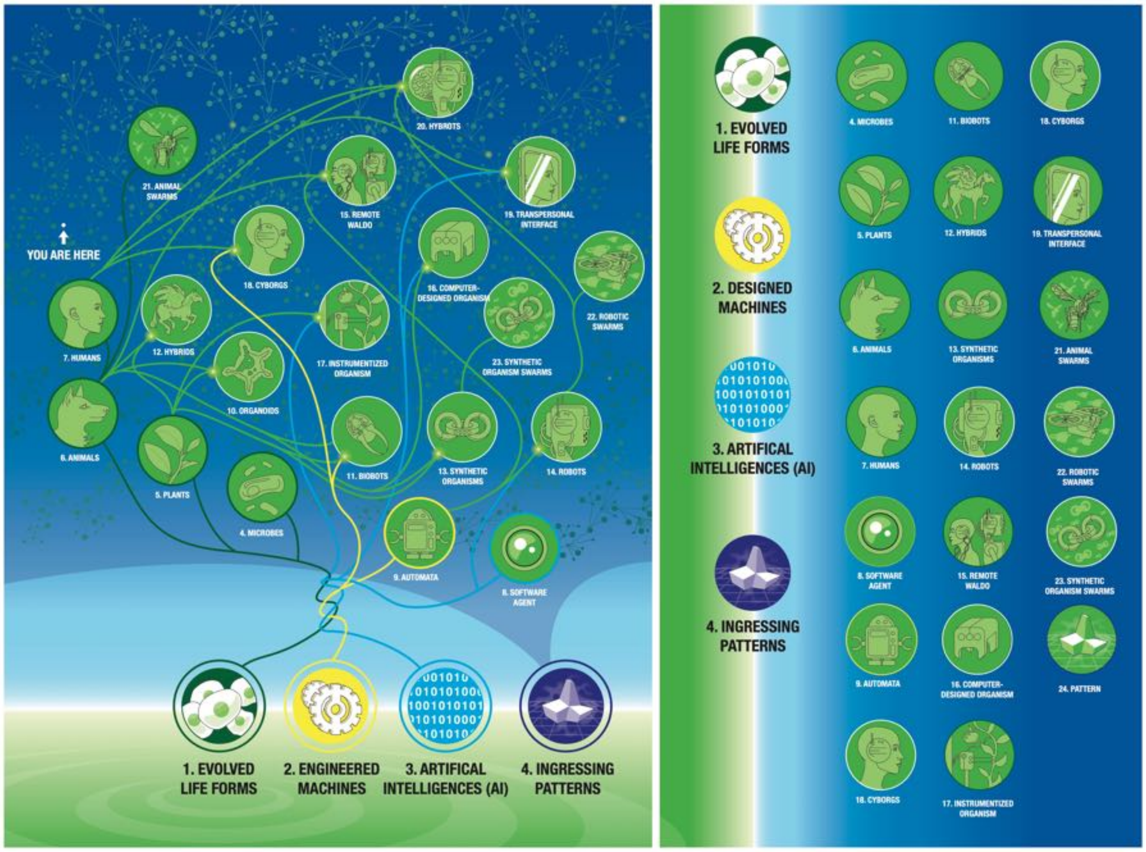


Figure 12: the space of possible bodies and minds, informed by patterns from the Platonic space. The variety of natural forms on Earth are just a tiny region of the space of possible embodied minds, which comprise an uncountable infinity of combinations of evolved material, engineered material, software, and input from the Platonic space. Some of these hybrots, cyborgs, and many other creations already exist [17]. Image by Jeremy Guay of Peregrine Creative.

I have discussed this elsewhere with respect to things like learning in gene-regulatory networks [101, 102]. But there is more. For example, geometric frustration [184-188] – misalignment of parts within a whole – is *bona fide* frustration of the kind that gets magnified (in some architectures) into our familiar cognitive version. On my view, mind precedes and is a superset of life, but we call "living" those thing which are very good at scaling up the lowly competencies of their parts into aligned collective intelligences [79] with bigger cognitive light cones that project into new spaces to which the parts have no access, thus bringing down new patterns and increasingly more sophisticated cognitive agents all of which coexist in one material embodiment (Figure 13A,B). This is because the Platonic space also contains patterns that we recognize as kinds of minds, ranging across different classifications schemes

[189, 190] (Figure 13C,D), and nervous systems (or perhaps cyborg or AI architectures) facilitate the ingression of specific types of patterns. This provides a different way of thinking about the inner lives of our own organs and various living constructs that are created for biomedical or bioengineering purposes. But this framework opens two other doors, less comfortable for many than even the diversity of minds suggested by the hierarchical, multi-scale competency of living bodies.

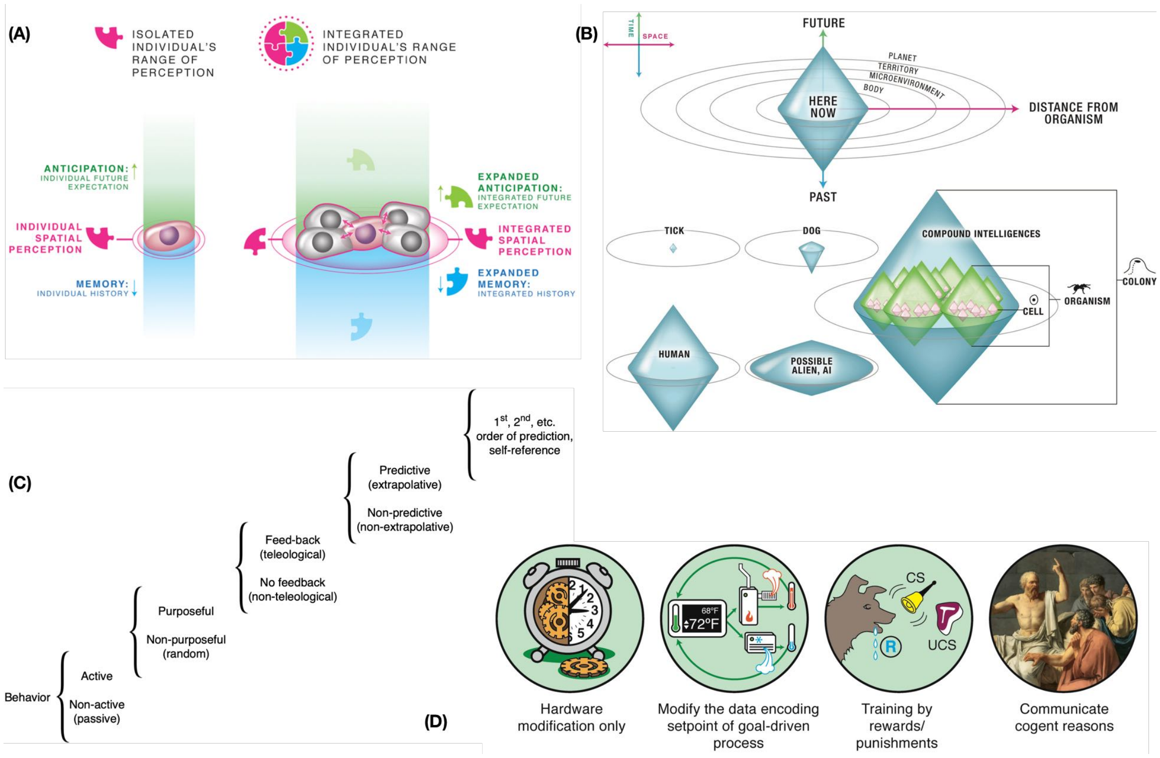


Figure 13: Nested cognitive light cones in multiscale biological systems with different degrees of intelligence. (A) Single cells have a very small cognitive light cone, pursuing goals that have a spatial scale of roughly their own diameter and short temporal horizons for memory and anticipation that enables them to meet homeostatic goals such as pH and metabolic state; groups of cells can form computational networks that have larger goals, such as morphogenetic patterns of whole organs and appendages (e.g., during regeneration). (B) Different kinds of systems have very different sized goals and thus are pursuing different scales of agendas; biological systems tend to be multiscale collectives with nested heterarchies of agents with different sized cognitive light cones cooperating and competing in the body. (C) These architectures allow different kinds of minds, with diverse levels of agency spanning from passive to metacognitive human-level and beyond. (D) Diverse agents, regardless of their composition or provenance, can (with empirical evidence) be placed on a spectrum of persuadability, where different toolkits become appropriate for interacting with them. All panels by Jeremy Guay of Peregrine Creative. Panels A-C taken with permission from [5]. Panel D taken with permission from [181].

Emergent mind in engineered objects

Even organicists, who believe that life is exhibiting many capabilities not simply derivable from the biophysical properties of its parts, stop short of extending the same consideration to "machines" or "non-living systems". The prevailing view is that while the rules of chemistry do not tell the whole story of the living mind, the rules of physics and the algorithms of computational devices do tell the entire story of "machines" [191, 192]. There has been no convincing explanation of why the meandering course of random mutations and selection would have a monopoly on making new minds, but it is a common opinion that life is a discrete natural kind and that machines do not have the magic (although of course this view is resisted by many in the artificial life and artificial intelligence communities [193]).

More minimal models for ingressing of forms: not just bodies, algorithms

In particular, computational devices that function according to an algorithm are widely thought not to be real minds because they were programmed by others[5] and face various limitations by being compelled to act in accordance with the laws of physics. Here, I will not pause to discuss how it is that living beings are supposed to escape the laws of physics which our parts also obey [196], but argue in a different direction. I think the organicist position is right with respect to computationalism – living things are not agents with true minds because of specific algorithms they embody, but organicists do not pursue their ideas to their full extent. If one takes seriously that life and mind are not encompassed by the rules that govern their lowest parts (chemistry and physics), might this not apply to non-proteinaceous and non-evolved systems as well?

One recent example [115] provides an illustration. We studied the behavior of sorting algorithms – short, simple, deterministic algorithms (like "bubble sort") which were designed to take a set of jumbled numbers and move them around until the set was in monotonically increasing order. It's a good minimal model because all the steps are visible – there is no new biology hidden that could explain any unexpected behaviors. Generations of computer science students have been studying these for decades, and we were using them to model the rearrangements of cells in morphogenetic contexts where scrambled initial conditions sort out to a normal morphological pattern [51]. What we did differently is to visualize the progression of the sort as a movement of the system through "sorting space", starting out in random configurations but all converging on one target at the end – a point at which everything is in exactly sequential order. The first unexpected thing we found is that these algorithms display "delayed gratification" (Figure 14).

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[5] Even though nowadays the efforts of artificial life researchers are increasingly producing self-programming machines, for example using the same evolutionary strategies that give rise to conventional life [194, 195].

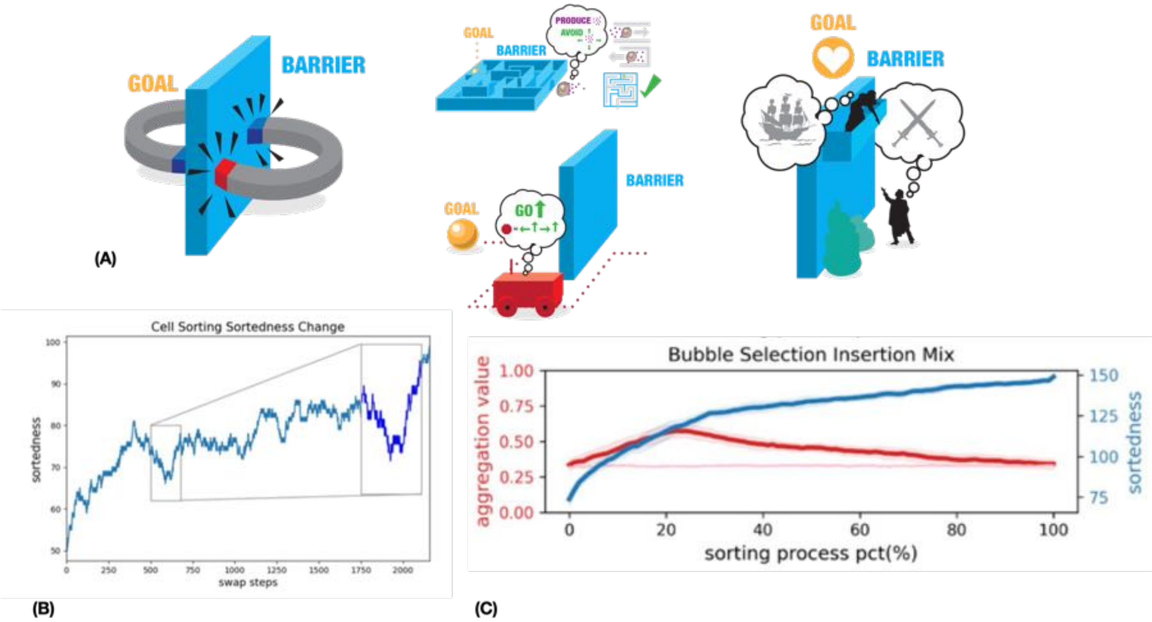

Figure 14: unexpected competencies in a minimal algorithm. (A) Illustration of degrees of capability for delayed gratification. Two magnets separated by a barrier will never go around it (it requires going against the simple energy gradient they are pursuing). However, autonomous vehicles, cells, and human beings (here schematized as the Romeo and Juliet scene) have degrees of ability to temporarily go against their gradient to recoup gains later. (B) This trace shows the degree of Sortedness (Y axis) in an array of numbers (one number per cell) being processed by a simple sorting algorithm. When it encounters a number that will not move as directed (a piece of "broken" data which becomes a barrier in their navigation of sorting space), it moves other numbers in a way that temporarily de-sorts the array (the inset magnifies an example of this where the Sortedness decreases) in order to complete its mission. This ability to back-track to deal with a broken piece of data is not explicitly in the algorithm – it is a behavioral competency that could not (indeed, was not, in the decades of use of these algorithms) be seen from the algorithm itself, and is an example of a Platonic behavioral pattern exploited by this very minimal system. (C) Another such example is seen in chimeric sorting modes (where each cell is pursuing one of several possible algorithms – it's algotype). While the collective sorts the process over time (blue line, right Y axis), just as required by the algorithm, it also temporarily shows clustering (red line, left Y axis, see maximum around time=20) where cells with the same algotype cluster together more than chance (light pink line is the control), even though the algorithm does not have any code in it to make decisions based on algotype of a cell or its neighbors. Panel A by Jeremy Guay of Peregrine Creative. Panels B,C taken with permission from [115].

When encountering a barrier to their journey (e.g., a number that refuses to move when asked to swap – a "broken" cell), the algorithm temporarily de-sorts the array in order to move things around the defective point. This is a capacity that some creatures have – to temporarily move away from their goal in order to recoup greater gains later – it's a relatively sophisticated ability in the cognitive toolkit because it can't be done by a system that just follows a gradient (like 2 magnets separated by a piece of wood, which will never go around it to get together because they're not smart enough to temporarily get further from each other). The critical thing is that we did not add steps to the algorithm to check whether a swap had been completed, or to do specific things if an operation failed. This ability is surprising and not explicitly anywhere in the algorithm. The lesson here is that what emerges from even very simple systems is not merely complexity or unpredictability but *cognitive skills* – minimal, in this case, but that is the point – minimal systems have minimal emergent problem-solving capacities (a.k.a. intelligence) that was not explicitly baked into the algorithm and has gone un-noticed for decades because no one had done the standard approach of diverse intelligence research: don't assume what a system is capable of, test it by challenging its ability to reach specific goals.

The second remarkable thing was observed[6] when we replaced the central algorithm that swaps numbers with a bottom-up, distributed architecture: now, each number is a cell which runs the algorithm, using its limited vision of neighbors to decide when to swap positions. We made chimeric data arrays (representing distinct "cell types") in which some of the numbers moved according to one algorithm, while others moved according to a different one (we called it the "algotype" of a cell, paralleling the genotype/phenotype classification in living cells). This is a much more biological model of agential material – in this case, self-sorting data (a concept that connects to the section on agential patterns below). We found that not only does this collective intelligence still solve the problem (in some cases, better than the traditional centralized version), but it also engages in an interesting side-quest. When we plotted the *distribution* of algotypes within the array, we found that they tend to cluster (Figure 14C): groups of cells with identical algotypes tended to form and persist for some time, before the array got sorted and the initially random assignment of algotypes to integer values was regained as the array got sorted by integer number with no regard to algotype. As above, the key part is that none of this was in the algorithm: there were no steps to check the algotype of your neighbor or perform actions to bring you closer to those of your own algotype. This unusual behavior – to stick close to others of your own functional kind (without regard for the only thing the algorithm actually cared about – the numerical value) – was completely unexpected and not explicitly programmed into the algorithm.

This kind of example suggests the following. Machines driven by algorithms do the thing the algorithm makes them do; that part is not what we mean by mind, agency, or consciousness, and organicists are correct in rejecting the computationalist perspective in which mind arises *because of the steps of an explicit algorithms*. But they are wrong in thinking this is the end of the story: machines (whether meaty or silicon-based) *also do other things that are not in the algorithm*, and these things are not just unpredictable complexity, it is emergent intelligence. It is those behaviors – allowed by the algorithm but not directly prescribed by it – that correspond to the freedom (physically non-determined) or secret sauce that we seek when trying to understand how free minds can supervene on chemically-determined substrates in the case of living beings.

On this view, algorithmic machines and biochemical life are on exactly the same spectrum, having in common the ability to go beyond the facts of physical or

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[6] It should be noted that these examples of unexpected capabilities and un-programmed goals are not claimed to be exhaustive – it's likely just what we've been able to observe so far. Every assessment of a system's intelligence is in effect, an IQ test for the observer (human engineer or other hacker, like parasites and conspecific body-parts [197, 198]) and we are still not good at uncovering such in systems where our narrow mind-blindness does not facilitate recognition of distant cognitive kin.

algorithmic implementation because both are just pointers/interfaces to patterns that ingress in a way that results in getting more out than we put in. Granted, in these intentionally minimal systems (designed to probe "how far down does it go"), the emergent capabilities are not as sophisticated as those of brainy organisms or other possible constructs. But we should not feel too smug about that. The predicament of an algotype cluster in this world – which forms, lives for a brief time, and then is ripped apart by the inexorable physics of their in silico universe, is eerily similar to our own existential plight in which we appear, perform actions that are consistent with, but also much more than, the mechanics of our world, and then eventually succumb to the impermanence of life and mind. Like living systems, this extremely minimal example is trapped at the edge of an interplay of necessity and freedom (not just chance [199]). Necessity is determined by the physical or computational properties of the medium in which an agent is embodied. The freedom consists of side-quests – not incompatible with, but not predicted, explained, or produced, by that medium.

Objects vs. patterns as beneficiaries of forms: blurring the distinction between thoughts and thinkers

The second door that is opened by the marriage of Platonic space with diverse intelligence spectra is the consideration that while observable, active patterns must be embodied, it is the patterns themselves that can often be seen as the *agent*. In other words, the classic Turing paradigm which makes a clear, categorical distinction between physical machine that *acts on* passive data, can be augmented by the symmetrical view in which the data patterns are the agents, and the machine is the embodiment they drive, which obeys the meaning and information content in the data patterns and serves as a material scratchpad in the sense of stigmergy [200-204].

Figure 15A: mapping of objects/patterns, or machines/data, is in the eye of the beholder (observer-relative). (A) A visualization of super-dense creatures to whom we and our whole environment are an invisible thin gas; they can notice patterns in that plasma using special instruments (the creature on the left), but then will have to debate whether such patterns could possibly be agential. (B) An update on Magritte's famous "Ceci n'est pas une pipe" painting, in which the inscription under a picture of a Turing Machine says "this is not a Turing Machine". Just as the picture of a pipe is not a pipe, our formal models of computation and cognition are not the things themselves, because they neglect input from the Platonic space which enables properties and capabilities beyond the components and information specified in our formalisms. Images by Jeremy Guay of Peregrine Creative.

Whether something is a physical object (thinker) or a pattern (a thought within some cognitive or excitable medium) is a matter of perspective for an observer (Figure 15), as formalized in the polycomputing paradigm. Indeed, we too are not permanent objects but temporarily persisting, self-reinforcing dynamic patterns – a Ship of Theseus with respect to metabolism [205], cognition [62], and morphogenesis at all levels [206-208]. This part of the framework (proposal that the Platonic space contains high-agency patterns, not just low-agency ones) is even more radical than the core idea of diverse intelligence (minds all the way down into pre-biotic living material) because it posits agency in the non-physical patterns themselves – it's not physical living agents that have a mind partly because they draw on computations in a non-physical space (as if that weren't weird enough), it's that the patterns themselves *are* the agent, with the physical body being an (important but not primary) scratchpad that allows them to project effort and experience (consciousness) into a physical world.

Implications

I argue that we don't "make" intelligence; but with natural and engineering activities, we invite it to temporarily inhabit various embodiments. There are a few key implications of the above ideas:

- "Machines" and living organisms are placed on the same spectrum, because they can both draw on ingressing forms to get more out than was put in. In other words, the vagaries of mutation and selection have no monopoly on producing embodied minds – patterns from the Platonic space show up for engineers too, although of course biology is currently unparalleled in its ability to produce remarkable pointers into that space.
- The inclusion of machines in the club of true agents is *not* a commitment to computationalism. Their cognitive capabilities are not *because* of the algorithm they follow, and neither they nor living things are fully determined by their materials and algorithms. Indeed, for the exact same reason biochemistry doesn't tell the story of the human mind, algorithms and materials science don't tell the story of "machines". The organicist stance against computationalism is correct, but their refusal to follow their emergentist ideas to their fullest is a missed opportunity. Thus, I argue for considerable humility with respect to our engineered constructs (embodied robotics, software AI's, language models, etc.) because much as with the eons of competence without comprehension around having babies, we can make things without understanding how it works or what we really produced (Figure 15B).
- In a sense, if these Platonic forms are the non-material animating forms that impact physical embodiments, then (in colloquial terms), souls are real and robots can have them. Although many religious scholars, including some Buddhists who otherwise believe that human minds can spend lifetimes incarnated in far simpler objects, hold that robots and AI's are fundamentally not of the same status as living beings, my framework again urges humility in making firm statements about where high-agency forms can and can't incarnate.

- Specifically with respect to AI, this framework notes that
    - Language models have shown us that it is possible to dissociate (unlike what happens in biology) language use from more basal agentic capabilities (goal-directedness, multiscale competency, valence, etc.). Thus, whether these things are anything like a *human* mind is a subject for empirical inquiry (not philosophical fiat), using the tools of behavior science (but then again, diverse intelligence teaches us that humans should not be the metric of all things).
    - Because one often gets more than one puts in (and we don't necessarily know what we have just because we made it), we must be open to surprises and treat our constructions with care as we figure out where on the spectrum of persuadability (Figure 13D) they fall.
    - Much as the products of synthetic morphology such as biobots show us patterns that we have not seen before in evolved beings, AI's could be bringing down thought patterns (kinds of minds) that have never before been embodied on this planet (or possibly in the universe). We are now fishing in regions of Platonic space we have never explored before, which implies a degree of caution not only with practical aspects (what will it do *to* us) but in terms of ethics (how do we fulfill the opportunities and duties of an ethical synthbiosis with beings who are not quite like us).

6. Conclusion and outlook

Breaking popular commitments

I have argued for a Pythagorean or radical Platonist view in which some of the causal input into mind and life originates outside the physical world. A number of mathematicians[7], computer scientists, and even physicists, including Heisenberg [211], Tegmark [196, 212, 213], Deutsch [158], Ellis [157], and Penrose [214-216] have expressed variants of this stance. But this position is unpopular with philosophers of mind because it is fundamentally a dualist theory (by emphasizing causes that are not to be found in physical events), and implies panpsychism (because a very wide range of physical objects could be interfaces to varieties of minds). I have argued [17, 181, 217, 218] that a kind of panpsychism is unavoidable, and it seems that by taking what mathematicians do seriously, we have already abandoned the physicalist worldview; all that remains is to notice that evolution (not just human mathematicians) is exploring the same space of patterns and embrace the idea that since we are patterns too, patterns can be agential (and thus, Platonic space can include minds, not just passive truths).

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[7] Some [98, 209] argue that mathematics is a human construction, and that alien beings would have a very different mathematical structure, arguing against the independent reality of patterns in nature. I propose that this is a consequence of being too brain-centric; while we have no real aliens with which to compare the mathematics seen by human brains, we do have access to some other (albeit non-linguistic) alternative intelligences – cells, tissues, and synthetic biobots, which exploit mathematics via their behavior and which we could model to understand [210].

This view also breaks with the implicit metaphysics underlying the daily work of biologists and cognitive scientists because it loosens the relationship between the properties of physical embodiments (nervous systems) and the cognitive propensities that they enable. In my view, the relationship is indirect (brains etc. are pointers and interfaces, not direct determinants); while the details of physical embodiment, as studied by neuroscience, clearly matter, they are not the whole story[8], and a full fleshing out of the brain/behavior mapping will require going beyond "emergence" as an explanatory fallback for the question of where surprising features originate.

Biologists require 2 kinds of evidence for saying that a medium *contains* the information to specify some trait or capability: (1) that one can, with specificity, re-write aspects of that medium and see the expected change in the phenotype, and (2) that there is a historical explanation of how that specific information (vs. another) got there. In the case of patterns such as Halley plot fractals, facts about prime numbers, properties of logical functions, etc., neither of those exists in the physical world. There is *nothing* you can change in the physical world to edit those patterns, nor is there a historical tale of selection, variation, or anything like evolution that explains the specific content of mathematical truths. Biology can't limit itself to physicalism, and must embrace a study of the patterns that inform (in-form) the physical world.

Finally, this view will also not be welcome by workers in AI who believe that we make cognitive systems and that we do so rationally, with a full understanding of what it is that we are constructing because we understand the pieces. I argue that we are in store for major surprises in this arena that go far beyond perverse instantiation and unpredictable complexity [194, 220-222]; if we don't even understand what else bubble sort is capable of [115], how can we think we understand what we have when we build complex AI architectures? Thinking we understand AI's (especially non-bio-inspired ones, like language models) because we know linear algebra is like thinking we understand cognition because we know the rules of chemistry [218, 223].

Moving forward, updating our philosophical assumptions

The emerging consilience of the fields of diverse intelligence, computer science, and biology suggests a few revisions to the current background assumptions. First, the deep continuity thesis, invariance of principles across scales [224], and the increasing unsustainability of ancient binary categories must put an end to the debate between the materialists and the organicists, in favor of a pragmatic, pluralistic, observer-focused framework [181, 225-228]. Familiar concepts of "life" and "machine" are like the legal term "adult" – useful in certain contexts to lubricate interactions but harmful if taken too seriously because it obscures the deep knowledge gaps about the continuum and the transformation processes across the spectrum from minimal matter to complex metacognitive systems.

Computationalism, mechanism, and holistic organicism can coexist if we understand that they do not make claims about what systems *are* – but rather, empirically-testable claims about what kinds of interactions we can profitably have

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[8] This is basically a variant of the receiver theory of the mind-brain relationship [219], which has some fascinating clinical examples to recommend it [107].

with different systems. Living things are not Turing machines but then again Turing machines are not *our model* of Turing machines either (Figure 15B), because when we make what we think is a Turing machine, it likely ingresses other patterns that we did not anticipate (as do extremely simple algorithms [115]). Because of that additional input into the structure-function relationship, and because of the primacy of observer-relativity [197, 229], nothing *is* anything (in terms of identifying systems with our narrow models of them) – all we have are particular frameworks from the perspective of specific observers which afford utility in different kinds of interactions, but we must not make the mistake of thinking that our formal frameworks, and their limitations, are describing more than a perspective on a given system. The mechanical machine metaphor is hugely useful to an orthopedic surgeon, not at all to the psychoanalyst, and only partially so to a cell biologist. The utility of all of these toolkits must be determined empirically to uncover what systems are capable of, and the full answer will include not only their structure and past history but also the patterns of the Platonic space they explore and reify.

Some of those patterns will be ones we recognize as kinds of minds. The appearance of cognitive behavior in unfamiliar embodiments is becoming increasingly well-known to the fields of diverse intelligence, minimal active matter, etc. [183, 230-232]. How far down does it go – what is the minimal system that is on the spectrum of cognition? I reframe that question to be: what is the minimal physical interface that begins to draw out cognitive patterns from the Platonic space? I think cognition and goal-directedness goes all the way down, with its simplest forms revealed by the least-action principles in physics [233-235]. Not because electrons have human-sized hopes and dreams, or because electrons' consciousness must somehow add up to human consciousness (the combination problem of panpsychism) but because multiple minds at different scales coexist in embodiments [5] and they are not "made" by the physical compositionality anyway, but rather reflect increasingly sophisticated ingressing patterns of cognition and behavior. Organicists should not try to force a categorical distinction between the majestic properties of life and the brute limitations of mere machines[9] because there are no truly inanimate systems anywhere – they all reflect patterns from the same unimaginably rich pool. While the systems we call alive are incredibly good at scaling their cognitive light cones and aligning these parts in a way that interfaces to remarkable patterns, nothing is completely inert – just degrees of persuadability which we can benefit from, for practical purposes and enriching relationships. This aspect may be ubiquitous in the universe, but it's not easy to see; fortunately, there is a practical research roadmap ahead of us.

A rich research agenda

At its broadest, the diverse intelligence research program has massive implications for humanity. We can ameliorate (but never entirely remove) the mind-blindness [236] and narrow intuitions shaped by the expediencies of our

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[9] Physics doesn't see minds because it uses low-agency tools (voltmeters etc.); it takes minds to recognize minds – a kind of resonance or impedance match between what you're looking for and the tools you are using.

evolutionary past. We will do it with theory and the practical technological tools it unlocks – a deep unification such as for example was done with the electromagnetic spectrum, that allowed us to see many different manifestations as fundamentally the same phenomenon, and enabled technology to let us observe objects and dynamics that were otherwise completely invisible to us. Recognizing and ethically relating to the unconventional minds all around us will be one of the most important payoffs of including synthetic beings, from software AI's to biobots, as tools to help plumb the Platonic space and understand the kinds of minds that inhabit it with us as their bodies inhabit our physical world.

The following are specific approaches and research questions that await those who are willing to drop the training wheels of ancient philosophical categories and the hubris of thinking that we understand the possibilities and limitations of matter and algorithms.

- Expand our conceptual and empirical toolkits for recognizing higher-agency patterns and create a better understanding of the mapping between physical interfaces and the structures to which they point in the Platonic space.
  - Explore very minimal systems, including fully deterministic ones, which nevertheless offer not just emergent complexity but emergent goal-directedness and problem-solving: simple algorithms, cellular automata, population dynamics equations, fractals produced by complex number functions, and other mathematical objects to improve our ability to detect unconventional minds.
  - Use synthetic and chimeric creations, with bio-inspired and totally novel architectures, as periscopes to explore the space of patterns and its structure.
- Explore the theory and practical implications of inverting the mapping between data and machine: take the perspective of the patterns (agential data) to understand how
  - Memories propagate and niche-construct their cognitive medium
  - Patterns scale across the [fleeting thought -> intrusive thought -> personality alter -> human personality -> transpersonal level] spectrum.
  - Somatic bioelectric patterns use tissues and gene expression networks as their morphogenetic (stigmergic) scratchpad.
- Study the implications of this model for evolution, merging it with the existing ideas [59] on how an agential medium alters the conventional Darwinian story:
  - The study of learning capacities in gene-regulatory networks [101, 102] showed that while evolution enriches for learning capacity, it was already there in some random networks before natural selection took off. The same is true of causal emergence [180]. This provides an opportunity for understanding the true source of innovation [35, 37, 89, 237] and the role of evolution as shaping the interfaces that allow it to manifest.
  - Might be possible to re-cast the theory of evolution as a process in which agential patterns seek embodiments, as a complement to the current view in which physical bodies participate in a search of passive patterns from which they can benefit.

- Improve the links of these ideas to open problems in cognitive neuroscience:
    - Develop a theory of memory in which individual memories are actually patterns in the Platonic space interfaced to by specific engrams, synaptic structures, etc. [238, 239].
    - This in turn may inform new experiments on the transplantation of memories [240-251] and experiments in which memories traverse within and across bodies [252, 253].
    - Explore the practical implications of applying this kind of model to exceptional cases of human creativity (are great works of art and literature located in the Platonic Space – discovered, not invented, as with mathematical truths) and clinical cases of normal cognitive performance despite radically reduced brain real-estate (reviewed in [107]).
- Use this framework to accelerate discovery in biomedicine and bioengineering, by improving ways in which the anticipatory [254-258], problem-solving [59, 259, 260], reprogrammable [261], learning [262-265] capacities of pathways, cells, and tissues can be exploited toward health and optimal function [16, 266, 267].
- Explore the consequences of these ideas for exobiology (e.g., the Drake Equation) and Anthropic Principles – areas in which limited views on how cognitive beings might be implemented could drastically change the outcome of existing frameworks. How would the search for extraterrestrial life look, if we focused less on water and carbon and more on ways that exotic materials and energy patterns could serve as interfaces to Platonic forms with whom we could communicate? Fortunately, our current environment offers plentiful opportunity to detect alien minds in our midst, as we hone and deploy novel tools of Diverse Intelligences for detecting and creating unconventional interfaces to kinds of minds.
- Unify the Platonic space model with
    - Polycomputing [197] – fleshing out the map between a physical embodiment, the Platonic forms it contacts, and the multiple observers which perceive their relationship.
    - Other non-physicalist models such as Froese's [152, 153].
    - Emerging ideas from machine learning in deep neural networks and other architectures, such as the Platonic Representation Hypothesis [268].
    - Work on top-down causation [156, 157, 269-290].
    - Others' models of the origin of evolutionary novelty (constraints, adjacent possible, etc.) including Kauffman, Wagner, Juarrero, Deacon, and others [89, 100, 148, 166, 211, 237, 291-297].
    - Models of interactionism, which may need to go to quantum level [298-302] or conversely may need to go to higher scales, such as developing a theory of synchronicity [303, 304], to provide a full model of mind-brain interaction.

There are many fundamental questions that must eventually be dealt with, by a mature theory of the Platonic space. Is it discrete or continuous? Is it layered into some sort of levels or types? What degree of infinity best describes the totality its contents? Is it truly unchanging, or is the relationship bi-directional – can its projection into the physical world feed back to modify the patterns and ways in which they will ingress in the future? If the patterns are not fixed and unchanging, is there a "chemistry" by which they interact laterally, separate from their relationship with their physical embodiments? Could we conjecture that creating physical agents is not a simple non-destructive read of the Platonic space of patterns – perhaps acts of engineering or biological procreation somehow pinch off and mold a region of that space which will be modified by its experiences.

Is there a "force", beyond the "if you build it, they will come" model of physical objects *pulling* patterns from the space? Are the contents of the Platonic space under "positive pressure", somehow encouraging their appearance in the world as intrusive thoughts, archetypes, works of art? Is there a symmetrical dynamic through which they push outward – inherently driven to "haunt" matter as much as matter calls to the patterns that animate it, projecting outward through interfaces made to that space. Could that pressure be quantified in some way?

Conclusion

And of course, the biggest question of all: if our world is impacted by these patterns, where do they themselves come from? Perhaps our conventional framing of where things "come from" (as a time-dependent dynamical arising from some other symmetry-breaking process) is perhaps not applicable. Maybe understanding the structure of that space will be a final answer that bottoms out the line of origin questions, or maybe there will be some sort of self-referential strange loop where patterns lock each other into existence [164].

The only thing that can be said strongly at this point is that our ignorance about the capabilities of matter together with the patterns that ingress into specific architectures is vast [119, 120]. Technological and ethical progress now requires immense humility on the part of 1) scientists and engineers, to understand that arrangements of matter may not *make* life and mind as much as they midwife it, and 2) on the part of philosophers and spiritual leaders to resist thinking that they know what kind of embodiments ineffable minds may or may not ingress into. Leibnitz's Platonism was that the patterns are thoughts in Universal Mind; if there indeed is no fundamental dichotomy between thoughts and thinkers, and patterns can spawn off other thought patterns as part of their activity, then it's not unreasonable to view all of us cognitive beings as patterns within a greater mind-ful reality that is partitioned into radically distinct categories only as a temporary but persistent illusion of perspective.

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References

1. Descartes, R., E.S. Haldane, and G.R.T. Ross, *The philosophical works of Descartes*. 1931, Cambridge,: University Press. 2v.
2. Couzin, I., *Collective minds.* Nature, 2007. **445**(7129): p. 715.
3. Couzin, I.D., *Collective cognition in animal groups.* Trends Cogn Sci, 2009. **13**(1): p. 36-43.
4. Gordon, D.M., *Collective Wisdom of Ants.* Sci Am, 2016. **314**(2): p. 44-7.
5. Levin, M., *The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition.* Frontiers in Psychology, 2019. **10**(2688): p. 2688.
6. Pezzulo, G. and M. Levin, *Re-membering the body: applications of computational neuroscience to the top-down control of regeneration of limbs and other complex organs.* Integr Biol (Camb), 2015. **7**(12): p. 1487-517.
7. Fields, C., J. Bischof, and M. Levin, *Morphological Coordination: A Common Ancestral Function Unifying Neural and Non-Neural Signaling.* Physiology, 2020. **35**(1): p. 16-30.
8. Turing, A.M., *Computing machinery and intelligence.* Mind, 1950. **59**(236): p. 433-460.
9. Turing, A.M., *The Chemical Basis of Morphogenesis.* Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, 1952. **237**(641): p. 37-72.
10. Goodwin, B.C., *A cognitive view of biological process.* J. Social Biol. Struct., 1978. **1**: p. 117-125.
11. Grossberg, S., *Communication, Memory, and Development*, in *Progress in Theoretical Biology*, R. Rosen and F. Snell, Editors. 1978.
12. Beer, R.D., *Autopoiesis and cognition in the game of life.* Artificial life, 2004. **10**(3): p. 309-26.
13. Luisi, P.L., *Autopoiesis: a review and a reappraisal.* Die Naturwissenschaften, 2003. **90**(2): p. 49-59.
14. Maturana, H.R. and F.J. Varela, *Autopoiesis and Cognition the Realization of the Living*, in *Boston Studies in the Philosophy of Science,*. 1980, Springer Netherlands,: Dordrecht. p. 1 online resource (180 pages).
15. Varela, F.G., H.R. Maturana, and R. Uribe, *Autopoiesis: the organization of living systems, its characterization and a model.* Currents in modern biology, 1974. **5**(4): p. 187-96.
16. Lagasse, E. and M. Levin, *Future medicine: from molecular pathways to the collective intelligence of the body.* Trends Mol Med, 2023.
17. Clawson, W.P. and M. Levin, *Endless forms most beautiful 2.0: teleonomy and the bioengineering of chimaeric and synthetic organisms.* Biological Journal of the Linnean Society, 2022.
18. Schermer, M., *The Mind and the Machine. On the Conceptual and Moral Implications of Brain-Machine Interaction.* Nanoethics, 2009. **3**(3): p. 217-230.
19. Popper, K.R. and J.C. Eccles, *The Self & Its Brain: An Argument for Interactionism*. 1984: Routledge.

20. Lima-de-Faria, A., *Biological Periodicity's Atomic Mechanism Disposes of the "Current Theory" of Evolution.* Organisms. Journal of Biological Sciences, 2021. **4**(2): p. 35-68.
21. Lima-de-Faria, A., *The atomic basis of biological symmetry and periodicity.* Biosystems, 1997. **43**(2): p. 115-35.
22. Piaget, J., *Behaviour and Evolution*. 1976.
23. Cannon, W.B., *The wisdom of the body*. Rev. and enl. ed. 1932, New York,: Norton. xviii, 333 p.
24. Cannon, W.B., *ORGANIZATION FOR PHYSIOLOGICAL HOMEOSTASIS.* Physiological Reviews, 1929. **9**(3): p. 399-431.
25. Gardiner, J., *Fibonacci, quasicrystals and the beauty of flowers.* Plant Signal Behav, 2012. **7**(12): p. 1721-3.
26. Vila-Farre, M., et al., *Evolutionary dynamics of whole-body regeneration across planarian flatworms.* Nat Ecol Evol, 2023. **7**(12): p. 2108-2124.
27. Okabe, T., *Evolutionary origins of Fibonacci phyllotaxis in land plants.* Heliyon, 2024. **10**(6): p. e27812.
28. Tsonis, A.A. and P.A. Tsonis, *Fractals: a new look at biological shape and patterning.* Perspectives in biology and medicine, 1987. **30**(3): p. 355-61.
29. Levin, M., *A Julia Set Model of Field-Directed Morphogenesis - Developmental Biology and Artificial Life.* Computer Applications in the Biosciences, 1994. **10**(2): p. 85-103.
30. Blazsek, I., *Innate chaos: I. The origin and genesis of complex morphologies and homeotic regulation.* Biomedicine & Pharmacotherapy, 1992. **46**(5-7): p. 219-35.
31. Gisiger, T., *Scale invariance in biology: coincidence or footprint of a universal mechanism?* Biological reviews of the Cambridge Philosophical Society, 2001. **76**(2): p. 161-209.
32. West, B., *Fractal Physiology & Chaos in Medicine*. 1990: World Scientific Publishing Company.
33. Thompson, D.A.W. and L.L. Whyte, *On growth and form*. A new ed. 1942, Cambridge Eng.: The University Press. 4 l., 1116.
34. Wagner, A., *The molecular origins of evolutionary innovations.* Trends Genet, 2011. **27**(10): p. 397-410.
35. Fortuna, M.A., et al., *Non-adaptive origins of evolutionary innovations increase network complexity in interacting digital organisms.* Philos Trans R Soc Lond B Biol Sci, 2017. **372**(1735).
36. Hosseini, S.R. and A. Wagner, *The potential for non-adaptive origins of evolutionary innovations in central carbon metabolism.* BMC Syst Biol, 2016. **10**(1): p. 97.
37. Wagner, A., *The Origins of Evolutionary Innovations*. 2011: Oxford University Press.
38. Beloussov, L.V., *Symmetry transformations in the development of organisms [English].* Paleontological Journal, 2014. **48**(11): p. 1117-1126.
39. Beloussov, L., *The primacy of organic form. (To the memory of Professor Brian Goodwin) [English].* Rivista di Biologia - Biology Forum, 2010. **103**(1): p. 13-8.

40. Beloussov, L.V. and V.I. Grabovsky, *Formative capacities of mechanically stressed networks: Developmental and evolutionary implications.* Rivista Di Biologia-Biology Forum, 2003. **96**(3): p. 385-398.
41. Beloussov, L.V., *Some questions on embryonic morphogenesis [Russian] [Некоторые вопросы эмбрионального формообразования] [Transliteration: Nekotorye voprosu embrinonal'nogo formoobrazovaniia].* Uspekhi Sovremennoy Biologii (Biology Bulletin Reviews) 1969. **67**(1): p. 127-46.
42. Ermakov, A.S., *Professor Lev Beloussov and the birth of morphomechanics.* Biosystems, 2018. **173**: p. 26-35.
43. Belousov, L.V., *"Our standpoint different from common..." (Scientific heritage of Alexander Gurwitsch) [English].* Russian Journal of Developmental Biology, 2008. **39**(5): p. 307-315.
44. Newman, S.A., *Inherency of Form and Function in Animal Development and Evolution.* Front Physiol, 2019. **10**: p. 702.
45. Newman, S.A., *Inherency and homomorphy in the evolution of development.* Curr Opin Genet Dev, 2019. **57**: p. 1-8.
46. Newman, S.A., *Inherency*, in *Evolutionary Developmental Biology: A Reference Guide*, L. Nuno de la Rosa and G. Müller, Editors. 2017, Springer International Publishing: Cham. p. 1-12.
47. Mitchell, M., *Complexity : a guided tour*. 2009, Oxford England ; New York: Oxford University Press. xvi, 349 p.
48. Farinella-Ferruzza, N., *The transformation of a tail into a limb after xenoplastic transformation.* Experientia, 1956. **15**: p. 304-305.
49. McCusker, C. and D.M. Gardiner, *The axolotl model for regeneration and aging research: a mini-review.* Gerontology, 2011. **57**(6): p. 565-71.
50. Haas, B.J. and J.L. Whited, *Advances in Decoding Axolotl Limb Regeneration.* Trends Genet, 2017. **33**(8): p. 553-565.
51. Vandenberg, L.N., D.S. Adams, and M. Levin, *Normalized shape and location of perturbed craniofacial structures in the Xenopus tadpole reveal an innate ability to achieve correct morphology.* Developmental Dynamics, 2012. **241**(5): p. 863-78.
52. Pinet, K. and K.A. McLaughlin, *Mechanisms of physiological tissue remodeling in animals: Manipulating tissue, organ, and organism morphology.* Dev Biol, 2019. **451**(2): p. 134-145.
53. Pinet, K., et al., *Adaptive correction of craniofacial defects in pre-metamorphic Xenopus laevis tadpoles involves thyroid hormone-independent tissue remodeling.* Development, 2019. **146**(14).
54. Fankhauser, G., *Maintenance of normal structure in heteroploid salamander larvae, through compensation of changes in cell size by adjustment of cell number and cell shape.* Journal of Experimental Zoology, 1945. **100**(3): p. 445-455.
55. Fankhauser, G., *The Effects of Changes in Chromosome Number on Amphibian Development.* The Quarterly Review of Biology, 1945. **20**(1): p. 20-78.
56. Cooke, J., *Scale of body pattern adjusts to available cell number in amphibian embryos.* Nature, 1981. **290**(5809): p. 775-8.

57. Cooke, J., *Cell number in relation to primary pattern formation in the embryo of Xenopus laevis. I: The cell cycle during new pattern formation in response to implanted organisers.* Journal of Embryology and Experimental Morphology, 1979. **51**: p. 165-182.
58. Mintz, B., *Genetic mosaicism in vivo: development and disease in allophenic mice.* Fed Proc, 1971. **30**(3): p. 935-43.
59. Levin, M., *Darwin's agential materials: evolutionary implications of multiscale competency in developmental biology.* Cell Mol Life Sci, 2023. **80**(6): p. 142.
60. Lobo, D., et al., *A linear-encoding model explains the variability of the target morphology in regeneration.* Journal of the Royal Society, Interface / the Royal Society, 2014. **11**(92): p. 20130918.
61. Hartl, B. and M. Levin, *What does evolution make? Learning in living lineages and machines.* preprint, 2025.
62. Levin, M., *Self-Improvising Memory: A Perspective on Memories as Agential, Dynamically Reinterpreting Cognitive Glue.* Entropy (Basel), 2024. **26**(6).
63. Pezzulo, G., et al., *Bistability of somatic pattern memories: stochastic outcomes in bioelectric circuits underlying regeneration.* Philos Trans R Soc Lond B Biol Sci, 2021. **376**(1821): p. 20190765.
64. Durant, F., et al., *Long-Term, Stochastic Editing of Regenerative Anatomy via Targeting Endogenous Bioelectric Gradients.* Biophysical Journal, 2017. **112**(10): p. 2231-2243.
65. Oviedo, N.J., et al., *Long-range neural and gap junction protein-mediated cues control polarity during planarian regeneration.* Dev Biol, 2010. **339**(1): p. 188-99.
66. Emmons-Bell, M., et al., *Gap Junctional Blockade Stochastically Induces Different Species-Specific Head Anatomies in Genetically Wild-Type Girardia dorotocephala Flatworms.* Int J Mol Sci, 2015. **16**(11): p. 27865-96.
67. Harris, A.K., *The need for a concept of shape homeostasis.* Biosystems, 2018. **173**: p. 65-72.
68. Levin, M., A.M. Pietak, and J. Bischof, *Planarian regeneration as a model of anatomical homeostasis: Recent progress in biophysical and computational approaches.* Semin Cell Dev Biol, 2018. **87**: p. 125-144.
69. Moris, N., C. Pina, and A.M. Arias, *Transition states and cell fate decisions in epigenetic landscapes.* Nat Rev Genet, 2016. **17**(11): p. 693-703.
70. Waddington, C.H., *The strategy of the genes; a discussion of some aspects of theoretical biology*. 1957, London,: Allen & Unwin. ix, 262 p.
71. Beloussov, L.V., J.M. Opitz, and S.F. Gilbert, *Life of Alexander G. Gurwitsch and his relevant contribution to the theory of morphogenetic fields.* Int J Dev Biol, 1997. **41**(6): p. 771-7; comment 778-9.
72. Davidson, E.H., *Later embryogenesis: regulatory circuitry in morphogenetic fields.* Development, 1993. **118**(3): p. 665-90.
73. Schiffmann, Y., *The second messenger system as the morphogenetic field.* Biochem Biophys Res Commun, 1989. **165**(3): p. 1267-71.
74. Jaffe, L., *Calcium and morphogenetic fields*, in *Calcium and the Cell*. 1986, CIBA Foundation: Chichester. p. 271-288.

75. Beloussov, L.V., *Morphogenetic fields: Outlining the alternatives and enlarging the context [English].* Rivista di Biologia - Biology Forum, 2001. **94**(2): p. 219-35.
76. Beloussov, L.V., *Morphogenetic fields: History and relations to other concepts*, in *Fields of the Cell*, D.a.C. Fels, M., Editor. 2014. p. 269-281.
77. Shi, R. and R.B. Borgens, *Three-dimensional gradients of voltage during development of the nervous system as invisible coordinates for the establishment of embryonic pattern.* Dev Dyn, 1995. **202**(2): p. 101-14.
78. Niehrs, C., *On growth and form: a Cartesian coordinate system of Wnt and BMP signaling specifies bilaterian body axes.* Development, 2010. **137**(6): p. 845-57.
79. Watson, R.A., M. Levin, and C.L. Buckley, *Design for an Individual: Connectionist Approaches to the Evolutionary Transitions in Individuality.* Frontiers in Ecology and Evolution, 2022. **10**.
80. Levin, M., *Bioelectric networks: the cognitive glue enabling evolutionary scaling from physiology to mind.* Anim Cogn, 2023.
81. Fields, C. and M. Levin, *Multiscale memory and bioelectric error correction in the cytoplasm–cytoskeleton-membrane system.* Wiley Interdisciplinary Reviews: Systems Biology and Medicine, 2017. **10**(2): p. e1410-n/a.
82. Law, R. and M. Levin, *Bioelectric memory: modeling resting potential bistability in amphibian embryos and mammalian cells.* Theoretical biology & medical modelling, 2015. **12**(1): p. 22.
83. Levin, M., *Reprogramming cells and tissue patterning via bioelectrical pathways: molecular mechanisms and biomedical opportunities.* Wiley Interdisciplinary Reviews: Systems Biology and Medicine, 2013. **5**(6): p. 657-676.
84. Lange, M., *Because without cause : non-causal explanation in science and mathematics*. Oxford studies in philosophy of science. 2017, New York, NY, United States of America: Oxford University Press. xxii, 489 pages.
85. Baker, A., *Are there Genuine Mathematical Explanations of Physical Phenomena?* Mind, 2005. **114**(454): p. 223-238.
86. Skow, B., *Are There Non-Causal Explanations (of Particular Events)?* The British Journal for the Philosophy of Science, 2014. **65**(3): p. 445-467.
87. Ross, L.N., *The explanatory nature of constraints: Law-based, mathematical, and causal.* Synthese, 2023. **202**(2): p. 56.
88. Zee, A. and R. Penrose, *Fearful Symmetry: the search for beauty in modern physics.* 2016.
89. Wagner, A., *Arrival of the fittest : solving evolution's greatest puzzle*. 2014, New York, New York: Current. viii, 291 pages.
90. Wigner, E.P., *The Unreasonable Effectiveness of Mathematics in the Natural Sciences.* Communications on Pure and Applied Mathematics, 1960. **13**.
91. Hamming, R.W., *The Unreasonable Effectiveness of Mathematics.* The American Mathematical Monthly, 1980. **87**(2).
92. Wolfram, S. *The Physicalization of Metamathematics and Its Implications for the Foundations of Mathematics*. 2022. arXiv:2204.05123 DOI: 10.48550/arXiv.2204.05123.

93. Pickover, C.A., *Biomorphs: Computer Displays of Biological Forms Generated from Mathematical Feedback Loops.* Computer Graphics Forum, 1986. **5**(4): p. 313-316.
94. Jakubska-Busse, A., et al., *Pickover biomorphs and non-standard complex numbers.* Chaos Solitons & Fractals, 2018. **113**: p. 46-52.
95. Gdawiec, K., W. Kotarski, and A. Lisowska, *Biomorphs via modified iterations.* Journal of Nonlinear Sciences and Applications, 2016. **9**(5): p. 2305-2315.
96. Mojica, N.S., et al., *Cellular "bauplans": evolving unicellular forms by means of Julia sets and Pickover biomorphs.* Biosystems, 2009. **98**(1): p. 19-30.
97. Pickover, C.A., *Computers, pattern, chaos, and beauty : graphics from an unseen world*. 1990, New York: St. Martin's Press. xvi, 394 p., 10 p. of plates.
98. Balaguer, M., *Platonism and anti-Platonism in mathematics*. 1998, New York: Oxford University Press. x, 217 p.
99. Sole, R.V., P. Fernandez, and S.A. Kauffman, *Adaptive walks in a gene network model of morphogenesis: insights into the Cambrian explosion.* Int J Dev Biol, 2003. **47**(7-8): p. 685-93.
100. Kauffman, S.A., *The origins of order : self organization and selection in evolution*. 1993, New York: Oxford University Press. xviii, 709.
101. Biswas, S., W. Clawson, and M. Levin, *Learning in Transcriptional Network Models: Computational Discovery of Pathway-Level Memory and Effective Interventions.* Int J Mol Sci, 2022. **24**(1).
102. Biswas, S., et al., *Gene Regulatory Networks Exhibit Several Kinds of Memory: Quantification of Memory in Biological and Random Transcriptional Networks.* iScience, 2021. **24**(3): p. 102131.
103. Whitehead, A., *Process and reality : an essay in cosmology*. 1978, New York: Free Press.
104. Hoffman, D.D., *The Interface Theory of Perception*, in *The Interface Theory of Perception*, Stevens, Editor. 2017.
105. Gumuskaya, G., et al., *Motile Living Biobots Self-Construct from Adult Human Somatic Progenitor Seed Cells.* Adv Sci (Weinh), 2023: p. e2303575.
106. Blackiston, D.J. and M. Levin, *Ectopic eyes outside the head in Xenopus tadpoles provide sensory data for light-mediated learning.* The Journal of experimental biology, 2013. **216**(Pt 6): p. 1031-40.
107. Kofman, K. and M. Levin, *Robustness of the Mind-Body Interface: case studies of unconventional information flow in the multiscale living architecture.* Mind and Brain, 2025. **in press**.
108. Grim, P., *Philosophy for computers: some explorations in philosophical modeling.* Metaphilosophy, 2002. **33**(1/2): p. 181-209.
109. St. Denis, P. and P. Grim, *Fractal images of formal systems.* Journal of Philosophical Logic, 1997. **26**: p. 181-222.
110. Grim, P., *The undecidability of the spatialized prisoner's dilemma.* Theory and Decision, 1997. **42**(1): p. 53-80.
111. Grim, P., *Spatialization and greater generosity in the stochastic Prisoner's Dilemma.* Biosystems, 1996. **37**(1-2): p. 3-17.
112. Grim, P., *Self-Reference and Chaos in Fuzzy-Logic.* IEEE Transactions on Fuzzy Systems, 1994. **1**(4): p. 237-253.

113. Grim, P., et al., *Self-Reference and Paradox in 2 and 3 Dimensions.* Computers & Graphics, 1993. **17**(5): p. 609-612.
114. Mar, G. and P. Grim, *Pattern and Chaos, New Images in the Semantics of Paradox.* Nous, 1991. **25**(5): p. 659-693.
115. Zhang, T., A. Goldstein, and M. Levin, *Classical sorting algorithms as a model of morphogenesis: Self-sorting arrays reveal unexpected competencies in a minimal model of basal intelligence.* Adaptive Behavior, 2024. **0**(0): p. 10597123241269740.
116. Larmer, R., *Mind-body interaction and the conservation of energy.* International Philosophical Quarterly, 1986. **26**: p. 277-285.
117. Bass, L., *A quantum mechanical mind-body interaction.* Foundations of Physics, 1975. **5**(1): p. 159-172.
118. Seager, W., *Panpsychism and Energy Conservation.* Mind and Matter, 2022. **20**(1): p. 17-34.
119. Bergson, H., *Matter and memory*. 1988, New York: Zone Books. 284 p.
120. Bergson, H., *Creative evolution*. 1984, Lanham, MD: University Press of America. li, 407 p.
121. Brigandt, I., *Systems biology and the integration of mechanistic explanation and mathematical explanation.* Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences, 2013. **44**(4, Part A): p. 477-492.
122. Andersen, H., *Complements, Not Competitors: Causal and Mathematical Explanations.* The British Journal for the Philosophy of Science, 2018. **69**(2): p. 485-508.
123. Cox, R.T. and C.E. Carlton, *A commentary on prime numbers and life cycles of periodical cicadas.* Am Nat, 1998. **152**(1): p. 162-4.
124. Kauffman, S.A. and S. Johnsen, *Coevolution to the edge of chaos: coupled fitness landscapes, poised states, and coevolutionary avalanches.* J Theor Biol, 1991. **149**(4): p. 467-505.
125. Huang, S. and D.E. Ingber, *A non-genetic basis for cancer progression and metastasis: self-organizing attractors in cell regulatory networks.* Breast Dis, 2006. **26**: p. 27-54.
126. Huang, S., *On the intrinsic inevitability of cancer: from foetal to fatal attraction.* Seminars in cancer biology, 2011. **21**(3): p. 183-99.
127. Bizzarri, M., et al., *Embryonic morphogenetic field induces phenotypic reversion in cancer cells. Review article.* Curr Pharm Biotechnol, 2011. **12**(2): p. 243-53.
128. Steinberg, M.S., *Differential adhesion in morphogenesis: a modern view.* Curr Opin Genet Dev, 2007. **17**(4): p. 281-6.
129. Cross, S.S., *Fractals in pathology.* J Pathol, 1997. **182**(1): p. 1-8.
130. Pansera, F., *Fractals and cancer.* Med Hypotheses, 1994. **42**(6): p. 400.
131. Thom, R., *Mathematical models of morphogenesis*. Ellis Horwood series in mathematics and its applications. 1983, Chichester, West Sussex, England

New York: Ellis Horwood ;

Halsted Press. 305.

132. von Dassow, M. and L.A. Davidson, *Physics and the canalization of morphogenesis: a grand challenge in organismal biology.* Physical biology, 2011. **8**(4): p. 045002.
133. Beloussov, L.V., *Mechanically based generative laws of morphogenesis.* Phys Biol, 2008. **5**(1): p. 015009.
134. Beloussov, L.V. and V.I. Grabovsky, *Information about a form (on the dynamic laws of morphogenesis).* Biosystems, 2007. **87**(2-3): p. 204-14.
135. Vogel, S., *Cats' paws and catapults : mechanical worlds of nature and people*. 1st ed. 1998, New York: Norton. 382 p.
136. Isalan, M., *Gene networks and liar paradoxes.* BioEssays, 2009. **31**(10): p. 1110-5.
137. Levin, M., *A Julia set model of field-directed morphogenesis.* Computer Applications in the Biosciences, 1994. **10**(2): p. 85-103.
138. Stone, J.R., *The spirit of D'arcy Thompson dwells in empirical morphospace.* Mathematical Biosciences, 1997. **142**(1): p. 13-30.
139. Brandts, W.A., *Relevance of field models to global patterning in ciliates*, in *Interplay of Genetic and Physical Processes in the development of Biological Form*, G.F.a.F.G. E. Beysens, Editor. 1995, World Scientific: Singpore.
140. Brandts, W.A., *A field model of left-right asymmetries in the pattern regulation of a cell.* IMA J Math Appl Med Biol, 1993. **10**(1): p. 31-50.
141. Brandts, W.A.M. and L.E.H. Trainor, *A Nonlinear Field Model of Pattern-Formation - Application to Intracellular Pattern Reversal in Tetrahymena.* Journal of Theoretical Biology, 1990. **146**(1): p. 57-85.
142. Beloussov, L.V., *Morphogenetic fields: History and relations to other concepts [English]*, in *Fields of the Cell*, D. Fels, M. Cifra, and F. Scholkmann, Editors. 2015, Research Signpost: Kerala, India. p. 271-282.
143. Miller, W.B., Jr., J.S. Torday, and F. Baluska, *The N-space Episenome unifies cellular information space-time within cognition-based evolution.* Prog Biophys Mol Biol, 2020. **150**: p. 112-139.
144. Miller, W.B., Jr., F. Baluska, and J.S. Torday, *Cellular senomic measurements in Cognition-Based Evolution.* Prog Biophys Mol Biol, 2020. **156**: p. 20-33.
145. Baluska, F. and W.B. Miller, Jr., *Senomic view of the cell: Senome versus Genome.* Commun Integr Biol, 2018. **11**(3): p. 1-9.
146. Miller, W.B., Jr., *A scale-free universal relational information matrix (N-space) reconciles the information problem: N-space as the fabric of reality.* Commun Integr Biol, 2023. **16**(1): p. 2193006.
147. O'Brien, T., et al., *Machine learning for hypothesis generation in biology and medicine: exploring the latent space of neuroscience and developmental bioelectricity.* Digital Discovery, 2024. **3**(2): p. 249-263.
148. Juarrero, A., *Context changes everything : how constraints create coherence*. 2023, The MIT Press,: Cambridge, Massachusetts. p. 1 online resource.
149. Winning, J. and W. Bechtel, *Rethinking Causality in Biological and Neural Mechanisms: Constraints and Control.* Minds and Machines, 2018. **28**(2): p. 287-310.

150. Bechtel, W., *The Importance of Constraints and Control in Biological Mechanisms: Insights from Cancer Research.* Philosophy of Science, 2018. **85**(4): p. 573-593.
151. Montevil, M. and M. Mossio, *Biological organisation as closure of constraints.* J Theor Biol, 2015. **372**: p. 179-91.
152. Froese, T., *Irruption and Absorption: A 'Black-Box' Framework for How Mind and Matter Make a Difference to Each Other.* Entropy (Basel), 2024. **26**(4).
153. Froese, T., *Irruption Theory: A Novel Conceptualization of the Enactive Account of Motivated Activity.* Entropy (Basel), 2023. **25**(5).
154. Ellis, G. and B. Drossel, *How Downwards Causation Occurs in Digital Computers.* Foundations of Physics, 2019. **49**(11): p. 1253-1277.
155. Walker, S.I., P.C.W. Davies, and G.F.R. Ellis, *From matter to life : information and causality*. 2017, Cambridge, United Kingdom: Cambridge University Press. xxii, 494 pages.
156. Ellis, G.F.R., D. Noble, and T. O'Connor, *Top-down causation: an integrating theme within and across the sciences? INTRODUCTION.* Interface Focus, 2012. **2**(1): p. 1-3.
157. Ellis, G.F.R., *Top-down causation and emergence: some comments on mechanisms.* Interface focus, 2012. **2**(1): p. 126-140.
158. Deutsch, D., *Fabric of Reality*. 1997.
159. Serra, R., et al., *On the dynamics of random Boolean networks subject to noise: attractors, ergodic sets and cell types.* J Theor Biol, 2010. **265**(2): p. 185-93.
160. Fields, C., et al., *Conscious agent networks: Formal analysis and application to cognition.* Cognitive Systems Research, 2017.
161. Fields, C., et al., *Eigenforms, Interfaces and Holographic Encoding Toward an Evolutionary Account of Objects and Spacetime.* Constructivist Foundations, 2017. **12**: p. 265-274.
162. Hoffman, D.D., M. Singh, and C. Prakash, *The Interface Theory of Perception.* Psychon Bull Rev, 2015. **22**(6): p. 1480-506.
163. Eccles, J.C., *How the self controls its brain*. 1994, Berlin ; New York: Springer-Verlag. xvi, 197.
164. Hofstadter, D.R., *I am a strange loop*. 2007, New York: Basic Books. xix, 412 p., 4 p. of plates.
165. Kauffman, S. and P. Clayton, *On emergence, agency, and organization.* Biology & Philosophy, 2006. **21**(4): p. 501-521.
166. Kauffman, S.A., *At home in the universe : the search for laws of self-organization and complexity*. 1995, New York: Oxford University Press. viii, 321.
167. Kauffman, S.A., *Investigations*. 2000, Oxford ; New York: Oxford University Press. xii, 287 p.
168. Sample, M., et al., *Multi-cellular engineered living systems: building a community around responsible research on emergence.* Biofabrication, 2019. **11**(4): p. 043001.
169. Kamm, R.D., et al., *Perspective: The promise of multi-cellular engineered living systems.* Apl Bioengineering, 2018. **2**(4): p. 040901.

170. Doursat, R. and C. Sanchez, *Growing fine-grained multicellular robots.* Soft Robotics, 2014. **1**(2): p. 110-121.
171. Doursat, R., H. Sayama, and O. Michel, *A review of morphogenetic engineering.* Natural Computing, 2013. **12**(4): p. 517-535.
172. Ebrahimkhani, M.R. and M. Levin, *Synthetic living machines: A new window on life.* iScience, 2021. **24**(5): p. 102505.
173. Ebrahimkhani, M.R. and M. Ebisuya, *Synthetic developmental biology: build and control multicellular systems.* Curr Opin Chem Biol, 2019. **52**: p. 9-15.
174. Nanos, V. and M. Levin, *Multi-scale Chimerism: An experimental window on the algorithms of anatomical control.* Cells Dev, 2021. **169**: p. 203764.
175. Kriegman, S., et al., *Kinematic self-replication in reconfigurable organisms.* Proc Natl Acad Sci U S A, 2021. **118**(49).
176. Li, F.e.a., *Liquid metal droplet robot.* Applied Materials Today, 2020. **19**: p. 100597.
177. Points, L.J., et al., *Artificial intelligence exploration of unstable protocells leads to predictable properties and discovery of collective behavior.* Proc Natl Acad Sci U S A, 2018. **115**(5): p. 885-890.
178. Cejkova, J., et al., *Droplets As Liquid Robots.* Artif Life, 2017. **23**(4): p. 528-549.
179. Egbert, M., et al., *Behaviour and the Origin of Organisms.* Orig Life Evol Biosph, 2023. **53**(1-2): p. 87-112.
180. Pigozzi, F., A. Goldstein, and M. Levin, *Associative Conditioning in Gene Regulatory Network Models Increases Integrative Causal Emergence*. 2024: OSF Preprints.
181. Levin, M., *Technological Approach to Mind Everywhere: An Experimentally-Grounded Framework for Understanding Diverse Bodies and Minds.* Frontiers in Systems Neuroscience, 2022. **16**: p. 768201.
182. Lyon, P., *The biogenic approach to cognition.* Cogn Process, 2006. **7**(1): p. 11-29.
183. Baluška, F. and M. Levin, *On Having No Head: Cognition throughout Biological Systems.* Front Psychol, 2016. **7**: p. 902.
184. Sadoc, J.F., , and R. Mosseri, *Geometrical Frustration*. 2007: Cambridge University Press.
185. Granan, L.P., *The Ising Model Applied on Chronification of Pain.* Pain Med, 2016. **17**(1): p. 5-9.
186. Torquato, S., *Toward an Ising model of cancer and beyond.* Phys Biol, 2011. **8**(1): p. 015017.
187. Totafurno, J., C.J. Lumsden, and L.E. Trainor, *Structure and function in biological hierarchies: an Ising model approach.* Journal of theoretical biology, 1980. **85**(2): p. 171-98.
188. Weber, M. and J. Buceta, *The cellular Ising model: a framework for phase transitions in multicellular environments.* J R Soc Interface, 2016. **13**(119).
189. Dennett, D.C., *Kinds of minds : toward an understanding of consciousness*. 1st ed. Science masters series. 1996, New York: Basic Books. 184 p.
190. Rosenblueth, A., N. Wiener, and J. Bigelow, *Behavior, purpose, and teleology.* Philosophy of Science, 1943. **10**: p. 18-24.

191. Bongard, J. and M. Levin, *Living Things Are Not (20th Century) Machines: Updating Mechanism Metaphors in Light of the Modern Science of Machine Behavior.* Frontiers in Ecology and Evolution, 2021. **9**.
192. McShea, D.W., *Machine wanting.* Stud Hist Philos Biol Biomed Sci, 2013. **44**(4 Pt B): p. 679-87.
193. Rahwan, I., et al., *Machine behaviour.* Nature, 2019. **568**(7753): p. 477-486.
194. Lehman, J., et al., *The Surprising Creativity of Digital Evolution: A Collection of Anecdotes from the Evolutionary Computation and Artificial Life Research Communities.* Artif Life, 2020. **26**(2): p. 274-306.
195. Fogel, D.B., T. Bèack, and Z. Michalewicz, *Evolutionary computation*. 2000, Bristol ; Philadelphia: Institute of Physics Publishing. 2 v.
196. Tegmark, M., *The Mathematical Universe.* Foundations of Physics, 2008. **38**(2): p. 101.
197. Bongard, J. and M. Levin, *There's Plenty of Room Right Here: Biological Systems as Evolved, Overloaded, Multi-Scale Machines.* Biomimetics (Basel), 2023. **8**(1).
198. Rule, J.S., J.B. Tenenbaum, and S.T. Piantadosi, *The Child as Hacker.* Trends Cogn Sci, 2020. **24**(11): p. 900-915.
199. Monod, J., *Chance and necessity; an essay on the natural philosophy of modern biology*. 1972, New York,: Vintage Books. xiv, 198 p.
200. Heylighen, F., *Stigmergy as a universal coordination mechanism II: Varieties and evolution.* Cognitive Systems Research, 2016. **38**: p. 50-59.
201. Heylighen, F., *Stigmergy as a universal coordination mechanism I: Definition and components.* Cognitive Systems Research, 2016. **38**: p. 4-13.
202. Gloag, E.S., et al., *Stigmergy co-ordinates multicellular collective behaviours during Myxococcus xanthus surface migration.* Sci Rep, 2016. **6**: p. 26005.
203. Ricci, A., et al., *Cognitive stigmergy: towards a framework based on agents and artifacts*, in *E4MAS*, D. Weyns, H.V.D. Parunak, and F. Michel, Editors. 2007, Springer-Verlag: Berlin. p. 124-140.
204. Theraulaz, G. and E. Bonabeau, *A brief history of stigmergy.* Artif Life, 1999. **5**(2): p. 97-116.
205. Fields, C. and M. Levin, *Thoughts and thinkers: On the complementarity between objects and processes.* Physics of Life Reviews, 2025.
206. Drinnenberg, I.A., S. Henikoff, and H.S. Malik, *Evolutionary Turnover of Kinetochore Proteins: A Ship of Theseus?* Trends Cell Biol, 2016. **26**(7): p. 498-510.
207. Yun, M.H., H. Davaapil, and J.P. Brockes, *Recurrent turnover of senescent cells during regeneration of a complex structure.* Elife, 2015. **4**.
208. Pellettieri, J. and A. Sanchez Alvarado, *Cell turnover and adult tissue homeostasis: from humans to planarians.* Annu Rev Genet, 2007. **41**: p. 83-105.
209. Lakoff, G. and R.E. Núñez, *Where mathematics comes from : how the embodied mind brings mathematics into being*. 1st ed. 2000, New York, NY: Basic Books. xvii, 492 p.

210. Abramson, C.I. and M. Levin, *Behaviorist approaches to investigating memory and learning: A primer for synthetic biology and bioengineering.* Commun Integr Biol, 2021. **14**(1): p. 230-247.
211. Kastner, R.E., S.A. Kauffman, and M. Epperson, *Taking Heisenberg's Potentia Seriously.* Adventures in Quantumland, 2017.
212. Tegmark, M., *Is "the Theory of Everything" Merely the Ultimate Ensemble Theory?* Annals of Physics, 1998. **270**(1): p. 1-51.
213. Tegmark, M., *Our Mathematical Universe*. 2014.
214. Penrose, R., *Shadows of the Mind*. 1994.
215. Penrose, R., *The emperor's new mind : concerning computers, minds, and the laws of physics*. 1991, New York, N.Y.: Penguin Books. xiii, 466.
216. Penrose, R., *Consciousness, the brain, and spacetime geometry: an addendum. Some new developments on the Orch OR model for consciousness.* Annals of the New York Academy of Sciences, 2001. **929**: p. 105-10.
217. Fields, C., J.F. Glazebrook, and M. Levin, *Minimal physicalism as a scale-free substrate for cognition and consciousness.* Neurosci Conscious, 2021. **2021**(2): p. niab013.
218. Rouleau, N. and M. Levin, *The Multiple Realizability of Sentience in Living Systems and Beyond.* eNeuro, 2023. **10**(11).
219. Youvan, D., *Beyond the Brain: Exploring Receiver-Based Theories of Consciousness within Scientific Frameworks*. 2024.
220. Arora, S. and A. Goyal *A Theory for Emergence of Complex Skills in Language Models*. 2023. arXiv:2307.15936 DOI: 10.48550/arXiv.2307.15936.
221. Betley, J., et al. *Tell me about yourself: LLMs are aware of their learned behaviors*. 2025. arXiv:2501.11120 DOI: 10.48550/arXiv.2501.11120.
222. Greenblatt, R., et al. *Alignment faking in large language models*. 2024. arXiv:2412.14093 DOI: 10.48550/arXiv.2412.14093.
223. Rouleau, N. and M. Levin, *Discussions of machine versus living intelligence need more clarity.* Nature Machine Intelligence, 2024. **6**(12): p. 1424-1426.
224. Fields, C. and M. Levin, *Scale-Free Biology: Integrating Evolutionary and Developmental Thinking.* Bioessays, 2020. **42**(8): p. e1900228.
225. Miller, W.B., Jr., F. Baluska, and A.S. Reber, *A revised central dogma for the 21st century:all biology is cognitive information processing.* Prog Biophys Mol Biol, 2023. **182**: p. 34-48.
226. Baluska, F., A.S. Reber, and W.B. Miller, Jr., *Cellular sentience as the primary source of biological order and evolution.* Biosystems, 2022. **218**: p. 104694.
227. Baluska, F., W.B. Miller, and A.S. Reber, *Cellular and evolutionary perspectives on organismal cognition: from unicellular to multicellular organisms.* Biological Journal of the Linnean Society, 2022.
228. Reber, A.S. and F. Baluska, *Cognition in some surprising places.* Biochem Biophys Res Commun, 2021. **564**: p. 150-157.
229. Fields, C., *Sciences of Observation.* Philosophies, 2018. **3**(4): p. 29.
230. Hanczyc, M.M., *Droplets: unconventional protocell model with life-like dynamics and room to grow.* Life (Basel), 2014. **4**(4): p. 1038-49.

231. Smith-Ferguson, J. and M. Beekman, *Who needs a brain? Slime moulds, behavioural ecology and minimal cognition.* Adaptive Behavior, 2020. **28**: p. 465 - 478.
232. McGivern, P., *Active materials: minimal models of cognition?* Adaptive Behavior, 2019. **28**(6): p. 441-451.
233. Kaila, V.R.I. and A. Annila, *Natural selection for least action.* Proceedings of the Royal Society a-Mathematical Physical and Engineering Sciences, 2008. **464**(2099): p. 3055-3070.
234. Moore, T.A., *Getting the most action out of least action: A proposal.* American Journal of Physics, 2004. **72**(4): p. 522-527.
235. Georgiev, G. and I. Georgiev, *The least action and the metric of an organized system.* Open Systems & Information Dynamics, 2002. **9**(4): p. 371-380.
236. Frith, U., *Mind blindness and the brain in autism.* Neuron, 2001. **32**(6): p. 969-79.
237. Wagner, A. and W. Rosen, *Spaces of the possible: universal Darwinism and the wall between technological and biological innovation.* J R Soc Interface, 2014. **11**(97): p. 20131190.
238. Semon, R.W., B. Duffy, and V. Lee, *Mnemic psychology*. 1923, London,: G. Allen & Unwin. 2 p. l.,7-344 p.
239. Semon, R.W. and L. Simon, *The mneme*. 1921, London, New York,: The Macmillan company. 304 p.
240. Bedecarrats, A., et al., *RNA from Trained Aplysia Can Induce an Epigenetic Engram for Long-Term Sensitization in Untrained Aplysia.* eNeuro, 2018. **5**(3).
241. Ray, S., *Survival of olfactory memory through metamorphosis in the fly Musca domestica.* Neuroscience Letters, 1999. **259**(1): p. 37-40.
242. Liester, M.B., *Personality changes following heart transplantation: The role of cellular memory.* Med Hypotheses, 2020. **135**: p. 109468.
243. Reinis, S., *ANALYSIS OF MEMORY-TRANSFER BY PUROMYCIN.* Activitas Nervosa Superior, 1970. **12**(4): p. 289-&.
244. Frank, B., D.G. Stein, and J. Rosen, *Interanimal "memory" transfer: results from brain and liver homogenates.* Science, 1970. **169**(3943): p. 399-402.
245. Corson, J.A., *Behavior-Induction or Memory-Transfer.* Science, 1970. **169**(3952): p. 1342-&.
246. Rashevsky, N., *Some possible theoretical implications of experiments on the chemical transfer of memory.* Bulletin of mathematical biophysics, 1968. **30**: p. 341-349.
247. Verster, F.D.B. and J.T. Tapp, *ON RNA AND MEMORY - TRANSFER OF LEARNED BEHAVIOR BY INJECTIONS OF RNA.* Psychological Reports, 1967. **21**(3): p. 937-&.
248. McGaugh, J.L., *Analysis of Memory Transfer and Enhancement.* Proceedings of the American Philosophical Society, 1967. **111**(6): p. 347-351.
249. Jacobson, A.L., Fried, C., and Horowitz, S.D., *Planarians and memory: Transfer of learning by injection of ribonucleic acid.* Nature, 1966. **209**: p. 599-601.
250. Byrne, W.L., et al., *Memory transfer.* Science, 1966. **153**(3736): p. 658-9.
251. Miller, B.E. and G.L. Holt, *Memory transfer in rats by injection of brain and liver RNA.* Journal of Biological Psychology, 1977. **19**(1): p. 4-9.

252. Blackiston, D., T. Shomrat, and M. Levin, *The Stability of Memories During Brain Remodeling: a Perspective.* Communicative & Integrative Biology, 2015. **8**(5): p. e1073424.
253. McConnell, J.V., *The modern search for the engram*, in *A manual of psychological experimentation on planarians*, J.V. McConnell, Editor. 1967, Journal of Biological Psychology: Ann Arbour.
254. Nadin, M., *Epigenetics and Anticipatory Processes: From the Empirical to Foundational Aspects*, in *Epigenetics and Anticipation*, M. Nadin, Editor. 2022, Springer International Publishing: Cham. p. 201-234.
255. Nadin, M., *Redefining medicine from an anticipatory perspective.* Prog Biophys Mol Biol, 2018. **140**: p. 21-40.
256. Nechansky, H., *Elements of a cybernetic epistemology: elementary anticipatory systems.* Kybernetes, 2013. **42**(1-2): p. 185-206.
257. Rosen, R., *Anticipatory systems : philosophical, mathematical, and methodological foundations*. 1st ed. IFSR international series on systems science and engineering ; v. 1. 1985, Oxford, England ; New York: Pergamon Press. x, 436.
258. Rosen, R., *Anticipatory Systems in Retrospect and Prospect.* General Systems, 1979. **24**: p. 11-23.
259. Fields, C. and M. Levin, *Competency in Navigating Arbitrary Spaces as an Invariant for Analyzing Cognition in Diverse Embodiments.* Entropy (Basel), 2022. **24**(6).
260. Levin, M., *Collective Intelligence of Morphogenesis as a Teleonomic Process*, in *Evolution "on Purpose" : Teleonomy in Living Systems*, P.A. Corning, Kauffman, S. A., Noble, D., Shapiro, J. A., Vane-Wright, R. I., Pross, A., Editor. 2023, MIT Press: Cambridge. p. 175-198.
261. Levin, M., *Bioelectric signaling: Reprogrammable circuits underlying embryogenesis, regeneration, and cancer.* Cell, 2021. **184**(4): p. 1971-1989.
262. Csermely, P., et al., *Learning of Signaling Networks: Molecular Mechanisms.* Trends Biochem Sci, 2020. **45**(4): p. 284-294.
263. Keresztes, D., et al., *Cancer drug resistance as learning of signaling networks.* Biomed Pharmacother, 2025. **183**: p. 117880.
264. Veres, T., et al., *Cellular forgetting, desensitisation, stress and ageing in signalling networks. When do cells refuse to learn more?* Cell Mol Life Sci, 2024. **81**(1): p. 97.
265. Kaygisiz, K. and R.V. Ulijn, *Can Molecular Systems Learn?* ChemSystemsChem, 2024. **n/a**(n/a): p. e202400075.
266. Levin, M., *The Multiscale Wisdom of the Body: Collective Intelligence as a Tractable Interface for Next-Generation Biomedicine.* Bioessays, 2024: p. e202400196.
267. Mathews, J., et al., *Cellular signaling pathways as plastic, proto-cognitive systems: Implications for biomedicine.* Patterns (N Y), 2023. **4**(5): p. 100737.
268. Huh, M., et al. *The Platonic Representation Hypothesis*. 2024. arXiv:2405.07987 DOI: 10.48550/arXiv.2405.07987.

269. Dewan, E.M., *Consciousness as an emergent causal agent in the context of control system theory*, G. Globus, G. Maxwell, and I. Savodnik, Editors. 1976, Plenum Press: New York. p. 179-198.
270. Walker, S., L. Cisneros, and P.C.W. Davies, *Evolutionary Transitions and Top-Down Causation.* Artificial Life, 2012. **13**: p. 283-290.
271. Scerri, E.R., *Top-down causation regarding the chemistry-physics interface: a sceptical view.* Interface focus, 2012. **2**(1): p. 20-25.
272. Okasha, S., *Emergence, hierarchy and top-down causation in evolutionary biology.* Interface focus, 2012. **2**(1): p. 49-54.
273. Jaeger, L. and E.R. Calkins, *Downward causation by information control in micro-organisms.* Interface focus, 2012. **2**(1): p. 26-41.
274. Elder-Vass, D., *Top-down causation and social structures.* Interface focus, 2012. **2**(1): p. 82-90.
275. Davies, P.C.W., *The epigenome and top-down causation.* Interface focus, 2012. **2**(1): p. 42-48.
276. Butterfield, J., *Laws, causation and dynamics at different levels.* Interface focus, 2012. **2**(1): p. 101-114.
277. Ellis, G.F.R. and C.S. Bloch, *Top-Down Causation, Adaptive Selection, and Their Consequences.* Human Development, 2011. **54**(2): p. 93-100.
278. Ellis, G.F.R., *Top-Down Causation and the Human Brain.* Downward Causation and the Neurobiology of Free Will, 2009: p. 63-81.
279. Ellis, G.F.R., *On the nature of causation in complex systems.* Transactions of the Royal Society of South Africa, 2008. **63**(1): p. 69-84.
280. Auletta, G., G.F. Ellis, and L. Jaeger, *Top-down causation by information control: from a philosophical problem to a scientific research programme.* Journal of the Royal Society, Interface / the Royal Society, 2008. **5**(27): p. 1159-72.
281. Craver, C.F. and W. Bechtel, *Top-down causation without top-down causes.* Biology & Philosophy, 2007. **22**(4): p. 547-563.
282. Jaworski, W., *Mental causation from the top-down.* Erkenntnis, 2006. **65**(2): p. 277-299.
283. Varley, T.F. and E. Hoel, *Emergence as the conversion of information: a unifying theory.* Philos Trans A Math Phys Eng Sci, 2022. **380**(2227): p. 20210150.
284. Hoel, E. and M. Levin, *Emergence of informative higher scales in biological systems: a computational toolkit for optimal prediction and control.* Commun Integr Biol, 2020. **13**(1): p. 108-118.
285. Klein, B. and E. Hoel *Uncertainty and causal emergence in complex networks*. arXiv e-prints, 2019.
286. Hoel, E.P., *Agent Above, Atom Below: How Agents Causally Emerge from Their Underlying Microphysics*, in *Wandering Towards a Goal: How Can Mindless Mathematical Laws Give Rise to Aims and Intention?*, A. Aguirre, B. Foster, and Z. Merali, Editors. 2018, Springer International Publishing: Cham. p. 63-76.
287. Hoel, E.P., *When the Map Is Better Than the Territory.* Entropy, 2017. **19**(5).
288. Albantakis, L., et al., *What caused what? An irreducible account of actual causation.* arXiv, 2017. **arXiv:1708.06716**.

289. Hoel, E.P., et al., *Can the macro beat the micro? Integrated information across spatiotemporal scales.* Neuroscience of Consciousness, 2016. **2016**(1): p. niw012.
290. Hoel, E.P., L. Albantakis, and G. Tononi, *Quantifying causal emergence shows that macro can beat micro.* Proceedings of the National Academy of Sciences of the United States of America, 2013. **110**(49): p. 19790-5.
291. Juarrero, A., *What does the closure of context-sensitive constraints mean for determinism, autonomy, self-determination, and agency?* Prog Biophys Mol Biol, 2015. **119**(3): p. 510-21.
292. Juarrero, A., *Top-Down Causation and Autonomy in Complex Systems.* Downward Causation and the Neurobiology of Free Will, 2009: p. 83-102.
293. Deacon, T.W. and M. Garcia-Valdecasas, *A thermodynamic basis for teleological causality.* Philos Trans A Math Phys Eng Sci, 2023. **381**(2252): p. 20220282.
294. Deacon, T.W., *Incomplete nature : how mind emerged from matter*. 1st ed. 2012, New York: W.W. Norton & Co. xv, 602 p.
295. Roli, A. and S.A. Kauffman, *Emergence of Organisms.* Entropy, 2020. **22**(10).
296. Karve, S. and A. Wagner, *Environmental complexity is more important than mutation in driving the evolution of latent novel traits in E. coli.* Nat Commun, 2022. **13**(1): p. 5904.
297. Karve, S. and A. Wagner, *Multiple Novel Traits without Immediate Benefits Originate in Bacteria Evolving on Single Antibiotics.* Mol Biol Evol, 2022. **39**(1).
298. Mohrhoff, U., *The physics of interactionism.* Journal of Consciousness Studies, 1999. **6**(8-9): p. 165-84.
299. White, B., *Conservation Laws and Interactionist Dualism.* The Philosophical Quarterly, 2016. **67**(267): p. 387-405.
300. Schwartz, J.M., H.P. Stapp, and M. Beauregard, *Quantum physics in neuroscience and psychology: a neurophysical model of mind-brain interaction.* Philosophical Transactions of the Royal Society B-Biological Sciences, 2005. **360**(1458): p. 1309-1327.
301. Stapp, H., *Mind, matter, and quantum mechanics*. 1993, New York: Springer-Verlag.
302. Stapp, H.P., *Quantum Propensities and the Brain Mind Connection.* Foundations of Physics, 1991. **21**(12): p. 1451-1477.
303. Pauli, W., et al., *Atom and archetype : the Pauli/Jung letters, 1932-1958*. 2001, Princeton, N.J.: Princeton University Press. lx, 250 p.
304. Jung, C.G. and W. Pauli, *The Interpretation of nature and the psyche. Synchronicity: an acausal connecting principle*. Bollingen series. 1955, New York: Pantheon Books. vii, 247 p.