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RESEARCH

Developmental Bioelectricity as an Explanatory Framework for Cognition and Meaning

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Abstract

We critically examine the intersection of developmental bioelectricity within the context of the Peircean philosophy of science. We address the criticism of Peirce's objective idealism and synechism, contest the conflation of semiotic and physical laws, and scrutinise Peirce's recovery of physical from psychological laws. The upshot is a nonmechanistic, nonreductive interpretation of the evolution of cognition in the bioengineering realm. The work of Kull and others is leveraged to demarcate semiotics and physics, emphasising the irreducibility of bioelectric phenomena to mechanistic explanations. Our paper advocates for methodological synechism in evolutionary biology, highlighting the heightened roles of bioelectricity in morphogenesis and basal cognition. We propose the free-energy principle as a unifying arbiter that sets an explanatory pathway toward integrated cognition and meaning in developmental bioelectricity.

Highlights

- We assess the conceptual underpinnings of developmental bioelectricity as a fledgling theory of cognition and meaning—a key question in biosemiotic research;
- We frame our critical evaluation using Peirce's theory of semiotics and its philosophical and methodological positioning of synechism (true continuity);
- We propose the free-energy principle to establish an explanatory pathway toward an integrated biosemiotic approach to cognition and meaning.

Keywords Developmental bioelectricity · Objective idealism · Synechism · Charles Peirce · Meaning and cognition · Free-energy principle

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Introduction: Is Cognition a Bioelectric Phenomenon?

Understanding life has long been a central pursuit in the scientific domain. Among these, the study of developmental bioelectricity stands out as a nascent field promising for revealing the electrical underpinnings of biological processes from morphogenesis to cognition. This paper explores the philosophical and theoretical dimensions of developmental bioelectricity, particularly through the lens of Charles S. Peirce's semiotic philosophy, which was an architectonic attempt to guess the riddle of the complex interplay between biological systems and their emergent competencies and properties.

The intersection of developmental bioelectricity with Peircean semiotics provides fertile ground for examining the foundational principles that govern living processes. In the strong tradition of biosemiotics, "semiosis is taken to be a steadfast, indeed bedrock, hallmark of life" (Sebeok, 1999: 86). Our present paper pivots to Peirce's concepts of objective idealism and synechism, which are taken to constitute the philosophical background against which bioelectric phenomena can be critically assessed. Objective idealism posits that Mind[1] and its laws precede the physical, whereas synechism emphasises the continuity of the universe, nondualism of mind and matter, and the interconnectedness of cognition and meaning.

These philosophical stances challenge the traditional mechanistic interpretations of biological evolution. The development of intelligence suggests a dynamic and interconnected view of life. We critically engage with the conflation of semiotic and physical laws, scrutinising the recovery of physical laws from psychological laws. The case in point is the work of Kalevi Kull (Kull, 2014) on delineating the boundaries between semiotics and physics. In contrast, we emphasise the irreducibility of bioelectric phenomena to purely mechanistic explanations. Building on recent advances in computational neuroscience, our paper explores how emerging quasi-mechanistic frameworks mediate between semiotics and physics. We advance a reconciliatory approach and seek to integrate these domains within a unified interpretive framework.

To do this, we propose the Free Energy Principle (FEP) as a unifying theoretical construct that could bridge the gap between life sciences and physics, providing a coherent explanatory pathway for top-down explanations of cognition and meaning in developmental bioelectricity. In the spirit of synechism, FEP, with its focus on minimising prediction error and understanding the generative models of organisms, offers a robust formal framework for linking diverse scientific fields and theories.

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[1] We highlight the realist understanding of the functioning of Mind – herein capitalised to agree with Peirce's practice of spelling concomitant words such as 'Reason': "Consider, for a moment, what Reason, as well as we can today conceive it, really is. I do not mean man's faculty which is so called from its embodying in some measure Reason, or Νοῦς, as a something manifesting itself in the mind, in the history of mind's development, and in nature. What is this Reason? In the first place, it is something that never can have been completely embodied …. The very being of the General, of Reason, consists in its governing individual events. So, then, the essence of Reason is such that its being never can have been completely perfected. It always must be in a state of incipiency, of growth" (1903, CP 1.615). (We thank the reviewer for the comment on the distinction of the colloquial understanding of the mind and Peircean understanding).

This paper thus contributes to the ongoing dialogue between biology, philosophy, and physics by illuminating the pathways through which life's electrical dimension informs its developmental and cognitive processes, enriching our theoretical grasp of the living world. The paper is structured first to lay the philosophical groundwork, followed by a critical examination of the current theoretical landscape in developmental bioelectricity. We then delve into the implications of bioelectricity for our understanding of basal cognition and the emergence of meaning within biological systems. In the last section, we briskly overview the FEP and advance it as a unifying framework to bridge semiotics and physics in explaining biological phenomena.

Criticism of the First Principles: Objective Idealism and Synechism

We believe that Peirce's methodological principle, namely, the doctrine that "continuity governs the whole domain of experience in every element of it" (CP 7.566, 1892), is a relevant and helpful regulative principle to follow in contemporary biology and life sciences. The principle of synechism is famously allied in Peirce's philosophy with the metaphysical tenet of objective idealism, which sees reality as a network of interconnected and growing ideas that exist independently of individual minds. We argue that the position of objective idealism and the regulative principle of synechism can advance the contemporary sciences of the mind and brain, as well as mental and biological matters, in novel ways. In the present paper, we approach the question of these first methodological and metaphysical principles from the perspective of the critiques that have been lodged in the literature against such holistic, top-down explanations of what we take to be the biosemiotically relevant and promising, integrated vision of cognition, meaning, and intelligence.

Kull's Critique

Peirce's *objective idealism* posits reality as a network of interconnected and growing ideas that exist independently of individual minds. This reality is comprehended through scientific inquiry and logical reasoning. The standard criticism of objective idealism is that the tenet is unfalsifiable, not unlike the simulation argument, the brain-in-a-vat thought experiment, and other epistemically sceptical arguments are unfalsifiable. Even if the enthusiasts claim that mind and its laws are prior to matter and physical laws, an issue remains that they will just be interpreting whatever facts there may be as those that verify the original statement. Therefore, a proponent of such tenets will never accept a tentative counterargument as a plausible refuter of the key statement.

A standard criticism of *synechism* takes a similar argumentative position. Peirce's synechism is the view that "continuity governs the whole domain of experience in every element of it" (CP 7.566, 1892; Haack, 2005). It is commonly held that the verification of such statements is problematic: "[I]t is clear that there is no way to demonstrate the world's continuity on the basis of facts" (Kull, 2014: 91).[2] If the scientific standard of the criterion for validity is verification through demonstration, then such arguments may be tedious. However, scientific progress is piecemeal, self-critical, unpredictable, and seldom a matter of verification by demonstration alone. The edifice of science has made advances through conjecture-making, plausible and implausible predictions, batteries of refutations and counter-refutations, and serendipitous error correction.

The opponents of a broadly Peircean perspective to the unification of synechism with objective idealism might focus on the problem of the demarcation between the two realms of the psychical and the mental phenomena and the physical and material concerns that arise within them. Citing Peirce,[3] Kull (2014: 87), whose engagement with Peirce's semiotic theory to underpin research in biosemiotics is implicit rather than explicit, distinguishes between the limits of the explanatory power of the theory of semiotics and that of contemporary physics, such as particle physics, high-energy physics, and cosmology. Kull (2014: 94) suggested several explanations for endorsing Peirce's idealistic position and explained errors in reasoning that might have led to the conclusion that the mind and its 'laws' have an ontological priority over the laws of physics, biology, and related sciences. Below, we expose the key problems involved in his suggested explanations.

The first level of explanation is philosophical: Kull (2014: 93–94) criticises the framework of ontological categories that led Peirce to materially identify semiotic rules with physical laws, while in fact, their identity is just a matter of formal structures. Specifically, the common roots of meaning and laws lie within the *universal category of Thirdness*, the "true continuity" (CP 1.420, 1896) exhibited in the elements of generality, representation, and mediation. Thirdness concerns the formation of *habits*, which, in Peirce's thought, spans from the evolutionary acquisition of traits to the natural laws of physics and stable tendencies in human cultural and social

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[2] We can adduce an extensive list of empirical facts and phenomena that adds to the plausibility of the conjecture of synechism. The list of continuities includes trans-disciplinary evidence such as: the earth's atmosphere, the first replicator between abiotic and biotic; habitat belts for migrating birds that show continuous change from one species to another; exocrine secretions to epithelial surfaces; newborn-parental exchanges (microbial, immunochemical, experiential); homeostasis and allostasis of holobionts; aspen as a colony; a coral shark pack collectively hunting fish; near nonexistence of isolated molecules; the breed-species continuity; inapplicability of the concept of 'species' to most life; constantly changing DNA throughout the lifespan; transient self-construction in the human mind; the brain's self-modelling coupled with its environment; dvandva words in language that blend dichotomic meanings; virtual particles occupying the boundaries between existence and nonexistence; everything in quantum field theory being consistent with the continuum as the structure of fundamental reality; neutron-to-proton, electron-to-neutrino nonboundary interactions and transformations; T2 spheres without an interior in topology; impossibility to place fermions on a lattice structure; integers as an emergent mathematical structure. The list can go on and on.

[3] The seminal Peircean framing of biosemiotics is from Thomas A. Sebeok (Sebeok, 1991, 2001). His towering contributions include the formulation of the very notion of biosemiotics; the centrality of its triadic model; the interconnectedness of life and sign processes; the key role of interpretants and experiences; the holistic and the top-down strategies for explanations; and the extended cultural and co-evolutionary perspectives to meaning and cognition. Kull cites Peirce's *Monist* article "Man's Glassy Essence" here: "It may fairly be urged that since the phenomena of habit may thus result from a purely mechanical arrangement, it is unnecessary to suppose that habit-taking is a primordial principle of the universe" (CP 6.262, 1892).

behavior[4]. However, sharing roots in such a loose universal category as 'Thirdness' is insufficient to establish the identities of law-like entities that are vastly different in kind. Kull concludes that the semiotic framework generalises well neither for physical nor psychological laws.

The second point of criticism is linked to Peirce's epistemological coherentism. In Kull's view (2014: 88), Peirce's goal was to recover physical laws from psychological and mental laws, therefore showing that physical laws have a fundamentally psychological nomology. The issue is the underivability of psychological laws (as they involve arbitrary relations) from physical laws (here rather narrowly understood in terms of deterministic and mechanistic laws and not including stochastic laws of qualitative physics, ergodic phenomena, or interpretations of quantum mechanics, for instance) that allegedly motivated Peirce's inverse derivation of the physical from the psychological.[5] Kull (2024: 594) also criticises the fallibilistic,[6] continuum vision of scientific metaphysics, in which no independent realm of sensations or feelings exists. Apparently, Kull thinks that scientific theories can cross paths without having to yield terminological and nomological reductions.

The third point concerns evolutionary theory and Peirce's rejection of the mechanical understanding of evolution (Peirce, 1893). Peirce writes, "Evolution means nothing but growth in the widest sense of that word. Reproduction, of course, is merely one of the incidents of growth. And what is growth? Not mere increase. Spencer says it is the passage from the homogeneous to the heterogeneous – or, if we prefer English to Spencerese – diversification …. And yet mechanical law, which the scientific infallibilist tells us is the only agency of nature, mechanical law can never produce diversification" (CP 1.174, c.1897). In contrast, Kull argues for the spontaneous emergence of the mind from the dynamic and quasi-mechanistic, law-like processes that govern the properties and behaviors of objects described by contemporary physical theories.

The solutions that Kull provides from modern evolutionary theory can be analysed from a threefold perspective. The first concerns the demarcation between semiotics and physics. From this perspective, Kull restricts habit taking to all living entities endowed with diversification, including speciation, the capacity for learning, error-

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[4] Santaella Braga (2001: 60) underlines the independence of semiosis of nature (physiosemiosis) from the human semiosis that grasps natural laws as appearances of Thirdness by continuity and affinity. Although "physical laws are derived from psychical" (ibid.: 56), mind and matter are represented as "*termini* of a single *continuum*" (ibid., italics of the author) not as an inversion of physicalism (ibid.: 56, 58). The unifying force of this continuum is the Law of Mind. While physiosemiosis may be paralleled with the FEP, both claiming for the priority of informational processing in non-living entities, we believe that (1) FEP is an epistemological and methodological rather than an ontological posit and that (2) our interpretation of Peirce's objective idealism takes the relation of continuity of matter and mind to have a complex phaneroscopic, mathematical, and logical form beyond their being as *termini*. We thank the reviewer for the reference to the relevant literature.

[5] The existence of semiosis prior to biogenesis remains contentious; however, recent reconciliatory efforts (Pietarinen & Beni, 2021) have argued for the simultaneous emergence of life and meaning. These arguments adopt a naturalist perspective, grounded in theoretical biology rather than the formalisation of life dynamics.

[6] Peirce famously argued for fallibilism as the hallmark of genuine, truth-seeking science: Provisional, inquiry-based, critical, communal, pragmatistic, and non-absolute in its ever-lasting endeavour to interrogate and seek explanations and understanding.

making and correction, the revision of fallible rules (codes, relations), and plastic memory (in the semiotic realm). Laws such as physical regularities in physics or cosmology are not habits, according to Kull (2014: 94). Thus, Kull believes that Peirce's fallibilism is not a universal principle and does not cover physical constants and parameters. Peirce, we recall, maintained that fallibilism follows from synechism – fundamental uncertainty of knowing all the possibilities involved in the continuum. Scientific progress is a continuous and fallibilistic endeavour to navigate error and uncertainty (Haack, 2005); therefore, a link to an idealistic framework in the avowed synechistic spirit allows no discontinuities in the functions that represent optimisation protocols across multidimensional fitness landscapes.

Second, the conformity of semiotics to physical laws is independent of the property of deducibility (e.g., boundary conditions are by physical laws but not derivable from them). The theory of semiotics follows physical laws and guides the field of meaning and knowledge yet is not deducible from physics.[7] Materialism sees physical laws as fundamental; therefore, semiotic continuity (of change) is not a feature of physical reality. Kull (2014: 91) further mentioned that consciousness provides no evidence for the ontological primacy of the experience of continuity because the immediacy of perception and voluntary action are not accessible to awareness. For Kull (ibid.), awareness relates just to the past, what has already been. The reality of continuity is directly evidenced by the first-person, non-inferential experience of time in consciousness (CP 1.167–1.169, c.1897). The mind, on the other hand – with or without the properties of consciousness – is the future-leaning, abduction-performing faculty that moderates action by anticipation of events to come to pass. We briefly return in Sect. 4 to the importance of abduction in solving tasks involving the navigation of morphospaces.

Third, Kull (2014: 92; 2024: 589) proposes synergetic analysis to support the mind as a product of the development of matter; its emergence results from prebiological states of indeterminacy in dissipative and chaotic systems, and with self-organisation, the thermodynamics of open systems, and complex systems theory, new and surprising properties can be observed. With respect to the critique that synergetic analysis supports the mind as a product of the development of matter, Wells (1996: 244) aptly noted that the founders of the synergetic philosophy of science, Ilya Prigogine and Isabelle Stengers, refer "directly to Peirce whom they regard as anticipating their position".

Rejoinders

In response to the criticism levelled against Peirce's synechism, objective idealism, and the Law of Mind, the following two rejoinders may be provided.

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[7] Sebeok (1991: 83–96) was inspired by Wheeler's (1984) vision of physics in the context of participatory 'meaning model' of the universe, stating that physics is the offspring of semiosis that owes to a circuit of dependencies of definitions from particles to fields, from fields to phases, and then distinguishability and complementarity, finally to interpretations and meaning.

1. Peirce intensively studied the role of laws of probability in science, such as statistical law in physics (the kinetic theory of gases, namely, the Maxwell distribution of molecular velocities, which was discovered in 1859), and their role in biology (statistical implications of Darwin's law of natural selection).
2. Framework-level attempts to unify psychological and physical laws continue in the sciences. Relationships between various parts and domains of the sciences are primarily about the scale of application rather than hierarchies, organisation, or ontological preferences.

Regarding the first *adversum*, Peirce's view was that what we call natural and physical laws are known estimates and approximations of reality. They are relatively stable tendencies of the living world to take habits, subject to evolutionary dynamics and not eternal or immutable. Peirce worked on the theory of probability distributions in measurement theory. His decision to attribute spontaneity to the mind was unconnected to the absence of knowledge of statistical laws. Peirce proposed an analogous relationship to obtain between the explanatory structure of the second law of thermodynamics and the Law of Mind (CP 6.47, 1892).[8]

Wells (1996) argued in favour of this analogy: (i) the most combustive/intensive state of gases/ideas in a gaseous mixture are in a state of relative disequilibrium; (ii) gases/ideas attain uniformity of temperature/generality in a state of equilibrium but lose their ability to perform work and entropize; and (iii) heat transfer/spreading of ideas in a closed system manifests pragmatic "effects", namely, qualitative distinctions and explanations.

However, the problem remains that "Peirce understood laws to be approximations just because they obscured the tychistic reality standing behind them" (Wells, 1996: 236). Thus, objective chance and probability were included in the scientific ontology, which is fundamentally indeterministic,[9] albeit at different scales: law-like principles were presented as the result of the development of order. Thus, whatever the reality happened to be was not determined by the initial conditions. Tychistic states – "feeling, sporting here and there in pure arbitrariness" (CP 6.33, 1891), like the energy levels of vacuum states – preceded habit-taking tendencies that took over the evolutionary process in the early universe.[10]

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[8] The connections between thermodynamics and semiotics later were formulated on the basis of the notion of information, for example, a lack of information about the statistical structure of a semiotic system (Sebeok, 1999: 87).

[9] Wells (1996: 236) points out that "Peirce did not accept the deterministic ontology associated with invariant or mechanical laws. Such laws would be accepted provisionally with the expectation that they would eventually be subsumed under statistical laws or law more consonant with his tychistic ontology".

[10] As will transpire in Sect. 5, this resonates with the FEP, which posits that self-organising systems, in order to persist and thrive, must continuously regulate their internal entropy. Entropy, in this context, refers to the system's uncertainty about environment, and the FEP suggests that these systems actively minimise surprise—defined as the discrepancy between their expectations and the actual sensory input—by adjusting their internal models or alternatively changing the world. By doing so, they navigate the inherent unpredictability of their environment, maintaining stability despite external fluctuations. In this process, the system fosters emergent order, where coherent structures, patterns, and behaviours arise from complex interactions within the system and with its surroundings. This regulatory mechanism allows the system

The second rejoinder highlights the transdisciplinary character of conceptual advances in linking meaning and cognition in scientific frameworks that seek to explain surprising phenomena. In the concluding section, we defend a case for such analysis in terms of the free-energy principle (FEP), conceived as a biosemiotic notion. Thus, relationships between various parts and domains of biosciences tend to form at varying levels and scales of application rather than with clear-cut hierarchies, organisations, or methodic or ontic preferences and boundaries. Early examples of such ideas are present in Peirce's reinterpretation of Darwinism, which he, by 1911, was prone to expand with reasoning, learning, and habit-taking: "Habit-taking faculty breeds good reasoners, by a process analogous to Darwinian natural selection. This does not absolutely require, as far as we can at present see, the inheritance of acquired characters, although I guess that *some* acquired characters are heritable" (Pietarinen, 2024: 58, R 673; LoF 3/1: 58).

Evolutionary theorists of the extended synthesis must agree, we surmise: take phenotypic plasticity, or the Baldwin effect, for example, that learning can become an inheritable trait, as such habit-taking faculty attests to the adequacy of Peirce's early conjecture in a well-understood scientific fashion. Epigenetic marks are commonly heritable beyond immediate offspring in plants and organisms to which the concept of basal cognition applies, such as the fungus *Neurospora crassa* and others that exploit language-like electric communication signals with high morphological complexity for reproductive and other purposes (Adamatzky et al., 2022). Chemical makeup fluctuates in the DNA of mammalian organisms. Nonrobust fluctuations may dissipate as the gamete matures, but the jury is still out concerning inheritance over germlines in general cases of sexual reproduction.

Far from being a member of the class of 'arguments' from design, Peirce's reinterpretations of evolution through teleonomic and habit-taking tendencies were anticipatory of the extended synthesis at multiple junctions. His reinterpretations catered to theoretical and inferential elements in the present search for top-down scientific explanations for biological phenomena and at multiple scales of surprising[11] phenomena.

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to adapt to changing conditions and optimise its energy states, ensuring its survival and facilitating the emergence of higher-order organisational principles that evolve over time.

[11] Here, "surprising" is used in a technical sense informed by the Free Energy Principle, discussed in Sect. 5. Surprising events are improbable occurrences—such as aquatic organisms suffering out of their natural environment of water—that deviate from expected states. Both in Peirce's work and in the FEP, the goal is not to eradicate surprise but to regulate it, for instance, by reasoning that imposes an upper bound on such deviations.

Developmental Bioelectricity: A Window to Cognition and Meaning

Ladders and Snakes: Is the Theory of Developmental Bioelectricity Unreasonably Incomplete?

The fledgling field of the philosophy of bioelectricity[12] has also had to cope with critiques, e.g., from physiology, molecular biology, and oncology (Adams et al., 2019). Defining bioelectricity "to include a wider range of the role that electrical signalling plays in excitable and nonexcitable cells" (Adams et al., 2019: 13), the critique routinely either rejects the holistic, broad-stroke and top-down (or at least 'sideways') perspectives or acknowledges that some of the most innovative results of this new and emerging field are premature or restricted in scope and implications. Some critiques (e.g., Newman, 2014; Hekstra et al., 2016; Li et al., 2020; Tyler, 2017) aim to show that the theory of bioelectricity is incomplete, and that better integration is needed with research on biochemical coding and signals. This, in turn, requires different explanations across different domains, despite similarities in the overall phenomenon of bioelectricity. The adjacent arguments cover *molecular biophysics* (Newman, 2014), *crystallography* (Hekstra et al., 2016) and *mechanobiology*, which exhibit increasingly mechanistic constitutive laws to cover phenomena such as the effects of force (Xu & Bassel, 2020), mechanical stress fields (Tsikolia, 2003), or mechanosensitive ion channels, which, gated by membrane tension, modulate ion fluxes, transmembrane electrodiffusion, and eventually bioelectrical forces.

Therefore, to acclaim the status of a general theory as its adherents have claimed the field of bioelectricity to be, one should consider the subtle chemical distinctions of signalling and the mechanical causes of biofields. However, there are still approaches that are largely unaccounted for. For example, *morphometrics*, "the discipline associated with the measurement of shape" (Xu & Bassel, 2020: 419), is a method used to convert shapes and patterns of diverse plant morphology into numbers via methods such as computational simulation, 3D phenotyping via X-ray computed tomography, and the discretization of data into networks. Geometric morphometrics regards the spatial distribution of shape properties, such as length (major axis), width (minor axis), surface area, ratios of these parameters, and analysis of shape outlines or contour-based methods, as key measures for performing quantitative phenotypic analysis of mesoscales. Morphometrics aims to bridge the gap between shapes and genes, including phenotypic plasticity influenced by the environment, thus striving to explain the emergence of higher levels of biological organisation. Thus, morphometrics refers to both bottom-up (structural molecular) and top-down (topological) explanations and may, in that sense, be a necessary counterpart of biofield theories.

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[12] For details, we refer the reader to useful figures (e.g., multi-scale bioelectric gradients in vivo) provided in Tseng and Levin (2013) and George and Bates (2022). Silver and Nelson (2018: 3, 8, 10) shows a figure of a bioelectric field gradient, factors influencing cellular membrane voltage (Vm), and mechanical and chemical signals present in the cell; Xu and Bassel (2020: 418) depicts intra- and intercellular interactions; Li et al. (2020: 212) visualise five routes of Ca2+bioelectrical influxes; Harris (2021: 4) incorporates useful figures on bioelectrical control in development; Silic and Zhang (2023: 18) diagrams perspectives of bioelectricity; Cohen and Venkatachalam (2014: 221) figure mechanisms by which membrane voltage can influence membrane-associated processes.

Ladders, as Gell-Mann (1994) famously suggested, are thus built between the two routes to explanations. Noble (2022), too, agrees that good explanations of physiological phenomena require simultaneous applications of both kinds of explanations.

Oncology and Embryogenesis

There are snakes, too. One issue that curtails the promise of bioelectricity is the acknowledged presence of somewhat conflicting results from oncology. Silver and Nelson (2018) analysed the ability of manipulating the membrane voltage (Vm, the electrical potential difference between the cytoplasm and extracellular space) to prevent tumorous proliferation. Initially, this was one of the optimistic assertions concerning bioelectricity's therapeutic potential; however, the experimental outcomes remained inconclusive owing to both mechanical (e.g., cell–cell adhesion, substratum stiffness, fluid flow) and chemical (e.g., pH, cell secretions, glucose levels) factors. The rub was that "similar Vm manipulations can trigger both growth and death" (Silver & Nelson, 2018). Therefore, at the cellular level, proliferation and apoptosis have been observed to be two sides of the same processual coin, where "it is still unclear how an individual cell translates a given Vm into a fate decision" (ibid.). Apoptosis and proliferation are so closely interconnected that tumor initiation signals may differ only slightly from regenerative signals resulting from cellular interactions. Moreover, the nature and role of Vm in embryogenesis have been questioned: Silver and Nelson (2018: 10) asked: Is Vm "an intrinsic signaling code emitted from cells during growth or a physiological memory imprinted on cells by their surroundings?" – or both, one might add. The critics see the ontogenetic development of the phenomenon shrouded in unclarity concerning how Vm signals are altered by the passage of time during aging. Research on bioelectricity has not agreed upon a general or conciliatory approach to heterogeneous phenomena in morphogenesis.

Our comment concerning the critiques received from oncology and embryogenesis is that while they rightly point out the thorny issue of threading the needle between triggers of proliferation and apoptosis, the argument is off target as a critique of the explanatory value of bioelectricity's hypotheses for conceptual and foundational purposes. The acclaimed virtue of developmental bioelectricity lies in the breadth of its working hypotheses concerning how developing organisms, tissues, or body parts could navigate morphospaces toward their target morphologies.

Our First Ladder: Morphogenesis as a Path Integral

Conceptually and mathematically, we propose that the structures of such processes and strategies should be viewed in the *path-integral* sense of navigation through the trajectory class, namely, the potential to consider all possible ways to sample the intermediate spaces to reach the targets that evolve in indeterminate contexts. This, we propose, can become a fruitful conceptual perspective to address the issue of the meaning of flexible problem-solving competences when new anatomical and other homeostatic states need to be reached in rare or novel circumstances. Path integrals address missing components and elements, given that the novelty of those circumstances precisely means the absence of what needs to be regenerated by the activation of cellular structure formation for the organism or biomatter to compensate for the missing elements by proliferation, which is expected to correct for the surprising errors encountered. The path-integral perspective solves the problem of missing solutions not in the sense of a differential that attempts to find the right signals that code for the missing structures, which necessitates searching for some singular factors, hardware solutions, pathways, or at least their initial conditions that could be used to effectuate and manipulate desired but divergent effects either by proliferation or apoptosis. The path integral tracks missing solutions by generalising the states into second-order relationships.

Second Ladder: Abductive Reasoning in Morphospace Navigation

Briefly put, the philosophy of bioelectricity is primarily to address "how possible" questions in problem-solving contexts involving novelty and innovation, not "why necessary" questions concerning the discovery of actual triggers, causes, or law-like mechanisms. In other words, the meaning of an 'absence' of the missing structures to be compensated by proliferation is to evoke new habits of action for the required remodelling within the totality of the space of possible anatomical shapes and other structures from metabolism to physiology, transcription, or even immunochemistry.

In other words, moving closer to the target morphologies refers to the abilities that can be engaged in terms of means-ends reasoning tasks. Such reasoning is retroductive, namely, it involves the creation of abductive hypotheses as the result of organisms or their subunits, who reason from desired effects to their plausible and fruitful (truth-conducive) causes. However, it is not that any random or quasi-random guess is equally valuable: the sampling of all trajectories means gravitating toward the selection of those hypotheses that are fruitful for the purpose of further orientation in navigation across the morphospaces, even if those hypotheses are strictly speaking false. The results of these samplings by abductive reasoning are, in Peirce's words, "gravid with your truth", which he designated with the words "uberous" and "uberty" – certain positive and delicate valences towards the fulfilment of the generalised path-sampling task. Hypotheses that have "living and esperable uberty" (LoF 3/2, 1913) refer to the property of guesses that orient further inquiries towards the target morphologies, although the hypothesis itself may be false. Thus, abduction is quite unparalleled by any other form of reasoning whenever (i) uncertainty reigns free (indeterminate targets), (ii) conclusive data are in short supply (limitations to test), and (iii) the future courses of events are unpredictable (biological processes).

Morphospace navigation is rife with backwards-moving inferences that develop in their guessing competence as the habits of abductive reasoning grow in reach and effectiveness. Explaining these phenomena calls for the precise theory of the type of which Peirce called abduction. Conceptually, these inferences can be used to account for the ability of biological systems to respond to novel conditions even at the small-scale cellular swarm and embryonic levels.

Third Ladder: Quasi-Mechanistic Habit-Taking Tendencies

The critique of top-down explanations in developmental bioelectricity thus comes around not only to Peirce's logic but also to his synechism, objective idealism, and, ultimately, to the semiotic hypothesis of habit-taking tendencies for all phenomena that take irreducible triadic forms. We recall the semiotic projects that preceded bioelectricity. The endosemiotics of Sebeok (1991) studied sign processes realized by chemical, thermal, mechanical, and electrical processes inside organisms to exchange meaning, regulate, and control. The subject matters included immunosemiotics, metabolic codes, "the universal RNA/DNA-based genetic code" (Sebeok, 1999: 88) and neural codes.

Such phenomena may well be explained by quasi-mechanistic or even purely mechanistic habit-taking tendencies. Peirce's view on the matter, understood in the late 19th century context of developmental biology, relates to his investigation of the protoplasm. He wrote, "Since the phenomenon of habit may thus result from a purely mechanical arrangement, it is unnecessary to suppose that habit taking is a primordial principle of the universe" (CP 6.262, 1892). Rather, 'the property' of feeling or sensations of the protoplasm "must be shown to arise from some peculiarity of the mechanical system" (ibid.). Supplanting the "purely mechanical arrangement" by modern "bioengineering" or "bioelectric rearrangement", we have a hypothetical mechanism at hand that explains the observable and testable phenomenon of habit-taking in the bioengineering context.

For example, bioelectrically and computationally reengineered biological creatures such as *xenobots* are reprogrammed cellular biobots capable of von Neumann-style kinematic reproduction (Kriegman et al., 2021). The novel behaviours of xenobots exemplify what Peirce discoursed in terms of protoplasms' habit-taking tendencies, like learning, communication, and novel and spontaneous reproductive means. The current explanations of such emergent competencies indeed resort to mechanistic explanations in the theories of bioelectricity by the mapping of electrical patterns to specific phenotypic functions (see, e.g., Levin, 2023).

Peirce, in his agapistic terms of an extended interpretation of evolution, spoke of "energetic projaculation" (Peirce, 1893).[13] What we mean by "energetic projaculation" are intelligent competences imprinted kinematically rather than genetically, without congenital inheritance or mutation. What directs the adaptation of, e.g. xenobots to novel environments thus happens not through selective mechanisms but by continuously interacting habits of behavior; meaningful changes in the offspring are attributable to habits that establish new features and bring novel organisms into harmony with the general morphologies of the environment. Thus, this historical approach gains conceptual and explanatory currency, given how the extended notion

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[13] Editors of Volume 8 of the Writings comment that "Peirce's parenthetical remark ['(lucky there is such a word ['Projaculation'], or this untried hand might have been put to inventing one)'] is probably facetious. It is pretty likely that his well-tried hand invented it. The word has no entry in the Oxford English Dictionary, nor does it in the first edition of the Century Dictionary. The CD Supplement of 1909 has an entry for the verb 'projaculate' (to dart or throw forward) and mentions that it is rare; it quotes a text of 1904 in which G. Stanley Hall uses the verb" (W 8).

of habits spans explanations that simultaneously are physical, computational, and biological.

Synechism and Bioelectrical Explanations from Basal Cognition

Peirce's synechism implies that cognition is, together with habit-taking tendencies, the other explanatory element not altogether absent from whatever form of life one is investigating (see e.g. Paolucci, 2021; Kirchhoff & Froese, 2017, for supporting views). Basal cognition refers to the roots of intelligent problem-solving behaviour in all forms of agential and biomatters that need not resort to complex, centralised or neuronal units of information processing for the explanation of actions. The cases of interest include nonneuronal organisms, their subparts, biomaterials, tissues, organs, and cellular swarms. Since the synechistic position supports the sensibility of basal cognition, we want to assess that principle against the arguments provided against basal and minimal-model theories of cognition. The following two arguments have been provided against theories and explanations that appeal to such basal frameworks.[14]

1. That one might be conflating information processing with cognition. The latter involves mental states, such as perception, intuition, and consciousness, as well as interaction with the environment. Information processing is distinct from higher-level cognitive functions such as abstract thinking, verbalised memory, willed actions, theory of mind, and reasoning.
2. Compelling evidence confirms the tight bond between cognitive functions and neural substrates and the correlates of those functions.

In turn, proponents of the basal cognition approach argue for a balanced, biologically grounded understanding of cognition from the following grounds:

1. According to comparative genomics studies (Lyon, 2020), theories of basal cognition consider the continuity of cognition to be a systemic biological function.[15]
2. Models of cognition concern observed problem-solving tasks such as minimal paths. Hypotheses about solving those tasks fruitfully cover a wide range of behaviours of organisms that lack central or distributed nervous systems, including polyps, plants, fungi, slime moulds (e.g., *Physarum policephalum* and *Dictyostelium discoideum*), bacteria (e.g., mixobacterias and *E. Coli*) and other types of life-forms, colonies and collectives that exhibit spontaneous low-frequency oscillations and other neurally relevant electrical phenomena. The concept of basal cognition is phyletically neutral (Adamatzky et al., 2022; Hanson, 2021;

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[14] Also called minimal (model of) cognition, sometimes understood to come close to 4E (embodied, embedded, extended, enactive) cognition or extended functionalism (Dempsey & Shani, 2013). At all events, the basal framework is "a method, not kind of cognition" (Lyon & Cheng, 2023: 1745).

[15] "The instantiation of the function may not be very complex, and the implementation details may differ, but it is the function nevertheless" (Lyon, 2020: 409).

> Lyon, 2020; Colaço, 2022; Gyllingberg et al., 2024; Vallverdú et al., 2018). Such models aim at simulating, rather than duplicating, the causal powers of real phenomena.

We agree that adherents of the basal cognition framework are typically careful to indicate the breadth of prospective applications of emerging methodologies. For example, cases of cognitively interesting behavior with promising biomedical applications that lack the necessary properties of basal cognition are acknowledged, such as active materials, including self-propelled oil droplets (Brancazio & Meyer, 2023), or shape memory alloys and polymers that can be trained to move on their own or return to their original shapes after multiple deformations (Buljak & Ranzi, 2021; Pisani et al., 2022).

Developmental bioelectricity explores the properties of materials that possess basal cognition in some minimal sense of agency and involvement: not only activity, memory, self-regulation or many other elements of interesting smart behaviors that are typically nonresponsive and not subject to the same evolutionary stressors and selective drivers that agential biomaterials are. Borderline cases for cognitive embodiment in non-biomaterials may be entertained (Harrison et al., 2022). The nonexistence of clear boundaries is not an objection to the approach but only a vocalisation of human limitations to follow the principle of synechism, together with anthropomorphic bias, to force premature conceptual categories for fluid cases.[16]

Facchin (2023) summarised the situation as one in which there is no consensus on whether cognitive science should address areas of botany and microbiology given that there is no distinct cognitive mark in cognitive science, a discipline in which many research traditions meet but thus far have failed to achieve significant convergence or consilience. Peirce's recommendation was "Do not block the road to inquiry" (Peirce, CP 1.135, 1898);[17] nature's basal cognition is intelligible and explainable through the exercise of reasoning in unexpected and unconventional ways.[18] Thus, the working hypothesis of basal cognition, together with the allied frameworks of synechism, abduction, and triadic semiotic structures as philosophical, mathematical and logical underpinnings and regulative principles to explain the phenomena of primitive cognition and intellect, should not be dismissed even in the presence of potential counterarguments, as these hypotheses serve to advance inquiry by explaining a certain class of phenomena that is currently difficult or even impossible to explain otherwise.

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[16] See, e.g., Meincke (2023: 285), according to which "there is a continuum between sensation and perception, reflecting an increasing ability to integrate impulses into a unified and homogeneous impression".

[17] Details on this can be found in Haack (2014).

[18] See also Ginsburg & Jablonka (2019), which addresses the further question of the origin of minimal consciousness. Like learning, we 'grow into' consciousness as evolving forms of life. Their arguments are insightful and cohere in places with Peirce's original theoretical position on the evolving nature of meanings and cognition, where learning to reason is the key (i.e., learning to partake in the evolving habits of reasoning in the process of gaining consciousness). Like Peirce, they evaluate learning as a driving force of evolutionary shifts, a non-mechanistic tendency towards diversification: they consider behavioral innovations as a major evolutionary engine of adaptation and diversification (Jablonka & Ginsburg, 2022).

Fourth Ladder: Role of the Free-Energy Principle in Biosemiotics

The above does not offer any bare-boned and uncriticised pluralism as an adequate scientific solution. One still needs theoretical and methodological perspectives that are both precise and unifying to guide future discoveries. Pursuing unification in science is not about imposing metaphysical narratives that lock-in courses for future research. Rather, we need to be aware of our metaphysical commitments in science and criticise them as the inquiry proceeds. This does not mean we shy away from metaphysical commitments; rather, we approach them in a Peircean spirit, grounded in the understanding that such commitments should remain open to revision and refinement as inquiry progresses. This perspective fosters a commitment to a pragmatic form of realism, wherein we engage with the world as it presents itself to us, continuously revising our theories and beliefs to align more closely with reality.[19]

Rationalising the scope of scientific knowledge means identifying hidden, underlying connections and general, hypostatic, and abstract patterns. The route to unification is itself a valuable framework for understanding the world, providing both ontological clarity (reality explored by different sciences) and epistemic order (systematising scientific data). By seeking connections with rigorous yet nonrigid frameworks, we enhance our understanding of the natural and human worlds. Once more, the synechistic principle urges the road to inquiry not to be blocked.

This concluding section draws on the free-energy principle (FEP)[20] as a tentative methodological framework-level perspective to contribute to a unified scientific image of transdisciplinary biological and biosemiotic theories. Unification is not an imposition on how to develop scientific agendas or draft research projects. Methodological unification is rational reconstruction, drawing significant connections between diverse enterprises in life sciences and physics, thereby bridging the cavity that Kull (2014) carves between features of living entities and allegedly general and universal laws of physics: “While physics is about laws, semiotics is about rules (these rules include relations, and codes)” (Kull, 2014, p. 92).

We propose that the desired unification could be established through the FEP. The application of the principle for these purposes is itself a guess at the architecture of the theories of biological reality. Two points are relevant in the context of the present paper. First, the FEP provides a sound theoretical explanation[21] of bioelectricity from

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[19] Concisely, our commitment is to this dynamic, evolving form of realism, which recognises that the search for truth is a collective, ever-evolving enterprise that reciprocally refines our metaphysical commitments and our scientific apprehension.

[20] For schematic and visual details, see Friston (2009: 294) on the circle of free energy processing (external states-sensation-internal states-action); Wiese and Metzinger (2017: 13) for a schematic illustration of minimisation free energy and surprise; Wiese (2024: 1960) for the causal flow diagram in self-organising systems according to the FEP.

[21] We present the FEP as a framework not only for descriptive theoretical purposes on but also for explanation in science. Friston et al. (2015a) considers simulations of cell migration and differentiation that demonstrate a principle that self-assembly towards a specific pattern in the setting of morphogenesis can be explained, as the authors clearly letter the situation on pages 2 and 8, in the free-energy-principle framework. The assumption is that at the beginning of the morphogenesis, all the undifferentiated cells are identical: they possess the same model of the cellular ensemble, which each cell uses to predict the signals it should encounter at each location in the target form and implicit (stem-cell-like) pluripotentiality. Fol-

the predictive and anticipatory points of view concerning intelligent behavior.[22] Second, it offers a robust formal framework for suggesting and drawing significant links between scientific fields and theories across psychology, life sciences, and physics.

FEP is an integrative approach for learning, perception, and action. Free energy is minimised by reducing the prediction error of generative models either by updating those models or by changing the world. Organisms resolve environmental uncertainty by changing or updating internal models and acting on the environment (Friston, 2013). We notice, in addition, that FEP compares with the Umwelt in biosemiotics: "a living system makes its own 'subjective space'… repertoire of perception–action pairings and the networks (both internal and external) that are joining them" (Kull & Favareau, 2022: 492). Umwelt, too, requires no connectome and no central systems of neurons. The function of generative models is to guide and control action rather than replicate faithful representations of the external world. The discrepancy between the predicted inputs and actual inputs triggers corrective actions that change the environment, hence the notion of active inference (Pezzulo et al., 2022), which is closely related to abductive inference as an invitation to inquiry and experiment (Pietarinen & Beni, 2021). In this way, the FEP provides a theoretical framework that links formalism inspired by physics with fundamental concepts in theoretical biology. The core logic of FEP applied to living processes is predicated on isomorphisms with nonliving processes, such as statistical entropy and the least action principle. We see the breadth of the principle as an illustration of synechism in action. FEP may be applied in uncovering meanings within the context of cognition and communication in the biological world, thus having direct relevance to biosemiotic research (e.g., the minimal cognition paradigms based on FEP; see, e.g., Kiverstein & Sims, 2021; Slijepcevic, 2024). Through active inference, the FEP elucidates how shared models, prediction errors, and perceptual learning shape our understanding of each other's intentions and meanings.

The general insight behind FEP is that self-organising systems tend to minimise their internal entropy.[23] An increased probability of survival necessitates stable inter-

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lowing the minimisation of variational free energy, each cell has inferred its unique place in the ensemble and is behaving according to that shared signal thus choreographed. Friston et al. (2024) propose how the minimisation of free energy at the individual level relates to the collective intelligence at the level of groups.

[22] This is because bioelectricity concerns information processing: endogenous bioelectric signalling controlling cell behaviour. FEP explains how bioelectric gradients and cellular communication minimise free energy and maintain homeostasis (Fields et al., 2022). Bioelectricity encompasses not only information processing at the individualistic level but also accounts for collective intelligence in bioelectric fields across cells and tissues, facilitating rapid information exchange. These fields enable both local and long-range communication through a hierarchical structure, with bioelectric networks adapting both locally (within cells) and hierarchically (across tissues). This aligns with the hierarchical minimisation of free energy in FEP, where at each hierarchical level, FEP manifests smart operations in a triadic fashion: *Locally*: Within local levels, the system adjusts its internal states to minimise free energy. (For example, in neural networks, neurons modify synaptic weights to covary with sensory input.). *Systemically*: Species adapt to environmental changes and stressors in ecosystems and metapopulations. *Hierarchically*: Based on lower-level evidence, systems make abductive and active inferences about higher-level causes.

[23] Deacon (2012) argues via his autogen model that self-organisation – and, thus, minimisation of internal entropy – is not enough to constitute semiosis in living dynamics. He argues that a very particular coupling of two complementary self-organising dynamics is the minimal unit of semiosis. It is how they both

nal dynamics, which in turn require the functional integrity of the internal structure to withstand environmental changes. As organisms continually interact with their environment, maintaining this structural and functional integrity relies on embodying patterns of law-like stabilities in the environment of the organism or its species (Friston, 2010; Friston et al., 2015b, 2018). Surprisal is the negative log probability of an outcome, and entropy is the time average surprisal of outcomes sampled from a density. The existential imperative of FEP indicates that surprisal needs to be controlled. Free energy is an information-theoretic measure that puts a bound on the surprise by being greater than it (Friston, 2010). Organisms embody their environment via generative models, which embed dependencies between causes and consequences. These consequences are perceptions that follow from hidden or latent environmental causes, aptly named because they are states external to the organism. Generative models embed predictions about the hidden causes that organisms may encounter in the environment. An increase in prediction errors (or a surprise) beyond a certain threshold disrupts functional and structural integrity and minimises an organism's chance of survival. A fish that erroneously presumes that it could survive out of water for days or a cat that presumes that it could survive under the water for hours would both be sourly surprised. The point is that elements of FEP, such as the minimisation of surprisal and entropy, contribute to the generation of meaning; a formal theory of semantics arises from within. In addition, there is an entropic divergence from the laws of physics to bridge physics, theoretical biology, and semantics (Ramstead et al., 2020). The FEP connects the formalisms of both physics and theoretical biology. Moreover, this approach not only is committed to the mind–life continuity thesis (Kirchhoff & Froese, 2017) in the Peircean spirit, but also transcends the traditional dichotomy between semiotic and biotic processes. It reconciles these as self-organising processes that are, at their core, modal physical phenomena. These processes are represented within the formalism of the FEP, which includes path integrals and gradient descent, among other mathematical models. These formalisms capture the dynamics of semiotic and biotic processes, yet it is crucial to note that they are not identified with the processes themselves. Instead, they serve as tools that model the interplay between meaning-making and biological function, highlighting the continuity between them.

Simultaneously, this framework could underpin a theory of the emergence of meaning, as an issue of semiotics, within the context of cognition and communication in the biological world. The solution to the problem of neural hermeneutics is based on active inference (Friston & Frith, 2015b). In active inference, our actions fulfil predictions about how we will behave (e.g., predicting that we will speak). These predictions can be used to anticipate both one's goals and one's intentions toward oneself and others. Active inference involves updating an internal model that generates predictions at fast (perceptual inference) and slower (perceptual learning) timescales. However, when gathered in groups, self-organising systems do not individually minimise their free energy but do so collectively. For example, when a pride

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constitute each other and keep each other from going to minimal equilibrium that together they constitute, at least in principle, the capacity to sustain the paradoxical nature of semiosis discussed in the previous comment. (We thank the reviewer for the comment.)

of lions, or a pack of coral sharks, hunts together, each lion does not aim to minimise its individual free energy but rather collaborates to achieve the goal by displaying actions that minimise the group-level free energy. Cutting off the course of flight of the prey may inflict an individual lion but is necessary for the success of the chase. To effectively minimise their collective free energy, self-organising systems share information on the trajectories of unit-level behaviours.

The point is that minimising free energy is not the same as entirely eliminating surprise. In the case of collective behaviour, managing risk at the group level may increase surprise for individual members. At the individual level, generative models are subject to a degree of surprise, as they anticipate future states on the basis of past experiences. A lion eliminates surprise by staying in a cave and avoiding novelty, thus minimising uncertainty. However, this would lead to stagnation from a lack of adaptation. A balance between simplicity (minimising surprise) and accurate representations of the environment that introduces stressors and surprise needs to be struck. This balance mirrors the artful tension between strategies of exploration (cooperative behaviour) and exploitation (competitive, self-regarding behaviour) in self-organising systems. Exploration involves novelty-seeking and successful engaging with the unknown, with surprise minimised by the collective, whereas exploitation seeks to utilise the known, reliable strategies that minimise risk and surprise. In self-organising systems, the goal is to maintain an optimal level of surprise—enough to drive adaptation, discovery, and learning—but not overly so as to engulf the system's ability to bootstrap itself and effectively function.

The most viable and efficient method of effectively minimising surprisal involves acting on the basis of a choreographer; the shared, collective generative model, which is explicated in terms of continuously connected generative models that minimise the shared entropy of communication. When two agents adopt the same model, they can predict each other and minimise mutual prediction errors. This ensures that they are metaphorically "singing from the same hymn sheet" (Friston & Frith, 2015a: 400, 2015b: 129, 135). The neural hermeneutics implicit in learning may occur, at least in part, through communication, enabling generative models to predict each other and facilitate long-term changes in understanding.

The critical view towards our proposal to link FEP to the core biosemiotic approach to cognition and meaning consists of the following three arguments.[24]

1. First, researchers use models to predict the behavior of animals. For example, one may use a probabilistic model to predict how ants distribute soil removed from their nest. Researchers have demonstrated that their model is predictive. The claim, therefore, is not that this is how ants actually reached decisions.
2. Second, given the example in the previous paragraph, FEP appears to contradict itself in scaling itself from the individual to the collective level, as it relies on a now higher-order generative model of the collective, whereas the lower-order model—the individual choice to increase surprisal – remains unexplained. Even if scaling could take place, the extra parameters, states, and dimensions needed

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[24] Our thanks to the reviewer for suggesting these critical considerations, which we here can only summarise and briefly respond to.

for this jump in complexity require another injunction on the FEP. How are all these injunctions at multiple scales mediated, if not by the FEP itself, risking a vicious circle?

3. Third, the FEP tends to collapse core problems of intention and meaning with its stepwise state variables and automated optimisation functions.

Our rejoinder to these three points is that here, too, the synechistic principle is helpful in taming the complex coordination task of gravitating to the adoption of the same shared model: what we mean by the underlying phenomenon of cognition was not wholly individualised in the first place. With respect to the first point, we agree on the critical remark and add that, indeed, many biosemioticians caution against reading too much of reality from these predictive models. Second, while the detailed explanation does not offer a specific method for implementing the dynamics artificially within a group of agents, it speaks to theoretical biology by accounting for the adaptive behaviour—and even the very existence—of animals that have survived for significant periods. Regardless of the debate surrounding the units of natural selection—be they genes, individuals, or groups—those animals that have endured have effectively managed to impose an upper threshold on their internal entropy. Without this regulation, they would have failed to adapt, and as a result, their species would have succumbed to extinction.

Third, Peirce's view was that "Nor must any synechist say, 'I am altogether myself, and not at all you'. If you embrace synechism, you must abjure this metaphysics of wickedness" (CP 7.571, 1892). Synechism, as a regulative principle, advises that lower-order models are not conceived as individual constructs. They are derivations from the collective, as are as such *degenerate* versions of the continuous generative model. Moreover, these individual constructs of selfhood and agency, which intelligent organisms are likely to attribute to their self-models, serve the purpose of escaping from "the vulgarest delusion of vanity" (CP 7.571, 1892). That is, individual constructs do not have explanatory priority. Bioelectricity, on the other hand, is the type of actual phenomenon that can transcend this stepwise functionalism. Our point of the present paper is to sketch some ways to conceive how that theory could go beyond models, functions, and purely mechanistic explanations.

There are at least two possible nondichotomic avenues for developing these insights into a unifying account of the emergence of meanings in the natural world. The first pathway traverses a theory of habit-making under the FEP. It is in harmony with the pragmatist tradition of habit formation, which originated in Peirce's early reinterpretations of the theory of evolution, his theory of signs, and his theory of scientific reasoning and proceeded through cycles of abduction, deduction, and induction. The second route involves incorporating FEP into a code model approach to biosemiotics.

With respect to the first route, habit formation entails the development of automatic behaviours or routines in response to specific cues. In environments where resources are scarce and survival depends on efficient energy usage, habit-change potentials (e.g., efficient foraging patterns and mating rituals) confer a selective advantage. Habit formation regulates internal entropy, as it enhances the chances of survival and reproduction. Once a behaviour becomes a habitual trait, much less cognitive effort and prediction error are expended on reproducing the desirable behaviour. Over time, habits become ingrained, enabling organisms to allocate resources more effectively and adapt to their ecological niche. This speaks to the FEP-based account that keeping the system's entropy (i.e., time-average surprise) within bounds is the key to the system's survival. The organism could achieve these goals by frequently visiting a set of attracting states (which constitute the attracting set of the organism) and by avoiding states that fall outside that set (Friston, 2012, 2018) The existential imperative is to visit only a limited set of possible states to stay in an organism-dependent echo niche that meets existential imperatives (Pezzulo et al., 2022: 2).

The principle can also be used to account for the meaning of physical laws, given that humans (as members of *Homo sapiens*) are bound to identify the stable habits of nature to be of notable existential importance. In this context, epistemic actions consist of gaining reliable information to motivate pragmatic actions, and active inferences aim at changing the features of the environment to fit one's expectations about the possible outcomes of future action (hence, the corollary of active inference from the principle). Self-organising systems implicitly minimise their surprisal or entropy by explicitly minimising their variational free energy, which can be specified in terms of a mathematical function of perceptions and a probability density over hidden causes. Under conditions of weak coupling, random dynamical systems with sufficient degrees of freedom tend to behave in a way that minimises an upper bound on surprisal, which is self-information. These notions, free energy and surprisal, are inversely related to fitness over evolutionary time (Fields et al., 2022). The minimisation of free energy, homeostasis, and fitness or survival are intertwined concepts that explain the survival of cognitive entities in a physical world. This is partly vouchsafed via the existential imperative, which posits that self-organising systems in equilibrium with their environment, which minimise their variational free energy, significantly increase their chances of survival imperatives (Pezzulo et al., 2022: 2).

From the first-principles standpoint, the above is to posit that organisms that have survived must be those that have statistically successfully minimised their free energy in the reference population. Habit-making in this context can be grounded in the physical domain on the basis of cultural and cognitive niche constructions (Laland & O'Brien, 2011; Magnani, 2024) under the FEP. The FEP underlies a multilevel account of socioculturally scaffolded affordance learning and the transmission of affordances through patterned sociocultural practices and regimes of shared attention (Constant et al., 2019; Ramstead et al., 2016). These factors enable communication, affect enduring changes in the social situation, and sustain ecologies through generations. All these factors contribute to minimising shared and collective free energy and entropy.

The other way of using the unifying trajectory of the FEP to account for the emergence of meaning can build on a well-established theory of biosemiotics.Barbieri (2003, 2011, 2014) posits semiotic systems characterised by coding, not just interpretation, with the ribotype serving as the locus of the genetic code within cells. Barbieri's hierarchical model of the emergence of meaning illustrates how layers of significance develop sequentially, from basic cellular processes to complex cognitive abilities. By transgressing cell limitations as biological computers, Barbieri underscores the importance of signs and codes in low-level processes, providing a scientific basis for multilevel explanatory pathways for biosemiotics.

This understanding of how cells encode and interpret information sheds light on life's fundamental mechanisms and encourages a deeper exploration of semiosis in biology. Although Barbieri explored this topic from the perspectives of bottom-up genetic hardware bridging biological information and biological meaning, we believe there is space for deeper unities that connect similar explanatory pathways to non-genetic, nonneural, and nonhardware-coding levels in developmental bioelectricity and FEP, complementing and expanding present biosemiotic theories endowed with top-down inferential explanations of largely Peircean ancestry with the bottom-up approach. In our view, Barbieri's insights into the hierarchical emergence of meaning in biological systems resonate with the emerging principles in the philosophy of bioelectricity, providing both complementary and new routes to explain how information processing contributes to the dynamics of living organisms, thus moving beyond the 'either top-down or bottom-up' dichotomies.

Conclusions

This paper investigated developmental bioelectricity through the Peircean philosophy of synechism, habits, and abduction. The paper reviewed the stressors and surprises that test these notions both conceptually and empirically. The paper suggested how the explanations of cognition and meaning from bioelectricity that survive uncertainty and surprise with our rejoinders contribute to scientific integration. As discussed by Kull (2014), the critique of conflating semiotic and physical laws emphasised the need for an approach that explores interconnections between semiotics, biology, and physics. While pluralistic scientific methodology is needed, particularly in evolutionary theory, a more specific agenda is recommendable.

We propose including developmental bioelectricity in this emerging agenda. We examined the main criticism of its holistic, top-down character and reflected it through Peirce's anti-mechanistic lens. We showed that Peirce's stance resonates with contemporary views on habit-taking and the fallibilistic nature of scientific exploration. This stance challenges mechanistic explanations and advocates for a dynamic understanding of evolutionary processes.

Our critical evaluation suggested that the field of bioelectricity, while promising for explaining morphogenesis and basal cognition, must speak to bottom-up biochemical signals, codifications, and mechanobiology to develop a cohesive theory. It is the ladders between the two perspectives that matter while avoiding the snakes. The importance of morphometrics and the implications of bioelectricity in oncology underscore the field's complexity and potential. Basal cognition includes a broad spectrum of life forms, linking cognition to environmental interactions across biological diversity. Finally, we posited the free energy principle (FEP) as a positive, unifying framework that connects life sciences and physics, offering insights into learning, perception, action, and the emergence of meaning within biological cognition.

In sum, this paper calls for an integrative inferential approach to developmental bioelectricity, with experimental findings illuminating its philosophical foundations, thus converging toward biosemiotic explanations of meaning and cognition.

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