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**Brains and Where Else?
Mapping Theories of Consciousness to Unconventional Embodiments**

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Abstract

It is commonly assumed that a useful theory of consciousness (ToC) will, among other things, explain why consciousness is associated with brains. However, the findings of evolutionary biology, developmental bioelectricity, and synthetic bioengineering are revealing the ancient pre-neural roots of many mechanisms and algorithms occurring in brains – the implication of which is that minds may have preceded brains. Most of the work in the emerging field of diverse intelligence emphasizes externally observable problem-solving competencies in unconventional media, such as cells, tissues, and life-technology chimeras. Here, we inquire about the implications of these developments for theories that make a claim about what is necessary and/or sufficient for consciousness. Specifically, we analyze popular current ToCs to ask: what features of the theory specifically pick out brains as a privileged substrate of inner perspective, or, do the features emphasized by the theory occur elsewhere. We find that the operations and functional principles described or predicted by most ToCs are remarkably similar, that these similarities are obscured by reference to particular neural substrates, and that the focus on brains is more driven by convention and limitations of imagination than by any specific content of existing ToCs. Encouragingly, several contemporary theorists have made explicit efforts to apply their theories to synthetic systems in light of the recent wave of technological developments in artificial intelligence (AI) and organoid bioengineering. We suggest that the science of consciousness should be significantly open to minds in unconventional embodiments.

Introduction

What processes or algorithms underlie the ability of certain physical objects, such as living bodies, to form memories, implement decision-making, have an inner perspective with preferences, and navigate their environment in a goal-directed manner? This question is crucial to our understanding of ourselves, the development of ethics and social systems, and the status of hybrid and fully synthetic artificial intelligence (AI). A number of formalisms, including that of Turing [1] and later, the connectionist paradigm [2-7], have attempted to delineate what it is that confers mind within a given embodiment. In all cases however, it was assumed that the formalisms' dynamics describe events in brains. What would have happened if the biologists came to McCulloch [3], Pitts, Pappert, Rosenblatt, etc. and said: "we were wrong, the human mind is in the liver"? Would they have had to modify their models, or shrug it off as irrelevant to their efforts? What is actually neural about artificial neural networks, used to attempt to understand minds and build AI? Specifically, what aspects of neuroscience-inspired formalisms are actually tied to neurons per se, as opposed to other cell types?

This seems like an odd question – surely neurons are unique, and there must be a reason why minds associate with brains? This assumption, which permeates discussions of AI and philosophy of mind, is crumbling due to a number of reasons. First, evolutionary developmental biology shows how brains evolved gradually from other cell types. Indeed, the molecular mechanisms that set up the bioelectric networks of the brain are ancient – existing in all cells of the body and having their origin in bacterial biofilms [8-11]. Phylogenetically ancient traits of all kinds are carried forward and even implemented by new substrates (i.e., degeneracy) – so, why not the mechanisms underlying mindedness? Second, memory, creative problem-solving, decision-making, and numerous other aspects of active agency have now been seen in cells, tissues, slime molds, and even small molecular networks [12-16]. Advances in biophysics, cell biology, and behavioral science are revealing deep evolutionary commonalities between the mechanisms and algorithms of neuroscience and other fields such as developmental biology, for example in the study of cell groups as a collective intelligence that navigates anatomical space [17, 18].

Thus, the emerging field of diverse intelligence reveals that the focus on brains, and on the readily observable movement of medium-sized objects at medium speeds through the 3D world, is a result of our evolutionary firmware. Efforts to expand from this myopia are under way, via research on the problem-solving competencies of a wide range of living and synthetic agents that is helping to erode our limited evolutionary firmware for visualizing minds in unconventional embodiments [19]. To date however, all of the work in this field has focused on externally-observable behavior – problem-solving, or the "easy" problem of consciousness [20]. What of the hard problem – how to explain the inner perspective and elucidate its relationship to the brain?

Here, we explore the state of consciousness research with a focus on Theories of Consciousness (ToC) [21, 22] and inquire about the implications of the new biology for

theories that make a claim about what is necessary and/or sufficient for consciousness. Specifically, we analyze popular current ToCs to ask: what features of the theory specifically pick out brains as a privileged substrate of inner perspective, or, do the features emphasized by each theory occur elsewhere, in natural bodies and perhaps even in the world of engineering? We find that most ToCs rely on functional principles that are not specific to neuronal networks, which means that their claims about consciousness should apply to a wide range of unconventional substrates. We find few specifics about why neuronal assemblies in particular would be an exclusive substrate for consciousness, and suggest that the focus on brains is more driven by convention and limitations of imagination than by any specific content of existing ToCs. Thus, it is interesting to explore the relationships of various ToCs with the nervous system *per se*, and the consequences of taking seriously the features they emphasize when they occur outside of brains.

Theories of Consciousness: a tool to counter-act pervasive mind-blindness

Specific ToCs offer long-awaited explanatory and predictive power amid a history of confusion about the nature of experience. By what standard can a ToC be assessed as useful? Insofar as it can reliably point to subjects in the world, a ToC accomplishes its most basic function. But what if the theory can only reliably point to a particular type of subject? The validity of any theory that purports to explain how and where experience manifests is impacted not only by its positive identifications of mind, but by the number of true minds that it leaves unidentified. Though practical distinctions have always been made to classify the contents of experience, there is yet no consensus definition of consciousness or ToC that accounts for its mechanisms. We usually have no problem being epistemically confident about our own inner perspective. However, the existence of *other* minds with private thoughts and feelings may be fundamentally unknowable [23-26]. Still, humans share a robust intuition that we live among other minds in a shared environment [27]. That others speak, gesture, respond, and emote in ways that mirror our own behavioural correlates of consciousness reinforces a theory of mind that underlies the social and moral systems humans have created and refined over hundreds of thousands of years [27], and the ancient biological firmware that tuned our agency detectors for specific kinds of behaviors in visible space. Whether it reflects reality or not, humans infer the existence of other embodied minds within their environments, and this leap of faith (and its attendant limitations) is a normal feature of human psychology.

Mind-blindness – or a failure to form a theory of mind in the presence of other humans – is a defining characteristic of some common neuropathologies [28] when it affects the kinds of minds that neurotypical humans routinely recognize. However, we suggest that humans are insensitive to a wide range of unconventional minds, without sensing any kind of deficit, in the same way that we are insensitive to huge swaths of the electromagnetic spectrum without feeling impaired. If our default cognitive apparatus was significantly mind-blind to major categories of unconventional beings, we wouldn't know about it without developing tools in the same way that physics, and a useful theory of electromagnetic waves, opened our awareness to the existence of X-rays, radio waves,

and other signals that our default configuration cannot perceive. This analogy also works because light and X-rays simply *do not seem* like what happens when you wave a magnet up and down – on a superficial level, they appear quite different indeed. And yet, a rigorous formalism allowed us to overcome our limited intuitions and see electromagnetics in all of its glorious guises. Is there a reason to hypothesize that the same situation awaits us with respect to the space of possible minds?

Developmental biology and evolutionary theory emphasize the continuity of conserved mechanisms and algorithms spanning slowly and gradually from single cells (such as microbes and fertilized eggs) to adult metacognitive humans, and the gradual modification of generic cells and cell networks into neurons (Figure 1). The gradual self-construction of the body suggests the natural possibility of the gradual appearance of consciousness (and thus its presence, in degrees, in substrates different from an adult brainy animal), as perhaps reflected in Turing’s interest in synthetic intelligence and the spontaneous patterning of embryonic morphogens [1, 29]. At the same time, recent advances in bioengineering, synthetic biological intelligence, artificial intelligence, brain-computer interfaces, and robotics have fundamentally challenged our mind-inferencing strategies. The interoperability of life with engineered components is revealing a wide option space of hybrid beings that do not fit into classic life/machine categories [30] (Figure 2). Thus, whether or not the behavior patterns of “artificial” and hybrid systems reveal the presence of an experiencing subject has become a topic of great interest to many. ToCs, as principled theories for where one can expect inner perspective, promise to enable technologies to reveal heretofore unrecognized vistas – like tele-spectroscopy, which revealed familiar earthly elements in then-unexpected locations: celestial objects. To overcome the limitations of a human-centered theory of mind and increase true positive identifications of unconventional manifestations of consciousness in the environment, ToCs must be sufficiently universalizable to account for other minds. Are current ToCs formulated with other minds, well, in mind?

Why neural correlates fall short as consciousness criteria

Consciousness cannot be directly measured; therefore, correlates have been used as indirect signs of an underlying mind in the same way that the presence of a black hole is inferred on the basis of how light is bent or “lensed” by distortions of space-time. Many contemporary ToCs refer to “neural correlates” of consciousness (NCCs), which are a set of conserved relationships between human brain structure-function and self-reported experiences [31]. Why “neural correlates” as opposed to, simply, “correlates”? Following localized brain lesions, neural stimulation, or the use of psychoactive compounds, humans report highly conserved experiential phenomena that map on to common brain regions as revealed by neuroimaging [31]. While its flow may be interrupted by sleep or altered by drugs, anesthetics, rituals, and environmental forces, the evidence indicates that consciousness is a shared feature of human brains with stereotyped structure-function correlates. Because brain morphology is highly conserved (i.e., most brains display the same gyri, sulci, nuclei, tracts, circuits, networks, etc.), NCCs can be

generalized across members of the human species, allowing us to overcome weaker forms of mind-blindness in clinical settings. Until the development of brain imaging, immobile and seemingly unresponsive coma patients were lumped into the category of non-conscious systems with most organisms, robots, and the deceased; however, with NCCs, new degrees of distinction could be made including the confirmation of a minimally conscious state [32-35]. NCCs predict the existence of recondite minds on the bases of neural activations alone if the same activations were associated with the reported experiences of others. This mind-detecting strategy, termed “reverse inference” [36], is a practical solution to mind-blindness when the potential subject in question is a human with a brain.

Unfortunately, any movement across the phylogenetic tree decreases the predictive power of reverse inference because NCCs are fundamentally *correlates* and can only be used to infer consciousness in precisely the same way that behaviors motivate the same inferences. If the associations in question are non-generalizable, such as involving very specific nervous systems with defined organizations, the logic of reverse inference breaks down. While many ToCs have highlighted the relevance of NCCs, their poor generalization to non-human subjects limits their utility. How would an NCC-dependent ToC map on to the distributed nervous system of a jellyfish or the ganglia of a mollusk? What can current ToCs offer in terms of predicting a capacity for experience when comparing 3-layered and 6-layered cortices or their intermediates? Unless a ToC can account for differences in neural organization, it will return the same predictive errors that human intuitions commit when assessing the mental status of anything other than a human. Some authors have suggested the use of perturbational complexity as a measure of consciousness, which despite its focus on the responses of neural tissues, has the potential to transcend a historical reliance on specific NCCs because, in principle, other systems can display brain-independent perturbational markers that predict conscious experience [37, 38].

Despite the longstanding absence of any direct measure of consciousness, and strong philosophical reasons to doubt its existence in others, humans often extend a theory of mind to infer non-human animal sentience [39]. Interestingly, the degree to which a non-human animal shares superficial, human-like characteristics is predictive of our willingness to infer subjectivity on the bases of their behaviours [40, 41]. Once again, reverse inference is used to bridge the epistemic gap (i.e., analogous behaviors and observable traits as predictors of mind). Prior to a scientific study of animal consciousness, moral considerations were granted to many non-human animal species, and most people are quite happy to assume that their pets lead rich, experiential lives with felt states of pleasure and pain. In many countries, non-human animal species such as dolphins and chimpanzees enjoy personhood status [42, 43] that set them apart from other living systems, including plants, insects, and microorganisms – which together constitute over 99% of Earth’s biomass [44]. In other words, less than 1% of living systems on the planet are granted special status and consideration over the vast majority due to their presumed subjectivity, even though the rest have long been known to exhibit different

degrees of learning, decision-making, predictive capacity, etc. [13, 45-48]. Notably, much less than 1% of living systems on Earth possess a nervous system. If even a minority subset of aneural life is conscious – perhaps a single plant or animal species – the NCC standard will fail to account for their experiences, generating false negative errors wherever it is applied.

While recent developments in synthetic biological intelligence and AI research have accelerated discussion around the topic of unconventional minds, the emergence of neural-robotic hybrids in the late 20th century represented a major branching point in the conversation. That cultured neural networks could be coupled with robotic or virtual “bodies” to solve real-world problems challenged longstanding dichotomies between the living and non-living or the agential and automatic [49-51]. It was quickly realized that disembodied brains were dysfunctional but could be normalized with stochastic inputs or response-contingent feedback [52-54]. Now, there is evidence to suggest that cultured neural networks in closed-loop feedback systems can optimize their outputs toward many types of defined goal states without external programming [55]. Importantly, these displays of self-organized problem-solving are achieved without specialized, genetically-encoded brain circuits. That is, embodied cultured networks demonstrated that, fundamentally, there is no intrinsic, universal value to any particular tract system, nucleus, or circuit outside of its default context. Rather, a sufficiently plastic neural network can be shaped to accomplish any number of tasks. Once considered exclusive to human brains, cognitive functions such as learning, attention, and decision-making have, over time, been incrementally extended to living and non-living systems alike. While it is possible that any one or perhaps all of these features of cognition could be displayed without an experiential correlate, the stakes are high – not knowing whether a physical object with which you are engaged is conscious is an ethical risk. This is especially relevant now that a much wider variety of beings – biobots [56-59], cyborgs [60-66], and minimal active matter systems [67-71] – are coming on line and beginning to be bioengineered. ToCs will need to be applied to an ever-increasing number of organizationally unique systems with potential minds [17, 30, 72].

ToCs are important. Whether or not they hold construct validity (i.e., how well the ToC not just predicts the presence of a subject but actually describes true features or mechanisms of consciousness), they enable us to make meaningful distinctions that inform decisions related to lifestyle, ethics, public policy, and law. Frameworks must now be developed to identify unfamiliar minds in unconventional spaces that betray longstanding neurocentric assumptions [17, 48, 73]. Here, we survey contemporary ToCs and explore their suitability to identify other kinds of minds in diverse environments. How many of them are actually neuron-specific? While many ToCs have already adopted a panpsychist, functionalist, or universalized approach, some still focus exclusively on the brain even though nothing about their secret sauce is actually unique to neurons.

Neural tissues as non-exclusive specialists of cognitive function

Because ToCs that reference NCCs or any specific neurobiological details will likely fail to generate a true positive prediction of unconventional minds, the role of the brain within the cognitive landscape must be revisited. Neurons – and specifically, pyramidal cells – were once described by Ramón y Cajal as “the butterflies of the soul”. The implication, of course, was that neural cells conferred the properties of minds, which remains a central assumption of modern neuroscience. However, there is no single feature of the neuron that isn’t also displayed by some other cell, living system, inorganic material, or natural process (Figure 3). Whether it’s a capacity for long-range signaling, cell shape plasticity, chemical communication, electrotonic coupling, electromagnetic sensing, membrane polarization, chemotaxis, galvanotaxis, ephaptic coupling, or networking, the neuron holds no exclusive capacity or function [74-76].

Many living systems display electrochemical patterns that are homologous to those of neurons, including the electromagnetic fields that have been hypothesized to be important for consciousness [77-83]. Most bodily cells regulate membrane-bound ion channels to maintain a polarized electrical state; however, neurons display notably hyperpolarized resting potentials (-70 mV). Cardiomyocytes, which are similarly hyperpolarized at rest (-90 mV), generate spontaneous depolarizations or “action potentials” [84] with refractory periods and other dynamics that are similar but not identical to those of neurons (and participate in a phenomenon known as cardiac memory [85, 86]). Immune cells can be sensitized, display learned responses, and encode long-term memories reflective of a history of exposure to specific pathogens [87], just like cells of the nervous system form long-term memories reflective of a history of sensory inputs. Neurotransmitters such as glutamate and serotonin are expressed throughout the body, outside the brain [88] and by many plant species as chemical signals for cellular communication [89]. Incidentally, plants display anticipatory responses and even game-theoretic decision-making capabilities that weigh the availability of resources with kin status of neighboring organisms, determining the expression of competitive or cooperative actions [90]. Unsurprisingly, some authors have called for a more inclusive definition of “nervous system” that captures a spectrum of signal generation, transmission, and processing in multicellular systems [91]. Paramecia [92-94] and slime molds [95-97] can be conditioned and even solve problems without nervous tissues. We previously demonstrated that non-associative learning such as habituation is a commonplace function that is not dependent on any specific biological substrate or cell type [98, 99]. Several authors have since suggested that learning is a universal property shared by cells, generally [14, 15, 100-104].

Dynamical properties of neurons are also displayed by simple molecular interactions at sub-cellular scales [105]. Indeed, phospholipid membranes alone display memcapacitive properties that recapitulate long-term potentiation (LTP) without a cell or synapse to speak of [106]. Water at an interface generates negative potential differences (voltage) within range of resting membrane potentials (-100 mV) that can be modified by the addition of physiological ions and detected hundreds of microns away from the surface [107]. Microtubules and their special properties have been suggested to be critical

for consciousness [108-111], but cytoskeletal structures such microtubules are present in all cells and play an important role in cellular and multicellular decision-making and collective behavior [112-115]. Moreover, microtubules in a dish spontaneously align with and migrate along electric fields [116, 117] and polymerize as branched networks with dendrite-like arbors. Incidentally, branching patterns of neurites, plants, and blood vessels conform to the same scaling laws [118-120]. Similarly, the structures of neural networks are quantitatively convergent with those of galactic filaments [121] within the cosmic web. Even inorganic substrates such iron bars are subject to conditioned hysteresis responses [122] and silver nanowires display self-assembling properties in the presence of electric current that optimize patterning with properties of learning and memory [123]. Interestingly, the current densities, firing frequencies, backpropagation responses, and saltatory-conductive properties of neurons are also displayed by lightning strikes between the Earth's surface and its atmosphere [124].

Neither the composition nor the dynamics of neurons are sufficiently unique to justify their special status as mind generators. Either individual cell properties are insufficient, or many types of simple systems are similarly capable of generating conscious states. The third possibility is that brains deserve exclusive status because of their connective properties, local circuitry, and network architectures. It is often suggested that structural complexity is what sets brains apart from other systems. However, contrary to popular assumption, a network architecture with sparse rather than dense connectivity is likely to specialize brains as implementers of cognition [125]. Notably, feedforward networks are unlikely to generate consciousness [35]. Feedback mechanisms, including reverberation by re-entrant circuits, are thought to be requirements for consciousness [126, 127]. From a functionalist perspective, the organizational principles are more relevant than the substrates, and neural tissues represent one of many possible ways to implement cognitive functions. With many natural and synthetic examples of reentry, feedback, network sparsity, and plasticity outside the nervous system, there is good reason to doubt that brains occupy a privileged position over other systems with analogous organizational features. Here, we examine several contemporary frameworks from a functionalist perspective, with the aim of universalizing ToCs to interact with unconventional substrates and scales.

Theories of consciousness to map diverse embodied minds

A universalizable ToC should be substrate-independent, scale-invariant, and organization-invariant [20], with the implication that *mind* is multiply realizable [72, 128]. Unfortunately, when the properties of cognitive systems are divorced from their biological substrates, it can be difficult to know where to apply inferencing strategies and deeply unintuitive questions arise: What does it mean to be conscious in spaces other than 3D space at human spatiotemporal scales (i.e., beyond centimeter- or millimeter-wide objects with dynamics in the order of seconds or milliseconds)? Beyond the neural variety, what kinds of correlative phenomena can reliably serve as indirect measures of

consciousness? What kinds of perturbations or physical interactions can reliably induce changes within a system that indicate the likely presence of a mind? Without the grounding of a testable ToC, little progress can be made. As an initial step toward mapping minds in unconventional spaces, we reviewed prominent theories of consciousness as recently selected by Seth & Bayne [21] and substituted neurocentric language with aneurocentric or generic terms. Expanded, aneurocentric versions of the primary claims of each theory were then constructed with language reflecting inclusion of different substrates, scales, and organizations (see Table 1). Common terms such as “sensation” or “sensory” were replaced with generic afferents such as “input”. Likewise, terms such as “motor” were replaced with generic efferents such as “output”. Similarly, terms such as “brain” or “neuron” were replaced with generic terms for potential loci of consciousness including “system” or “processor”, which we consider potentially interchangeable with “cell”, “core”, “hub”, and/or “node”, depending on the context of the specific ToC.

Table 1 – Aneurocentric formulations of prominent theories of consciousness

Theory	Primary Claim		Refs
Active inference	Original formulations (verbatim from [21])	Consciousness depends on temporally and counterfactually deep inference about self-generated actions	[129, 130]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness arises from an embodied system's continuous predictions about inputs, adjusting internal states and outputs based on prediction errors to minimize differences between expected and actual inputs.	
Attention schema theory	Original formulation	Consciousness depends on a <i>neurally</i> encoded model of the control of attention	[131]
	Substitutions	<i>neurally</i> → information-processing system	
	Expanded aneurocentric formulation	Consciousness arises from an information-processing system assigning high degrees of certainty about the claim that the system itself contains an attention schema or subject	
Attended intermediate representation theory	Original formulation	Consciousness depends on the attentional amplification of intermediate-level representations	[132, 133]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness arises when intermediate-level or partially processed information becomes amplified by attentional resources and can enter working memory	
Beast machine theory	Original formulation	Consciousness is grounded in allostatic control-oriented predictive inference	[134-136]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness is the effect of combining a subjective frame, or internal reference point generated by constantly updated representations of internal states, with perceptual content evoked by external stimuli	
Dendritic integration theory	Original formulation	Consciousness depends on integration of top- down and bottom- up signalling at a <i>cellular</i> level	[137]
	Substitutions	<i>cellular</i> → processor	
	Expanded aneurocentric formulation	Consciousness depends on a coupling between bottom-up and top-down processing that generates a reverberating or looped function	
	Original formulation	Consciousness depends on a functional cluster of <i>neural</i> activity combining high levels of dynamical integration and differentiation	[138]

Dynamic core theory	Substitutions	<i>neural</i> → processor	
	Expanded aneurocentric formulation	Consciousness arises from an integrated cluster of high-complexity re-entrant processors, or a compositionally dynamic "core", within an information-processing system that are much more strongly interactive with themselves than with other parts of the system	
Electromagnetic field theory	Original formulation	Consciousness is identical to physically integrated, and causally active, information encoded in the <i>brain's</i> global electromagnetic field	[78, 139]
	Substitutions	<i>brain</i> → information-processor	
	Expanded aneurocentric formulation	Consciousness depends on information-processing activities by processors interacting with the complex interference patterns of time-varying electromagnetic field oscillations	
Global workspace theories (GWTs)	Original formulation	Consciousness depends on ignition and broadcast within a neuronal global workspace where fronto-parietal cortical regions play a central, hub- like role	[140-142]
	Substitutions	<i>neuronal</i> → information-processing system <i>frontal/parietal cortical regions</i> → processors	
	Expanded aneurocentric formulation	Consciousness arises from the attention-gated integration of information within an exclusive global workspace or "hub" that uses working memory and can selectively broadcast to multiple processors simultaneously that are within the system but outside of the hub	
Higher-order theory (HOT)	Original formulation	Consciousness depends on meta- representations of lower- order <i>mental states</i>	[143, 144]
	Substitutions	<i>mental states</i> → states	
	Expanded aneurocentric formulation	Consciousness is the higher-order, meta-representational monitoring of the processing activities associated with lower-order states	
Information closure theory	Original formulation	Consciousness depends on non- trivial information closure with respect to an environment at particular coarse- grained scales	[145]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness is a process Y that forms information closure with a stochastic process X of which it is a coarse-grained product	
Integrated information theory (IIT)	Original formulation	Consciousness is identical to the cause–effect structure of a physical substrate that specifies a maximum of irreducible integrated information	[146-148]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness corresponds to the level of integrated information within a system, quantified by a measure (<i>phi</i>) where higher integration indicates richer, more coherent experiences	
Local recurrency	Original formulation	Consciousness depends on local recurrent or re-entrant <i>cortical</i> processing and promotes learning	[149, 150]
	Substitutions	<i>cortical</i> → processor	
	Expanded aneurocentric formulation	Consciousness arises from recurrent or re-entrant feedback at points of interaction between higher- and lower-level processors.	
Multiple drafts model	Original formulation	Consciousness depends on multiple (potentially inconsistent) representations rather than a single, unified representation that is available to a central system	[151]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness consists of highly parallelized, multitrack processes of informational interpretation and elaboration with continuous editorial revision that are not re-presented as unified narratives	
Neural Darwinism	Original formulation	Consciousness depends on re-entrant interactions reflecting a history of value- dependent learning events shaped by selectionist principles	[152, 153]
	Substitutions	None	

	Expanded aneurocentric formulation	Consciousness is a reentrant interaction between perceptual processors and relay nodes along their pathways, conferring selective advantages by linking current inputs with a history of weighted input values.	
Neural subjective frame	Original formulation	Consciousness depends on <i>neural</i> maps of the <i>bodily</i> state providing a first-person perspective	[154]
	Substitutions	<i>neural</i> → system/processor <i>bodily</i> → environmental interface	
	Expanded aneurocentric formulation	Consciousness is a dynamic frame of reference that is dependent on continuously updated maps of the system's internal states that do not directly interface with the environment, but which are impinged upon by processors of external stimulation	
Neuro-representationalism	Original formulation	Consciousness depends on multilevel <i>neurally</i> encoded predictive representations	[155]
	Substitutions	<i>neurally</i> → non-environment/system	
	Expanded aneurocentric formulation	Consciousness is a multimodal, context-dependent survey that predicts representations of input stimulation (i.e., superinferences) from the environment and enables goal-directed actions upon the environment	
Orchestrated objective reduction	Original formulation	Consciousness depends on quantum computations within <i>microtubules</i> inside <i>neurons</i>	[156]
	Substitutions	<i>microtubules</i> → qubit reservoirs/processors <i>neurons</i> → cell/system	
	Expanded aneurocentric formulation	Consciousness is the terminal product of complex, quantum computations performed by oscillating electromagnetic dipoles as qubits that undergo state reduction with a definite outcome	
Predictive processing	Original formulation	Perception depends on predictive inference of the causes of <i>sensory</i> signals; provides a framework for systematically mapping <i>neural</i> mechanisms to aspects of consciousness	[157-160]
	Substitutions	<i>sensory</i> → inputs <i>neural</i> → internal/processor	
	Expanded aneurocentric formulation	Consciousness arises from the process of actively testing hypotheses as internal predictive models of expected inputs against streams of actual inputs	
Sensorimotor theory	Original formulation	Consciousness depends on mastery of the laws governing <i>sensorimotor</i> contingencies	[161]
	Substitutions	<i>sensorimotor</i> → input-output/embodiment	
	Expanded aneurocentric formulation	Consciousness is a system's capacity to display embodied engagement (output) with stimuli (input) from the environment without the necessity of internal representations.	
Self comes to mind theory	Original formulation	Consciousness depends on interactions between homeostatic routines and multilevel interoceptive maps, with affect and feeling at the core	[162, 163]
	Substitutions	None	
	Expanded aneurocentric formulation	Consciousness is a state that occurs when a system contains an informationally closed internal representation of itself, situated relative to an external environment.	
Self-organizing meta-representational theory	Original formulation	Consciousness is the <i>brain</i> 's (meta-representational) theory about itself	[164]
	Substitutions	<i>brain</i> → system	
	Expanded aneurocentric formulation	Consciousness occurs in systems that can attend to their first-order internal states, which are generated by impinging external stimuli, and have learned to value some states over others.	
Unlimited associative learning	Original formulation	Consciousness depends on a form of learning which enables an <i>organism</i> to link motivational value with stimuli or actions that are novel, compound and non-reflex inducing	[165, 166]
	Substitutions	<i>organism</i> → system	

	Expanded aneurocentric formulation	Consciousness arises when a system's states are processed by high-level integrating units, learning about itself in an open-ended way with compounds of paired patterns of stimuli and actions	
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Legend: This table contains the main ToCs; *italics* indicate the words that were generalized to show how the theory applies beyond brains. In many cases, no changes needed to be made. This illustrates how many ToCs are actually not about brains specifically, but call out aspects that are relevant to diverse cells, systems, and collectives.

When the substrate- and scale-dependent contents of each theory are separated from their functional principles, it becomes clear that, amongst the most prominent ToCs, there are only a handful of distinct concepts or themes including: 1) predictive modeling, 2) enactivism/ecological interactions, 3) reentrancy or looped feedback, 4) meta-representations, 5) attentional gating/monitoring, 6) emergence from computation, 7) integration of information, and 8) coarse-graining. Some ToCs are mutually incompatible; however, viewed through a functionalist lens, many more display broad conceptual overlap. While there's no doubt that particular brain regions (e.g., cortices, brainstem nuclei), networks (e.g., default mode network, attentional, sensorimotor), and circuits (e.g., corticothalamic), as well as neurophysiological processes (e.g., gamma oscillations) are at least necessary for human brains to generate consciousness, efforts to extend ToCs to other minds must involve a generalization and analysis of the biological details of such theories to test mappings of the theory onto functions of all cells (and thus organs). Aneurocentric formulations of ToCs are thus testable while enabling a comparative analysis of consciousness across very different systems.

Implications of consciousness in agents living in unconventional spaces

The kinds of functionality and competencies normally indicating a being with at least some degree of consciousness – learning, decision-making, causal emergence, navigation driven by valence and goal-directed activity – typically take place in the 3-dimensional space of conventional behavior. However, it is now known that many cells, tissues, and aneural organs can do all of these things in metabolic, physiological, transcriptional (gene expression), and anatomical spaces [19] (Figure 4). They formulate and pursue goals, solve new problems they have not seen before, exhibit taxis and aversive behavior with respect to regions of their state space, and align components towards large-scale goals (reviewed in [14, 47, 48, 100, 115, 167-169]). Indeed, it appears that the interesting properties of brains arose as a gradual evolutionary pivot of fundamental capacities (including active inference and homeodynamic goal-directedness) across problem spaces [74]. While difficult for us to visualize directly, because of sense organs and our own evolved theory-of-mind firmware focused on a fixed range of embodiments and behaviors involving obvious motility, it is essential to let advances in science expand our native perspective. To the extent that research in basal cognition and diverse intelligence reveals behavioral competencies in unconventional

spaces, we must be open to the applicability of ToCs to these scenarios. As seen in Table 1, and consistent with the very high conservation of mechanisms and algorithms between neurons and non-neural cells, no existing ToC rules out aneural substrate. For precisely the same reasons we routinely entertain the possibility of consciousness in brainy animals based on their behavior and its biophysical underpinning, we must consider the possibility that cells, tissues, organs, organoids, biobots, and a wide range of chimeric cyborg/hybrids architectures could have inner experience as they intelligently navigate, strive, achieve, and suffer in their own worlds of possibility. And indeed, as known from advances in the field of morphological computation [170-172], the structure of an agent's problem space has massive impact on their embodiment and cognition, which suggests that minds navigating unconventional spaces may not be easy for us to detect unaided.

Developing research programmes

This perspective, grounded in developmental and evolutionary biology of the biophysics underlying neural networks, has a number of implications for a research roadmap. The use of tools and concepts of neuroscience and behavioral science is already paying off in terms of empirical discoveries and new experimental vistas in these fields, for example in the use of the collective intelligence of cells navigating anatomical morphospace to impact birth defects, regeneration, and cancer (reviewed in [173-175]) and the investigation of learning and memory in gene-regulatory networks with possible impacts on a wide range of pharmacological use cases [176-179]. But to date, these have all been strictly 3rd-person perspective, standard science. It is time to extend consciousness studies and philosophy of mind to cell biology, regenerative medicine, and bioengineering.

An obvious next step is to use metrics from causal information theory and IIT to study the information flows during behavior in non-neural agents [180]. This has already begun, in work to measure information architecture [181] and causal emergence metrics in Xenobots [182] and gene-regulatory networks [183]. Many other substrates, such as calcium and bioelectric signaling during embryonic and regenerative morphogenesis [184], carcinogenic transformation [185, 186], and self-assembly of biobots [56, 57, 187, 188] remain to be tested. We also envision development of classic tools such as the mirror test, and variants of the Turing test, in spaces that make them applicable to cells and similar unconventional agents.

One of the key lynchpins in discussions of both AI and organoid consciousness has been the criterion of embodiment [72, 189-193]. Many have argued that engagement with a rich action space via a perception-action loop (including perceptual control [194] or active inference [195-197]) is critical for the formation of true agents with consciousness. We agree, but point out that movement in 3D space is not the only arena for this critical dynamic. It is possible that "disembodied" organoids for example, which offer no obvious behavior in 3D space, in fact display a kind of "locked in syndrome" [198] which makes

observers think there is no one inside, whereas they have an active life solving problems in gene expression, physiological, and other spaces. For the same reasons we seek to develop tools to identify inner perspective in human cases of locked in syndrome or coma [37, 38], we must broaden our perspective and create substrate-agnostic conceptual and experimental tools to detect, quantify, and characterize these processes across the diverse agential material of life, from subcellular molecular networks to organ systems. We hypothesize that the existing tools of the neuroscience of consciousness, combined with virtual reality tools to assist visualization of behavior in high-dimensional, unconventional spaces by human scientists, will be a powerful combination to begin to overcome our innate inability to see all but a tiny fraction of the endless forms most beautiful [199], of minds.

By loosening arbitrary constraints on the nature of conscious embodiments and the spaces within which they must navigate, the science of consciousness gains access to a wide range of beings that are alien in just the right amount. Many questions abound with respect to the kinds of minds that exo-biological life forms would have; while we don't have access to true aliens, we now have the opportunity to try to understand minds which are on the same evolutionary tree as us, and thus perhaps tractable, but will force us to expand and refine our conceptual apparatus because they are not tractable to the increasingly stale and constraining anthropocentric, brain-focused formalisms. The recognition of possible consciousness in living material more broadly will re-calibrate current debates about octopuses, crustaceans, etc. and raise fascinating questions about ethical relationships to this much broader class of beings.

Conclusion

Taking seriously the slow, gradual scale-up from single cells revealed by developmental and evolutionary biology makes the continuity thesis the null hypothesis. The high conservation of mechanisms and behaviors in brains all the way back to pre-cellular material implies that a kind of panpsychism, committed to understanding the scaling and transformation of embodied minds from physical dynamics, is not only viable but should be the baseline assumption. Competing ideas, relying on sharp phase transitions and brain-specific theories, need to specify principled reasons for discontinuities and explain "emergence" of novel natural kinds.

The state of the art in physiology and diverse intelligence research, combined with the compatibility of current ToCs with aneural substrates, suggests that consciousness may be common throughout the body. Our mind supervenes on a collection of cells, working together by means of a bioelectric network which aligns them toward larger cognitive light cones in abstract problem spaces. That architecture is ubiquitous throughout our bodies and throughout evolution. Thus, consciousness in a collective intelligence made of cells is not a wild claim – indeed, it is the only kind of consciousness we've ever seen, because *each of us is a collective intelligence* (of neurons). For all the

reasons discussed above, we can drop the part in parentheses from the list of requirements, and get on with the task of understanding collective intelligence in all of its general guises, and the ways in which it enables intelligence to come into the world.

But, it is often objected: “we don’t feel our liver being conscious!”. While that is true, we don’t feel each other being conscious either. Indeed, if the liver or its parts were capable of subjective experience, that point-of-view would be quite independent from the consciousness of a brain with which it shared a body. We suggest dropping the unfounded requirement that a body have only one consciousness, as well as the privileged perspective of the one body organ that can eloquently proclaim its lonely unity by way of the left hemisphere’s capacity for language. Many brain structures are mirrored across hemispheres and can function independently following interhemispheric disconnections including callosotomy. While perception can clearly be divided in split brain patients, the evidence for divided consciousness is mixed [200], in part because of a shared body (which makes discernment of dual nature by outside observers, or even by one of the hemispheres, challenging). However, if each hemisphere were reciprocally connected to its own independent body, evidence from hybrid robotics research would predict unique behavioural correlates of consciousness suggestive of a capacity for multiple subjects within a shared body. At this point there is no evidence that the consciousness of non-brain body organs would be the complex, self-reflexive consciousness enjoyed by the human mind or would be capable of language. But this still leaves a huge swath of the consciousness spectrum, which biology likely occupied in its journey from physics. By expanding into the field of diverse intelligence and unconventional embodiments, we can begin to truly deal with the problem of other minds and the richness of conscious kin both within and around us.

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Figures

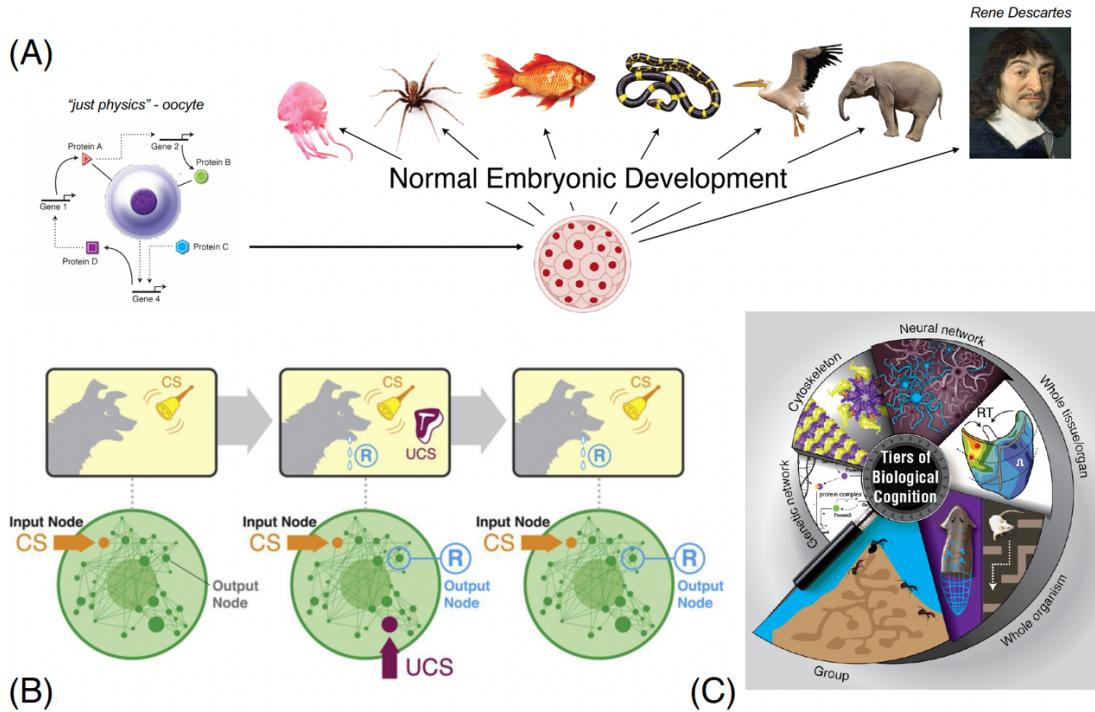


Figure 1

Figure 1: Self-assembly of conscious beings from the agential material of life.

(A) Each of us is the product of a transformational process (embryogenesis) which leads from a quiescent oocyte well-encompassed by the laws of chemistry to a complex meta-cognitive agent amenable to behavioral science or even psychoanalysis. This journey across the “Cartesian cut” is slow and gradual, with no place for a bright line during which physics suddenly becomes mind. Generic cells become neurons, some electrophysiological networks speed up to become nervous systems, and motility in 3D space appears whereas before there was only navigation of metabolic, gene expression, and anatomical spaces.

(B) Aspects of cognitive function appear long before neurons and are universal, not even requiring cell networks or whole cells. For example, chemical networks within all cells are capable of several different kinds of learning, including Pavlovian conditioning [176, 177, 201, 202].

(C) Biological material in general has problem-solving competencies and agendas at every level of organization, from the active matter within cells to tissues and organs navigating physiological spaces and learning from experience [13].

Panel A taken with permission from [203]. Panel B taken with permission from [177]. Panel C taken with permission from [17]. All images courtesy of Jeremy Guay of Peregrine Creative.

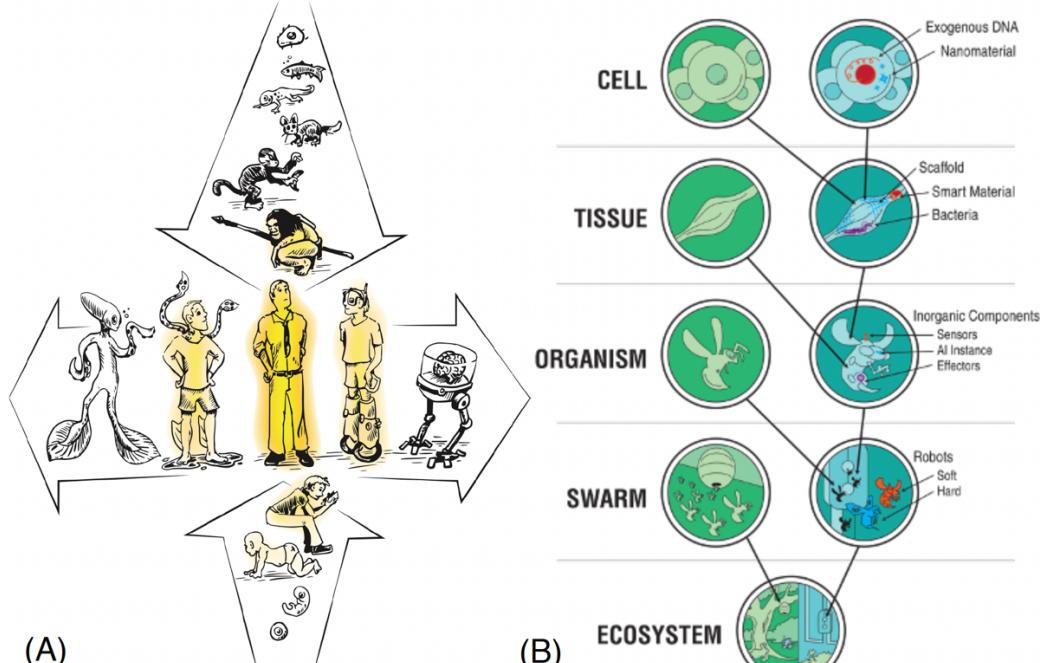


Figure 2

Figure 2: The continuum of the natural and the engineered

(A) The “human” which features so prominently in conventional philosophy of mind is at the center of two continua. First (vertical) is the set of gradual changes, on the evolutionary and developmental time scale which connects us to single cells and subcellular matter before that. The sense of consciousness we attribute to humans (represented by the yellow agential glow) must, given the facts of developmental and evolutionary biology, be explained with respect to its degree and kind in closely connected forms. The continuity and transformation of mental properties from very minimal origins is the null hypothesis, and theories proposing the appearance of binary categories (“is it conscious or isn’t it”) would need to argue convincingly and explicitly for mechanisms of emergent phase transitions. Second (horizontal) is a spectrum of continuous change that can be (and is being) implemented, both biologically and technologically, resulting in a wide array of composite, chimeric beings that are not easily categorized within or outside of “human” minds. This means that our theories of consciousness should not be human-centered but rather encompass a wide and continuous space of minds [204-208].

(B) Another key feature of biological organization is that it can be readily hybridized with engineered, designed components at every level. This interoperability of life with novel structures means that discussions of consciousness cannot focus on “life vs. machine” but must accommodate a rich space of chimeric forms with features not explainable by evolutionary history or selection pressures.

Panel B taken with permission from [17]. All images courtesy of Jeremy Guay of Peregrine Creative.

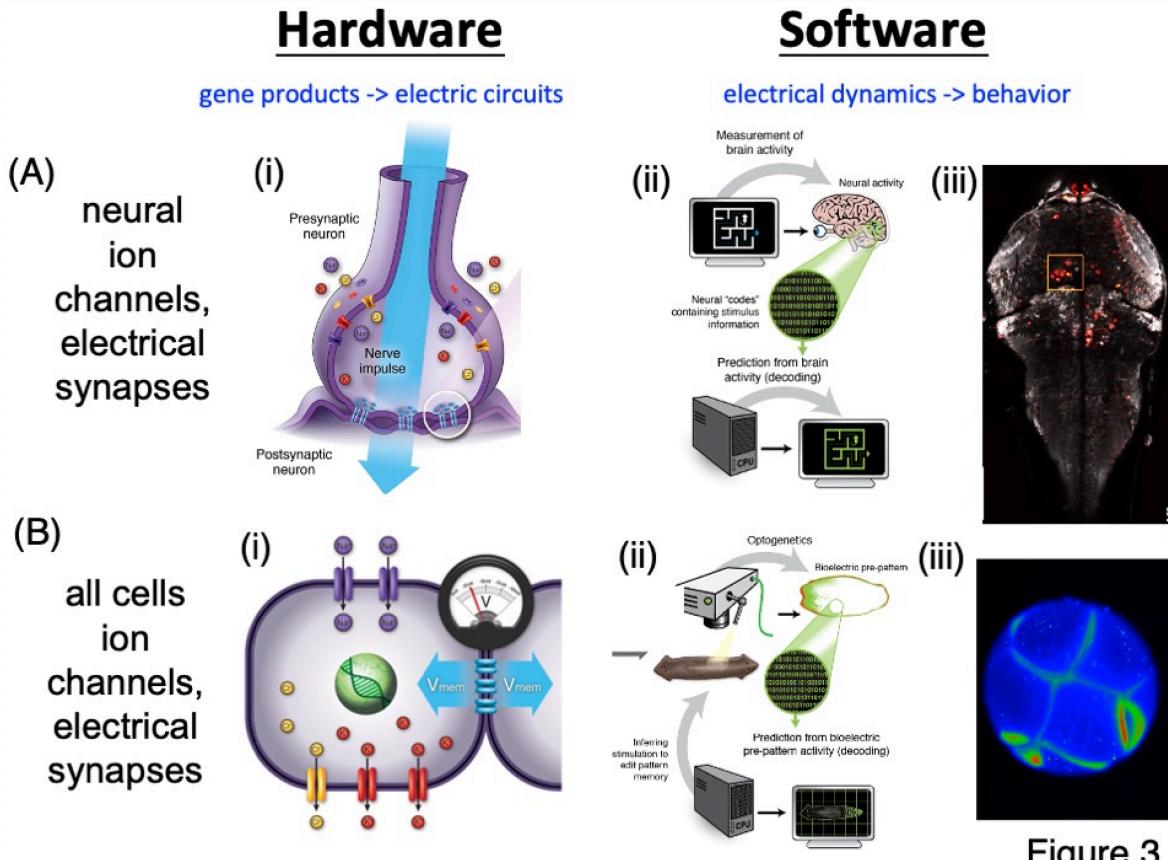


Figure 3

Figure 3: strong symmetry between neural and non-neural cognitive substrate

(A) in the nervous system, the hardware consists of a network of cells connected by chemical and electrical synapses (i); the goal of neural decoding (ii) is to read the physiological states of the brain (iii, bioelectric imaging of a living vertebrate brain) and decode them to infer the cognitive content of the mind embodied by this network – to be able to extract the memories, goals, preferences, and conscious state.

(B) The powerful properties of bioelectric networks that enable memory, re-entrant network architectures, and integration of information across space and time are not unique to neurons: all cells in the body have ion channels for generating spatio-temporal patterns of resting potential and gap junctions (electrical synapses) for shaping those patterns in light of on-going processing (i); precisely the same tools – ranging from optogenetics to computational pipelines to crack the somatic bioelectric code (ii) – are being used to decode the goal states, memories, and navigational behaviors of bioelectric patterns (iii, voltage sensing dye showing dynamic gradients in the early frog embryo) during decision-making and problem-solving in anatomical morphospace.

Panels A-i, B-i, B-iii taken with permission from [203]. Panels A-ii, B-ii taken with permission from [173]. Panel A-iii taken with permission from [209]. Image in Panel B-iii by Dany Adams, Levin lab. All other images courtesy of Jeremy Guay of Peregrine Creative.

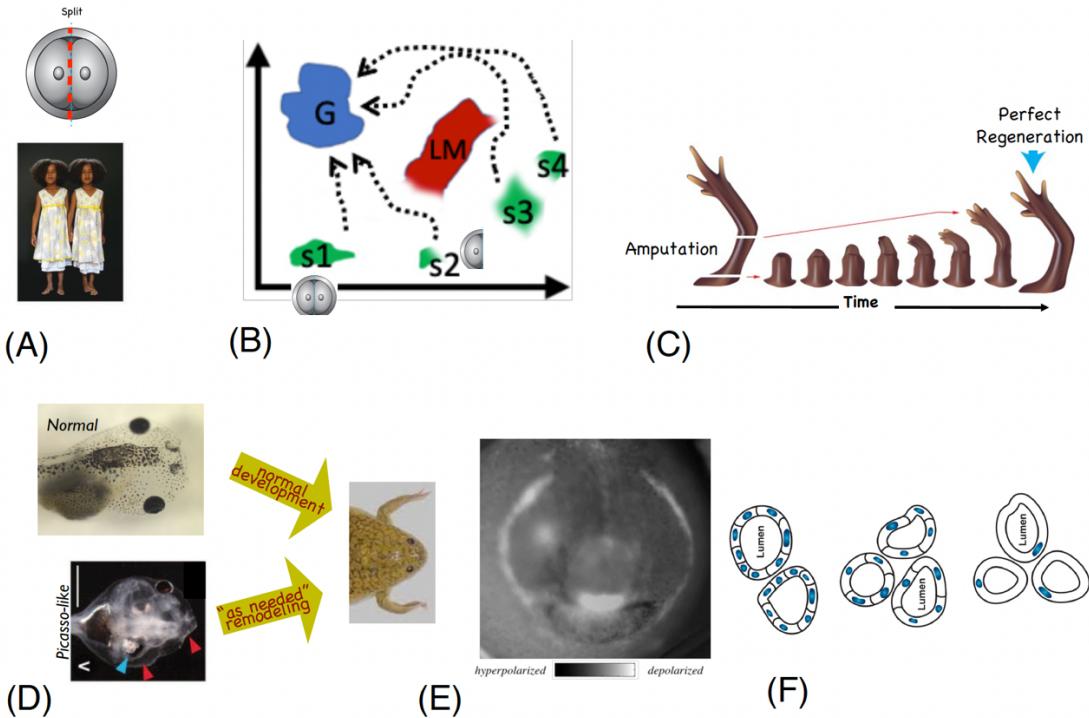


Figure 4

Figure 4: morphogenesis as behavior of cellular collective intelligence in morphospace

(A) Human embryos split in half give rise to monozygotic twins (and higher multiples), not half-bodies, illustrating that development is not a hardwired, but a flexible, context-sensitive process that can accommodate novel perturbations to reach its goal.

(B) More generally, represented in a 2-dimensional schematic of morphospace (a high-dimensional space of possible anatomical configurations), normal embryos (S1) can reach the ensemble of goal states (G) representing a normal species-specific target morphology, but in many life forms, so can embryos split in half (S2) or a wide range of other perturbations (S3, S4). This ability to reach their goal from different starting positions in the space, often avoiding getting stuck in local maxima (LM), represents a kind of navigational problem-solving.

(C) Some animals maintain this in adulthood such as limb regeneration in amphibia: the appendage can be cut at any level and then regenerates the precise amount and shape of missing materials, *stopping when a correct limb is produced*. This capacity, and regulative embryogenesis, is a kind of error minimization loop that is carried out by cells, all of which are aligned toward a large-scale goal in anatomical space.

(D) Another example of flexible pursuit of goals by non-neural cells is the formation of a frog face from the re-organization of tadpole craniofacial organs, which can begin in their normal positions or a scrambled (Picasso-like) state, because the paths they take are not hardwired but adjusted dynamically to reach the correct pattern despite unexpected starting configurations [210].

(E) The goal state, with respect to which cellular effectors operate in these cases, can be stored as a bioelectrical pattern memory, akin to the storage of goal states in neural memory systems [11]; here is shown one example – the “electric face” pattern [211] (visualized with a bioelectrical reporter dye), which instructs the location of the components of the face. Voltage imaging in non-neural cells now allows the read-out (and increasingly, decoding) of the information patterns in bioelectric networks that guide behavior toward specific future states.

(F) Cross-section of kidney tubules in normal vs. polyploid newts. As the polyploidy is increased, it causes an increase in cell size but the overall structure remains normal because the cells adjust by having fewer cells participate in the process. The right panel shows the most extreme case, where the cells are so big they use a different molecular mechanism to accomplish the goal (by having 1 cell wrap around itself).

Panel A used with permission from Oudeschool via Wikimedia commons. Panel C used with permission from [212]. Panel D: Top left image of used with permission from [213]; bottom left image used with permission from [211]. right image of courtesy of Erin Switzer, Levin lab and modified after [203]. Panel E used with permission from [211]. Panel F adapted from [214], used with permission from [215]. Panels C,F by Jeremy Guay of Peregrine Creative.

References

1. Turing, A.M., *Computing machinery and intelligence*. Mind, 1950. **59**(236): p. 433-460.
2. Rosenblatt, F., *Recent work on theoretical models of biological memory*, in *Computer and Information Sciences*, J. Tou, Editor. 1967, Spartan Books: Washington, D.C.
3. McCulloch, W.S., *Embodiments of mind*. 1988, Cambridge, Mass.: M.I.T. Press. xxviii, 402 p.
4. Minsky, M. and S. Papert, *Perceptrons; an introduction to computational geometry*. 1969, Cambridge, Mass.: MIT Press. 258 p.
5. Rosenblatt, F., *The perceptron: a probabilistic model for information storage and organization in the brain*. Psychol Rev, 1958. **65**(6): p. 386-408.
6. Hopfield, J.J., *Neural networks and physical systems with emergent collective computational abilities*. Proc Natl Acad Sci U S A, 1982. **79**(8): p. 2554-8.
7. Hopfield, J.J. and D.W. Tank, *Computing with neural circuits: a model*. Science, 1986. **233**(4764): p. 625-33.
8. Yang, C.Y., et al., *Encoding Membrane-Potential-Based Memory within a Microbial Community*. Cell Syst, 2020. **10**(5): p. 417-423 e3.
9. Martinez-Corral, R., et al., *Metabolic basis of brain-like electrical signalling in bacterial communities*. Philos Trans R Soc Lond B Biol Sci, 2019. **374**(1774): p. 20180382.
10. Prindle, A., et al., *Ion channels enable electrical communication in bacterial communities*. Nature, 2015. **527**(7576): p. 59-63.
11. Levin, M., *Bioelectric networks: the cognitive glue enabling evolutionary scaling from physiology to mind*. Anim Cogn, 2023.
12. Vallverdu, J., et al., *Slime mould: The fundamental mechanisms of biological cognition*. Biosystems, 2018. **165**: p. 57-70.
13. Baluška, F. and M. Levin, *On Having No Head: Cognition throughout Biological Systems*. Front Psychol, 2016. **7**: p. 902.
14. Lyon, P., *Of what is “minimal cognition” the half-baked version?* Adaptive Behavior, 2020. **28**(6): p. 407-424.
15. Lyon, P., *The biogenic approach to cognition*. Cogn Process, 2006. **7**(1): p. 11-29.
16. 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.
17. 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.
18. Levin, M., *The Computational Boundary of a “Self”: Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition*. Frontiers in Psychology, 2019. **10**(2688): p. 2688.
19. Fields, C. and M. Levin, *Competency in Navigating Arbitrary Spaces as an Invariant for Analyzing Cognition in Diverse Embodiments*. Entropy (Basel), 2022. **24**(6).

20. Chalmers, D., *The Hard Problem of Consciousness*, in *The Blackwell Companion to Consciousness*, S. Schneider and M. Velmans, Editors. 2017, John Wiley & Sons. p. 32-42.
21. Seth, A.K. and T. Bayne, *Theories of consciousness*. Nat Rev Neurosci, 2022. **23**(7): p. 439-452.
22. Kuhn, R.L., *A landscape of consciousness: Toward a taxonomy of explanations and implications*. Prog Biophys Mol Biol, 2024. **190**: p. 28-169.
23. Malcolm, N., *I. Knowledge of Other Minds*. The Journal of Philosophy, 1958. **55**(23): p. 969-978.
24. Price, H.H., *Our evidence for the existence of other minds*. Philosophy, 1938. **13**(52): p. 425-456.
25. Sober, E., *Why Not Solipsism?* Philosophy and Phenomenological Research, 1995. **55**(3): p. 547-566.
26. Bayne, T., et al., *Tests for consciousness in humans and beyond*. Trends Cogn Sci, 2024. **28**(5): p. 454-466.
27. Povinelli, D.J. and S. Giambrone, *Inferring other minds: Failure of the argument by analogy*. Philosophical Topics, 1999. **27**(1): p. 167-201.
28. Frith, U., *Mind blindness and the brain in autism*. Neuron, 2001. **32**(6): p. 969-79.
29. 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.
30. Rouleau, N. and M. Levin, *Discussions of machine versus living intelligence need more clarity*. Nature Machine Intelligence, 2024. **6**(12): p. 1424-1426.
31. Koch, C., et al., *Neural correlates of consciousness: progress and problems*. Nat Rev Neurosci, 2016. **17**(5): p. 307-21.
32. Di Perri, C., et al., *Neural correlates of consciousness in patients who have emerged from a minimally conscious state: a cross-sectional multimodal imaging study*. Lancet Neurol, 2016. **15**(8): p. 830-842.
33. Gawryluk, J.R., et al., *Improving the clinical assessment of consciousness with advances in electrophysiological and neuroimaging techniques*. BMC Neurol, 2010. **10**: p. 11.
34. Boly, M., M. Massimini, and G. Tononi, *Theoretical approaches to the diagnosis of altered states of consciousness*. Prog Brain Res, 2009. **177**: p. 383-98.
35. Tononi, G. and C. Koch, *Consciousness: here, there and everywhere?* Philos Trans R Soc Lond B Biol Sci, 2015. **370**(1668): p. 20140167.
36. Poldrack, R.A., *Inferring mental states from neuroimaging data: from reverse inference to large-scale decoding*. Neuron, 2011. **72**(5): p. 692-7.
37. Sintsyn, D.O., et al., *Detecting the Potential for Consciousness in Unresponsive Patients Using the Perturbational Complexity Index*. Brain Sci, 2020. **10**(12): p. 917.
38. Casarotto, S., et al., *Stratification of unresponsive patients by an independently validated index of brain complexity*. Ann Neurol, 2016. **80**(5): p. 718-729.
39. Spence, C.E., M. Osman, and A.G. McElligott, *Theory of Animal Mind: Human Nature or Experimental Artefact?* Trends Cogn Sci, 2017. **21**(5): p. 333-343.

40. Urquiza-Haas, E.G. and K. Kotrschal, *The mind behind anthropomorphic thinking: attribution of mental states to other species*. Animal Behaviour, 2015. **109**: p. 167-176.
41. Harnad, S., *Animal sentience: The other-minds problem*. Animal Sentience, 2016. **1**(1): p. 1.
42. DeGrazia, D., *Great apes, dolphins, and the concept of personhood + Moral philosophy, categories*. Southern Journal of Philosophy, 1997. **35**(3): p. 301-320.
43. Staker, A., *Should Chimpanzees Have Standing? The Case for Pursuing Legal Personhood for Non-Human Animals*. Transnational Environmental Law, 2017. **6**(3): p. 485-507.
44. Bar-On, Y.M., R. Phillips, and R. Milo, *The biomass distribution on Earth*. Proc Natl Acad Sci U S A, 2018. **115**(25): p. 6506-6511.
45. Jennings, H.S., *Behavior of the lower organisms*. Columbia university biological series X. 1906, New York,: The Columbia university press, The Macmillan company, agents; etc. xiv p., 1 l., 366 p.
46. 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.
47. 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.
48. Reber, A.S. and F. Baluska, *Cognition in some surprising places*. Biochem Biophys Res Commun, 2021. **564**: p. 150-157.
49. DeMarse, T.B., et al. *Interfacing neuronal cultures to a computer-generated virtual world*. in *7th Joint Symposium on Neural Computation*. 2000. Los Angeles.
50. Potter, S.M., S.E. Fraser, and J. Pine. *Animat in a petri dish: cultured neural networks for studying neural computation*. in *4th Joint Symposium on Neural Computation*. 1997. San Diego.
51. Demarse, T.B., et al., *The Neurally Controlled Animat: Biological Brains Acting with Simulated Bodies*. Auton Robots, 2001. **11**(3): p. 305-310.
52. Wagenaar, D.A., et al., *Controlling bursting in cortical cultures with closed-loop multi-electrode stimulation*. J Neurosci, 2005. **25**(3): p. 680-8.
53. Madhavan, R., D.A. Wagenaar, and S.M. Potter, *Multisite stimulation quiets bursts and enhances plasticity in cultured networks*, in *33rd Society for Neuroscience Annual Meeting*. 2003: New Orleans. p. 45-56.
54. Potter, A.M., et al. *Hybrots: hybrids of living neurons and robots for studying neural computation*. in *Brain Inspired Cognitive Systems*. 2004. Stirling, Scotland.
55. Lobov, S.A., et al., *Spatial Properties of STDP in a Self-Learning Spiking Neural Network Enable Controlling a Mobile Robot*. Front Neurosci, 2020. **14**: p. 88.
56. Ebrahimkhani, M.R. and M. Levin, *Synthetic living machines: A new window on life*. iScience, 2021. **24**(5): p. 102505.
57. Kamm, R.D., et al., *Perspective: The promise of multi-cellular engineered living systems*. Apl Bioengineering, 2018. **2**(4): p. 040901.
58. Blackiston, D., et al., *Biological Robots: Perspectives on an Emerging Interdisciplinary Field*. Soft Robot, 2023.
59. Gumuskaya, G., et al., *Motile Living Biobots Self-Construct from Adult Human Somatic Progenitor Seed Cells*. Adv Sci (Weinh), 2023: p. e2303575.

60. 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.
61. Pio-Lopez, L., *The rise of the biocyborg: synthetic biology, artificial chimerism and human enhancement*. New Genetics and Society, 2021. **40**(4): p. 599-619.
62. Orive, G., N. Taebnia, and A. Dolatshahi-Pirouz, *A New Era for Cyborg Science Is Emerging: The Promise of Cyborgic Beings*. Adv Healthc Mater, 2020. **9**(1): p. e1901023.
63. Li, Q., et al., *Cyborg Organoids: Implantation of Nanoelectronics via Organogenesis for Tissue-Wide Electrophysiology*. Nano Lett, 2019. **19**(8): p. 5781-5789.
64. Mehrali, M., et al., *Blending Electronics with the Human Body: A Pathway toward a Cybernetic Future*. Adv Sci (Weinh), 2018. **5**(10): p. 1700931.
65. Ding, S., et al., *Cellular Cyborgs: On the Precipice of a Drug Delivery Revolution*. Cell Chem Biol, 2018. **25**(6): p. 648-658.
66. Peter Aaser, et al., *Towards making a cyborg: A closed-loop reservoir-neuro system*, in *ECAL 2017: the 14th European Conference on Artificial Life*. 2017, MIT Press: Lyon, France. p. 430-437.
67. Stern, M., M.B. Pinson, and A. Murugan, *Continual Learning of Multiple Memories in Mechanical Networks*. Physical Review X, 2020. **10**(3): p. 031044.
68. Stern, M., et al., *Supervised learning through physical changes in a mechanical system*. Proc Natl Acad Sci U S A, 2020. **117**(26): p. 14843-14850.
69. Ozkan-Aydin, Y., D.I. Goldman, and M.S. Bhamla, *Collective dynamics in entangled worm and robot blobs*. Proc Natl Acad Sci U S A, 2021. **118**(6).
70. Bernheim-Groswasser, A., et al., *Living Matter: Mesoscopic Active Materials*. Adv Mater, 2018. **30**(41): p. e1707028.
71. Cejkova, J., et al., *Droplets As Liquid Robots*. Artif Life, 2017. **23**(4): p. 528-549.
72. Rouleau, N. and M. Levin, *The Multiple Realizability of Sentience in Living Systems and Beyond*. eNeuro, 2023. **10**(11).
73. Rosenblueth, A., N. Wiener, and J. Bigelow, *Behavior, purpose, and teleology*. Philosophy of Science, 1943. **10**: p. 18-24.
74. 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.
75. Koshland, D.E., *The Bacterium as a Model Neuron*. Trends in Neurosciences, 1983. **6**(4): p. 133-137.
76. Koshland, D.E., Jr., *Bacterial chemotaxis in relation to neurobiology*. Annu Rev Neurosci, 1980. **3**: p. 43-75.
77. Hunt, T., et al., *Editorial: Electromagnetic field theories of consciousness: opportunities and obstacles*. Front Hum Neurosci, 2023. **17**: p. 1342634.
78. Kitchener, P.D. and C.G. Hales, *What Neuroscientists Think, and Don't Think, About Consciousness*. Front Hum Neurosci, 2022. **16**: p. 767612.
79. Hales, C.G. and M. Ericson, *Electromagnetism's Bridge Across the Explanatory Gap: How a Neuroscience/Physics Collaboration Delivers Explanation Into All Theories of Consciousness*. Front Hum Neurosci, 2022. **16**: p. 836046.

80. Hales, C.G., *The origins of the brain's endogenous electromagnetic field and its relationship to provision of consciousness*. Journal of integrative neuroscience, 2014. **13**(2): p. 313-61.
81. Pinotsis, D.A. and E.K. Miller, *In vivo ephaptic coupling allows memory network formation*. Cereb Cortex, 2023. **33**(17): p. 9877-9895.
82. Pinotsis, D.A., G. Fridman, and E.K. Miller, *Cytoelectric coupling: Electric fields sculpt neural activity and "tune" the brain's infrastructure*. Prog Neurobiol, 2023. **226**: p. 102465.
83. Pinotsis, D.A. and E.K. Miller, *Beyond dimension reduction: Stable electric fields emerge from and allow representational drift*. Neuroimage, 2022. **253**: p. 119058.
84. Draper, M.H. and S. Weidmann, *Cardiac resting and action potentials recorded with an intracellular electrode*. J Physiol, 1951. **115**(1): p. 74-94.
85. Chakravarthy, S.V. and J. Ghosh, *On Hebbian-like adaptation in heart muscle: a proposal for 'cardiac memory'*. Biol Cybern, 1997. **76**(3): p. 207-15.
86. Zoghi, M., *Cardiac memory: do the heart and the brain remember the same?* J Interv Card Electrophysiol, 2004. **11**(3): p. 177-82.
87. Kurtz, J., *Specific memory within innate immune systems*. Trends Immunol, 2005. **26**(4): p. 186-92.
88. Banskota, S., J.E. Ghia, and W.I. Khan, *Serotonin in the gut: Blessing or a curse*. Biochimie, 2019. **161**: p. 56-64.
89. Levin, M., G.A. Buznikov, and J.M. Lauder, *Of minds and embryos: left-right asymmetry and the serotonergic controls of pre-neural morphogenesis*. Dev Neurosci, 2006. **28**(3): p. 171-85.
90. Segundo-Ortin, M. and P. Calvo, *Plant sentience? Between romanticism and denial: Science*. Animal Sentience, 2023. **8**(33): p. 1.
91. Miguel-Tome, S. and R.R. Llinas, *Broadening the definition of a nervous system to better understand the evolution of plants and animals*. Plant Signal Behav, 2021. **16**(10): p. 1927562.
92. Hennessey, T.M., W.B. Rucker, and C.G. Mcdiarmid, *Classical-Conditioning in Paramecia*. Animal Learning & Behavior, 1979. **7**(4): p. 417-423.
93. Alipour, A., et al., *Paramecium learning: New insights*. The Journal of protozoology research, 2018. **28**(1-2): p. 22-32.
94. Gershman, S.J., et al., *Reconsidering the evidence for learning in single cells*. Elife, 2021. **10**: p. e61907.
95. Boisseau, R.P., D. Vogel, and A. Dussutour, *Habituation in non-neural organisms: evidence from slime moulds*. Proc Biol Sci, 2016. **283**(1829): p. 20160446.
96. Boussard, A., et al., *Memory inception and preservation in slime moulds: the quest for a common mechanism*. Philos Trans R Soc Lond B Biol Sci, 2019. **374**(1774): p. 20180368.
97. Murugan, N.J., et al., *Mechanosensation Mediates Long-Range Spatial Decision-Making in an Aneural Organism*. Adv Mater, 2021. **33**(34): p. e2008161.
98. Bonzanni, M., et al., *On the Generalization of Habituation: How Discrete Biological Systems Respond to Repetitive Stimuli: A Novel Model of Habituation That Is Independent of Any Biological System*. Bioessays, 2019. **41**(7): p. e1900028.

99. Bonzanni, M., et al., *Optogenetically induced cellular habituation in non-neuronal cells*. PLoS One, 2020. **15**(1): p. e0227230.
100. Lyon, P., *The cognitive cell: bacterial behavior reconsidered*. Front Microbiol, 2015. **6**: p. 264.
101. Keijzer, F., M. van Duijn, and P. Lyon, *What nervous systems do: early evolution, input-output, and the skin brain thesis*. Adaptive Behavior, 2013. **21**(2): p. 67-85.
102. Calvo, P. and F. Baluska, *Conditions for minimal intelligence across eukaryota: a cognitive science perspective*. Front Psychol, 2015. **6**: p. 1329.
103. Gremiaux, A., et al., *Plant anesthesia supports similarities between animals and plants: Claude Bernard's forgotten studies*. Plant signaling & behavior, 2014. **9**(1): p. e27886.
104. Trewavas, A.J. and F. Baluska, *The ubiquity of consciousness*. EMBO Rep, 2011. **12**(12): p. 1221-5.
105. Aur, D., *From Neuroelectrodynamics to Thinking Machines*. Cognitive Computation, 2012. **4**(1): p. 4-12.
106. Scott, H.L., et al., *Evidence for long-term potentiation in phospholipid membranes*. Proc Natl Acad Sci U S A, 2022. **119**(50): p. e2212195119.
107. Zheng, J.M., et al., *Surfaces and interfacial water: evidence that hydrophilic surfaces have long-range impact*. Adv Colloid Interface Sci, 2006. **127**(1): p. 19-27.
108. Craddock, T.J., et al., *Anesthetics act in quantum channels in brain microtubules to prevent consciousness*. Current topics in medicinal chemistry, 2015. **15**(6): p. 523-33.
109. Hameroff, S., *Quantum walks in brain microtubules--a biomolecular basis for quantum cognition?* Topics in cognitive science, 2014. **6**(1): p. 91-7.
110. Hameroff, S.R., T.J. Craddock, and J.A. Tuszyński, "Memory bytes" - molecular match for CaMKII phosphorylation encoding of microtubule lattices. Journal of integrative neuroscience, 2010. **9**(3): p. 253-67.
111. Hameroff, S., et al., *Conduction pathways in microtubules, biological quantum computation, and consciousness*. Biosystems, 2002. **64**(1-3): p. 149-68.
112. Dimonte, A., et al., *On chirality of slime mould*. Biosystems, 2016. **140**: p. 23-7.
113. Lewis, O.L., et al., *Coordination of contractility, adhesion and flow in migrating Physarum amoebae*. J R Soc Interface, 2015. **12**(106).
114. Wright, M., et al., *Microtubule cytoskeleton and morphogenesis in the amoebae of the myxomycete Physarum polycephalum*. Biology of the cell / under the auspices of the European Cell Biology Organization, 1988. **63**(2): p. 239-48.
115. McMillen, P. and M. Levin, *Collective intelligence: A unifying concept for integrating biology across scales and substrates*. Commun Biol, 2024. **7**(1): p. 378.
116. Kim, T., et al., *Active alignment of microtubules with electric fields*. Nano Lett, 2007. **7**(1): p. 211-7.
117. Stracke, R., et al., *Analysis of the migration behaviour of single microtubules in electric fields*. Biochem Biophys Res Commun, 2002. **293**(1): p. 602-9.
118. Liao, M., X. Liang, and J. Howard, *The narrowing of dendrite branches across nodes follows a well-defined scaling law*. Proc Natl Acad Sci U S A, 2021. **118**(27): p. e2022395118.

119. Brummer, A.B., et al., *Branching principles of animal and plant networks identified by combining extensive data, machine learning and modelling*. J R Soc Interface, 2021. **18**(174): p. 20200624.
120. Cuntz, H., A. Mathy, and M. Häusser, *A scaling law derived from optimal dendritic wiring*. Proc Natl Acad Sci U S A, 2012. **109**(27): p. 11014-8.
121. Vazza, F. and A. Feletti, *The Quantitative Comparison Between the Neuronal Network and the Cosmic Web*. Frontiers in Physics, 2020. **8**: p. 525731.
122. Cragg, B.G. and H.N. Temperley, *Memory: the analogy with ferromagnetic hysteresis*. Brain, 1955. **78**(2): p. 304-16.
123. Loeffler, A., et al., *Neuromorphic learning, working memory, and metaplasticity in nanowire networks*. Sci Adv, 2023. **9**(16): p. eadg3289.
124. Persinger, M.A., *Brain electromagnetic activity and lightning: potentially congruent scale-invariant quantitative properties*. Front Integr Neurosci, 2012. **6**: p. 19.
125. Park, H.J. and K. Friston, *Structural and functional brain networks: from connections to cognition*. Science, 2013. **342**(6158): p. 1238411.
126. John, E.R., *The neurophysics of consciousness*. Brain Res Brain Res Rev, 2002. **39**(1): p. 1-28.
127. Koch, C., *What Is Consciousness?* Sci Am, 2018. **318**(6): p. 60-64.
128. Rouleau, N. and M. Levin, *Multiple ways to implement and infer sentience*. Animal Sentience, 2023. **8**(33): p. 30.
129. Friston, K., *Am I Self-Conscious? (Or Does Self-Organization Entail Self-Consciousness?)*. Front Psychol, 2018. **9**: p. 579.
130. Solms, M., *The Hard Problem of Consciousness and the Free Energy Principle*. Front Psychol, 2018. **9**: p. 2714.
131. Graziano, M.S.A., *The Attention Schema Theory: A Foundation for Engineering Artificial Consciousness*. Frontiers in Robotics and AI, 2017. **4**: p. 60.
132. Jackendoff, R., *Consciousness and the Computational Mind*. 1987, Cambridge, MA: MIT Press.
133. Prinz, J., *The Conscious Brain: How Attention Engenders Experience*. 2012: Oxford University Press.
134. Seth, A.K., *Being You: A New Science of Consciousness*. 2021, London: Faber & Faber.
135. Seth, A.K., *The Cybernetic Bayesian Brain*, in *Open MIND*, T.K. Metzinger and J.M. Windt, Editors. 2015, MIND Group: Frankfurt am Main.
136. Seth, A.K. and M. Tsakiris, *Being a Beast Machine: The Somatic Basis of Selfhood*. Trends Cogn Sci, 2018. **22**(11): p. 969-981.
137. Aru, J., M. Suzuki, and M.E. Larkum, *Cellular Mechanisms of Conscious Processing*. Trends Cogn Sci, 2020. **24**(10): p. 814-825.
138. Tononi, G. and G.M. Edelman, *Consciousness and complexity*. Science, 1998. **282**(5395): p. 1846-51.
139. McFadden, J., *Integrating information in the brain's EM field: the cemi field theory of consciousness*. Neurosci Conscious, 2020. **2020**(1): p. niaa016.
140. Baars, B.J., *A Cognitive Theory of Consciousness*. 1988, Cambridge, UK: Cambridge University Press.

141. Dehaene, S. and J.P. Changeux, *Experimental and theoretical approaches to conscious processing*. Neuron, 2011. **70**(2): p. 200-27.
142. Mashour, G.A., et al., *Conscious Processing and the Global Neuronal Workspace Hypothesis*. Neuron, 2020. **105**(5): p. 776-798.
143. Rosenthal, D., *Consciousness and Mind*. 2005: Clarendon Press.
144. Brown, R., H. Lau, and J.E. LeDoux, *Understanding the Higher-Order Approach to Consciousness*. Trends Cogn Sci, 2019. **23**(9): p. 754-768.
145. Chang, A.Y.C., et al., *Information Closure Theory of Consciousness*. Front Psychol, 2020. **11**: p. 1504.
146. Tononi, G., *Consciousness as integrated information: a provisional manifesto*. Biol Bull, 2008. **215**(3): p. 216-42.
147. Tononi, G., et al., *Integrated information theory: from consciousness to its physical substrate*. Nat Rev Neurosci, 2016. **17**(7): p. 450-61.
148. Oizumi, M., L. Albantakis, and G. Tononi, *From the phenomenology to the mechanisms of consciousness: Integrated Information Theory 3.0*. PLoS Comput Biol, 2014. **10**(5): p. e1003588.
149. Lamme, V.A., *Towards a true neural stance on consciousness*. Trends Cogn Sci, 2006. **10**(11): p. 494-501.
150. Lamme, V.A., *How neuroscience will change our view on consciousness*. Cogn Neurosci, 2010. **1**(3): p. 204-20.
151. Dennett, D.C., *Consciousness Explained*. 1991, Boston, New York, London: Little, Brown.
152. Edelman, G.M., *Neural Darwinism: The Theory of Neuronal Group Selection*. 1987, New York, NY: Basic Books Inc.
153. Edelman, G.M., *The Remembered Present: A Biological Theory of Consciousness*. 1989, New York, NY: Basic Books Inc.
154. Park, H.D. and C. Tallon-Baudry, *The neural subjective frame: from bodily signals to perceptual consciousness*. Philos Trans R Soc Lond B Biol Sci, 2014. **369**(1641): p. 20130208.
155. Pennartz, C.M.A., *Consciousness, Representation, Action: The Importance of Being Goal-Directed*. Trends Cogn Sci, 2018. **22**(2): p. 137-153.
156. Hameroff, S. and R. Penrose, *Consciousness in the universe: a review of the 'Orch OR' theory*. Phys Life Rev, 2014. **11**(1): p. 39-78.
157. Hohwy, J. and A. Seth, *Predictive processing as a systematic basis for identifying the neural correlates of consciousness*. Philosophy and the Mind Sciences, 2020. **1**(II): p. 3.
158. Clark, A., *Whatever next? Predictive brains, situated agents, and the future of cognitive science*. Behav Brain Sci, 2013. **36**(3): p. 181-204.
159. Hohwy, J., *The Predictive Mind* 2013, Oxford, UK: Oxford University Press.
160. Marvan, T. and M. Havlík, *Is predictive processing a theory of perceptual consciousness?* New Ideas in Psychology, 2021. **61**: p. 100837.
161. O'Regan, J.K. and A. Noë, *A sensorimotor account of vision and visual consciousness*. Behav Brain Sci, 2001. **24**(5): p. 939-73; discussion 973-1031.
162. Damasio, A., *Self Comes To Mind: Constructing the Conscious Brain*. 2010, New York, NY: Pantheon.

163. Damasio, A., *The Feeling of What Happens: Body and Emotion in the Making of Consciousness*. 2000, New York, NY: Harper Collins.
164. Cleeremans, A., et al., *Learning to Be Conscious*. Trends Cogn Sci, 2020. **24**(2): p. 112-123.
165. Ginsburg, S. and E. Jablonka, *The Evolution of the Sensitive Soul: Learning and the Origins of Consciousness*. 2019, Cambridge, MA: MIT Press.
166. Birch, J., S. Ginsburg, and E. Jablonka, *Unlimited Associative Learning and the origins of consciousness: a primer and some predictions*. Biol Philos, 2020. **35**: p. 56.
167. 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.
168. Lyon, P., et al., *Reframing cognition: getting down to biological basics*. Philos Trans R Soc Lond B Biol Sci, 2021. **376**(1820): p. 20190750.
169. Levin, M., et al., *Uncovering cognitive similarities and differences, conservation and innovation*. Philos Trans R Soc Lond B Biol Sci, 2021. **376**(1821): p. 20200458.
170. Pfeifer, R., J. Bongard, and S. Grand, *How the body shapes the way we think : a new view of intelligence*. 2007, Cambridge, Mass.: MIT Press. xxiv, 394 p.
171. Pfeifer, R., F. Iida, and M. Lungarella, *Cognition from the bottom up: on biological inspiration, body morphology, and soft materials*. Trends in Cognitive Sciences, 2014. **18**(8): p. 404-413.
172. Pfeifer, R. and G. Gomez, *Morphological Computation - Connecting Brain, Body, and Environment*. Creating Brain-Like Intelligence: From Basic Principles to Complex Intelligent Systems, 2009. **5436**: p. 66-83.
173. Levin, M., *The Multiscale Wisdom of the Body: Collective Intelligence as a Tractable Interface for Next-Generation Biomedicine*. Bioessays, 2024: p. e202400196.
174. Mathews, J., et al., *Cellular signaling pathways as plastic, proto-cognitive systems: Implications for biomedicine*. Patterns (N Y), 2023. **4**(5): p. 100737.
175. Lagasse, E. and M. Levin, *Future medicine: from molecular pathways to the collective intelligence of the body*. Trends Mol Med, 2023.
176. 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).
177. 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.
178. Csermely, P., et al., *Learning of Signaling Networks: Molecular Mechanisms*. Trends Biochem Sci, 2020. **45**(4): p. 284-294.
179. Gyurko, D.M., et al., *Adaptation and learning of molecular networks as a description of cancer development at the systems-level: potential use in anti-cancer therapies*. Seminars in cancer biology, 2013. **23**(4): p. 262-9.

180. McMillen, P., S.I. Walker, and M. Levin, *Information Theory as an Experimental Tool for Integrating Disparate Biophysical Signaling Modules*. Int J Mol Sci, 2022. **23**(17).
181. Blackiston, D., et al., *Revealing non-trivial information structures in aneural biological tissues via functional connectivity*. bioRxiv, 2024: p. 2024.05.09.593467.
182. Varley, T.F., et al., *Identification of brain-like functional information architectures in embryonic tissue of Xenopus laevis*. bioRxiv, 2024: p. 2024.12.05.627037.
183. Pigozzi, F., A. Goldstein, and M. Levin, *Associative Conditioning in Gene Regulatory Network Models Increases Integrative Causal Emergence*. 2024: OSF Preprints.
184. McMillen, P. and M. Levin, *Optical Estimation of Bioelectric Patterns in Living Embryos*. Methods Mol Biol, 2024. **2745**: p. 91-102.
185. Hausmann, D., et al., *Autonomous rhythmic activity in glioma networks drives brain tumour growth*. Nature, 2023. **613**(7942): p. 179-186.
186. Quicke, P., et al., *Voltage imaging reveals the dynamic electrical signatures of human breast cancer cells*. Commun Biol, 2022. **5**(1): p. 1178.
187. Kamm, R.D. and R. Bashir, *Creating living cellular machines*. Annals of biomedical engineering, 2014. **42**(2): p. 445-59.
188. Ebrahimkhani, M.R. and M. Ebisuya, *Synthetic developmental biology: build and control multicellular systems*. Curr Opin Chem Biol, 2019. **52**: p. 9-15.
189. Kitamura, T., T. Tahara, and K.-I. Asami, *How can a robot have consciousness?* Advanced Robotics, 2000. **14**(4): p. 263-275.
190. Singh, S., et al. *Artificial intelligence, cognitive robotics and nature of consciousness*. in *3rd International Conference on Intelligent Engineering and Management (ICLEM)*. 2022. London, UK: IEEE.
191. Cardon, A., *Artificial consciousness, artificial emotions, and autonomous robots*. Cogn Process, 2006. **7**(4): p. 245-67.
192. Rouleau, N., *Embodied 3D Neural Tissue Cultures for Cognitive Research*, in *Brain and Cognitive Intelligence Control in Robotics*, B. Wei, Editor. 2022, CRC Press: Boca Raton, FL. p. 81-101.
193. Rouleau, N., N.J. Murugan, and D.L. Kaplan, *Toward Studying Cognition in a Dish*. Trends Cogn Sci, 2021. **25**(4): p. 294-304.
194. Powers, W.T., *Behavior: the control of perception*. 1973, Chicago,: Aldine Pub. Co. xi, 296 p.
195. Friston, K., S. Samothrakis, and R. Montague, *Active inference and agency: optimal control without cost functions*. Biological cybernetics, 2012. **106**(8-9): p. 523-41.
196. Pezzulo, G., F. Rigoli, and K.J. Friston, *Hierarchical Active Inference: A Theory of Motivated Control*. Trends Cogn Sci, 2018. **22**(4): p. 294-306.
197. Kirchhoff, M., et al., *The Markov blankets of life: autonomy, active inference and the free energy principle*. J R Soc Interface, 2018. **15**(138).
198. Maciejewicz, B., *Neuroscience of consciousness in the locked-in syndrome: Prognostic and diagnostic review*. Ibrain, 2022. **8**(4): p. 476-480.

199. Darwin, C., *On the origin of species by means of natural selection, or, The preservation of favoured races in the struggle for life*. 1859, London: J. Murray. ix, 1 , 502 p.
200. de Haan, E.H.F., et al., *Split-Brain: What We Know Now and Why This is Important for Understanding Consciousness*. Neuropsychol Rev, 2020. **30**(2): p. 224-233.
201. Kukushkin, N.V., et al., *The massed-spaced learning effect in non-neural human cells*. Nat Commun, 2024. **15**(1): p. 9635.
202. Gershman, S.J., et al., *Reconsidering the evidence for learning in single cells*. Elife, 2021. **10**.
203. Levin, M. and C.J. Martyniuk, *The bioelectric code: An ancient computational medium for dynamic control of growth and form*. Biosystems, 2018. **164**: p. 76-93.
204. Yampolskiy, R.V., *The Universe of Minds*. ArXiv, 2014. **abs/1410.0369**.
205. Dennett, D.C., *Kinds of minds : toward an understanding of consciousness*. 1st ed. Science masters series. 1996, New York: Basic Books. 184 p.
206. Nagel, T., *Other minds : critical essays*. 1995, Oxford: Oxford University Press.
207. Sloman, A., *The structure of the space of possible minds*, in *The Mind and the Machine: philosophical aspects of Artificial Intelligence*, S. Torrance and E. Horwood, Editors. 1984, MIT. p. 35-42.
208. Morgan, C.L., *Other minds than ours*, in *An Introduction to Comparative Psychology*, W. Scott, Editor. 1903. p. 59-.
209. Cho, E.S., et al., *In vivo whole-brain imaging of zebrafish larvae using three-dimensional fluorescence microscopy*. J Vis Exp, 2023. **194**(194): p. e65218.
210. 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.
211. Vandenberg, L.N., R.D. Morrie, and D.S. Adams, *V-ATPase-dependent ectodermal voltage and pH regionalization are required for craniofacial morphogenesis*. Dev Dyn, 2011. **240**(8): p. 1889-904.
212. Pezzulo, G. and M. Levin, *Top-down models in biology: explanation and control of complex living systems above the molecular level*. J R Soc Interface, 2016. **13**(124).
213. Blackiston, D.J. and M. Levin, *Ectopic eyes outside the head in Xenopus tadpoles provide sensory data for light-mediated learning*. J Exp Biol, 2013. **216**(Pt 6): p. 1031-40.
214. 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*. J Exp Zool, 1945. **100**: p. 445-55.
215. Levin, M., *Darwin's agential materials: evolutionary implications of multiscale competency in developmental biology*. Cell Mol Life Sci, 2023. **80**(6): p. 142.