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REVIEW

Foundations of cognitive systems: exploring the architecture of mind and intelligence

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Abstract
This article investigates the emergence of cognitive systems as properties arising from chemical processes, elucidating how cognitive capabilities evolve through the dynamic progression of these systems. Employing the Dynamic Kinetic Stability (DKS) framework, the study traces the evolutionary trajectory from simple chemical reactions to complex cognitive behaviors, emphasizing the emergence of self-organization, adaptability, and information processing within molecular networks. The research examines the transition from non-living chemical systems to living organisms, offering insights into how basic cognitive mechanisms evolve into advanced neural networks and, ultimately, give rise to human consciousness. The interplay between sensory input and cognitive processes in shaping awareness is analyzed, providing a comprehensive understanding of how experiences are formed and interpreted. By integrating perspectives from evolutionary biology, cognitive science, and philosophy, this study addresses both the "hard problem" and "easy problems" of consciousness, shedding light on the intricate relationship between neurochemical processes and mental phenomena.

Keywords Cognitive systems of the mind · Consciousness experience · Philosophy of mind · Awareness

Preliminaries and introduction

The nature of the mind and its cognitive systems has captivated scholars across disciplines for centuries, bridging philosophy, psychology, and neuroscience (Nagel 1974; Damasio 1999). This article investigates the foundational processes underlying the formation of cognitive systems, proposing that these mechanisms are deeply embedded in chemical and physical interactions. Utilizing the Dynamic Kinetic Stability (DKS) framework (Pross 2012; Pascal and Pross 2023), the study explores how molecular networks evolve from simple chemical reactions into complex behaviors characteristic of cognition, ultimately giving rise to human consciousness.

The DKS framework provides a theoretical lens to understand self-organization, adaptability, and information processing within molecular networks, bridging the gap between the physical and mental realms. This work examines the interplay between sensory data, cognitive biases, and emotional states in shaping awareness, emphasizing the dynamic and subjective nature of these processes.

Carruthers (2019) highlights phenomenal consciousness, the subjective aspect of experience that captures "what it is like" to perceive or feel. This form of consciousness, a subset of mental-state awareness, includes sensory experiences such as seeing, hearing, and smelling, each marked by a distinctive qualitative character. Despite extensive study, consciousness remains a profoundly complex and contested concept. Competing theories variously regard it as emerging from intricate neural dynamics (Block 1992, 2007) or as a fundamental or emergent property of physical systems. Across neuroscience, psychology, philosophy, and cognitive science, ongoing research continues to integrate empirical findings and theoretical models to clarify the mechanisms and nature of conscious experience (Block 2019).

Philosophical inquiries into the nature of consciousness have significantly expanded our understanding of this profound phenomenon. Discussions around the subjective, first-person experience of consciousness, known as "qualia", have emphasized the challenge of explaining the

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qualitative, phenomenal aspects of mental states (Nagel 1974; Block 1992). Theories such as Integrated Information Theory (IIT) (Tononi 2008) and Global Workspace Theory (GWT) (Baars 1988) have sought to bridge the gap between the objective, third-person descriptions of neural activity and the subjective, first-person experience of consciousness.

These theories aim to elucidate how the complex interplay of neural processes gives rise to the rich, nuanced tapestry of human experience, offering deeper insights into the enigmatic nature of conscious awareness (Block 2007). By integrating philosophical perspectives with neuroscientific frameworks, IIT and GWT contribute to unraveling the mysteries of how physical systems generate subjective experience.

Chalmers (2009) delineates consciousness into two primary categories: the easy problem and the hard problem. He asserts that the hard problem of consciousness cannot be effectively tackled using reductionist approaches. Conversely, the easy problems can be addressed using standard cognitive science methods and can be elucidated in terms of computational or neural mechanisms. Some examples of the easy problems of consciousness include:

1. The ability to perceive, classify, and respond to external stimuli: This refers to the capacity to sense, recognize, and react to various environmental cues and inputs.
2. The integration of various streams of information: This describes the process of combining and coordinating multiple sources of information into a coherent whole.
3. The ability to report on one's mental states: This involves the capacity to express, communicate, and provide an account of one's own internal experiences and thought processes.
4. The accessibility of mental states: This refers to the degree to which an individual's mental states, such as thoughts, feelings, and perceptions, are readily available and can be accessed or reflected upon.
5. The capacity for attention: This describes the ability to focus, concentrate, and direct one's cognitive resources towards specific stimuli or tasks.
6. The deliberate control of behavior: This involves the conscious regulation and purposeful guidance of one's actions and responses.
7. The distinction between sleep and wakefulness: This refers to the clear differentiation and alternation between the states of being asleep and being awake, which are associated with distinct patterns of brain activity and levels of consciousness.

Chalmers (2018) has delineated the "easy problems" in cognitive science, so termed because we have established paradigms and methods for addressing them. To explain a particular cognitive function, we identify the appropriate neural or computational mechanisms responsible for that function. This task is straightforward in principle, and as Chalmers has noted, cognitive science has made steady progress in elucidating the underlying mechanisms for many "easy" cognitive capacities, such as perception, memory, language, and decision-making. This progress has been achieved through the integration of findings from various disciplines like neuroscience, psychology, and computer science.

Chalmers famously distinguishes the "easy problems" of consciousness, those concerning cognitive mechanisms such as perception, attention, and behavior, from the "hard problem," which addresses the nature of subjective experience, or qualia. While the easy problems can, in principle, be explained through empirical investigation and mechanistic models, the hard problem probes why and how physical processes give rise to the felt quality of experience.

This distinction reveals a profound conceptual gap between third-person descriptions of neural activity and the first-person reality of conscious experience. The hard problem challenges reductionist frameworks because subjective awareness appears irreducible to physical, computational, or behavioral accounts. Addressing it requires philosophical reflection alongside interdisciplinary approaches that consider emergent, holistic, and relational properties of mind, potentially extending beyond traditional scientific paradigms.

For cognitive science and philosophy of mind, the hard problem represents a central frontier. It calls for integrating phenomenology, metaphysics, and theories of complex systems to explore the unity of experience, the emergence of selfhood, and the intimate connection between awareness and the physical world. Though progress is necessarily gradual and methodologically demanding, grappling with these questions is essential for understanding the very nature of consciousness and what it means to exist as a conscious being.

Over recent decades, numerous theories have attempted to bridge this explanatory gap, each illuminating one aspect of consciousness but failing to account for its full phenomenological depth. Physicalist and functionalist theories, such as those proposed by Dennett (1991) and Churchland (2002), reduce consciousness to neural activity or information processing. Yet, these approaches fall short of explaining why subjective experience accompanies such processes, focusing instead on their causal and computational correlates. As Levine (1983) and Nagel (1974) emphasize, these models do not bridge the explanatory gap, the transition from objective mechanisms to subjective awareness remains conceptually opaque.

Other frameworks, such as Integrated Information Theory (Tononi 2008; Tononi and Koch 2015) and panpsychism (Goff 2019), seek to generalize consciousness as a fundamental property of physical systems. While these theories broaden the scope of inquiry, they often conflate the structural with the experiential: IIT, for instance, quantifies information integration, but does not explain why specific informational structures correspond to specific experiences. Similarly, panpsychism disperses consciousness across matter, transforming the problem rather than solving it.

Cognitive and representational approaches, such as Global Workspace Theory (Baars 1988; Dehaene and Changeux 2011) and Higher-Order Thought Theory (Rosenthal 2005), illuminate the organizational logic of conscious access but remain silent on the intrinsic subjectivity of experience. Recent predictive and neurodynamic models, such as those grounded in the free energy principle (Friston 2023) or affective neurobiology (Solms 2021), suggest that consciousness may emerge from self-organizing inference and homeostatic regulation. These models provide valuable dynamical insights but still do not fully resolve the qualitative question of why such processes feel like something from the inside (Seth and Bayne 2022).

In this article, the process of developing cognitive systems in living beings is first explored, followed by an explanation of how these systems are enhanced to generate a sense of consciousness and awareness in the mind. The evolutionary and biological mechanisms underlying cognition are examined to illuminate the pathways through which complex mental states emerge from simpler processes. This exploration is intended to provide a comprehensive understanding of how experiences are constructed and interpreted by the mind, ultimately contributing to the knowledge of consciousness and the nature of self-awareness.

Within this framework, cognitive capacities in living systems are understood in terms of their functional and structural organization rather than through anthropomorphic interpretation. For instance, the decision-making or memory-like behaviors observed in bacteria exemplify elementary forms of cognition grounded in biochemical self-regulation, manifestations of adaptive responsiveness rather than conscious or subjective mental states.

The cognitive systems of living organisms

According to Levin (2023), life begins as a quiescent oocyte governed by the laws of chemistry and physics, gradually developing into an organism capable of complex metacognitive processes and aspirations. Although we perceive ourselves as unified Selves, intelligence is, in essence, a collective phenomenon arising from the coordinated activity of countless cells working toward shared goals, preferences, and memories.

Cognition, as a fundamental property of life, enables organisms to adapt their physiology and behavior to changing conditions (Shapiro 2007; Lyon 2015). Even the simplest forms of life, Bacteria and Archaea, demonstrate cognitive behaviors such as environmental sensing and adaptive response. This capacity was retained through evolution, particularly when a bacterial cell merged with an archaeal host to form the first eukaryotic ancestor about two billion years ago (Margulis 1993; Lane 2015). The continuity of these adaptive processes reveals that the roots of cognition extend deeply through evolutionary history, linking the collective intelligence of ancient cells to the integrated cognitive systems of modern multicellular life (McFall-Ngai 2013).

Although there is no single accepted definition of cognition, (Shettleworth 1998) offered one of the earliest scientific formulations, describing it as “the mechanisms by which living things acquire, process, store, and act on information from the environment”. Originally developed in the context of neural systems, this definition has since been extended to aneural organisms such as bacteria (Lyon 2015; Shapiro 2007).

Research over the past decades has revealed that cognitive-like processes occur across diverse life forms, from single-celled bacteria to plants (McFall-Ngai 2013). Bacteria, for instance, can sense and respond to environmental cues, make adaptive decisions, and coordinate collective behavior through biochemical signaling networks (Lyon 2015; Shapiro 2007). Similarly, plants perceive stimuli, transmit information, and organize responses without a nervous system (Lane 2015).

This broadened view of cognition suggests that the mechanisms of information acquisition and adaptive response emerged early in life’s evolution, indicating that cognition is a fundamental property of living systems rather than one limited to organisms with nervous systems (Margulis 1993).

Higher-order cognitive functions encompass complex mental processes that facilitate advanced reasoning, problem-solving, decision-making, and abstract thinking. These functions are built upon foundational cognitive abilities such as awareness, emotion, perception, attention, and memory. They are predominantly associated with the prefrontal cortex and other brain regions involved in executive functions. Higher-order cognitive functions play a crucial role in adapting to novel situations, planning for the future, comprehending abstract concepts, and navigating social interactions. Some key examples include:

Executive Functioning: This includes skills such as planning, organizing, and controlling attention and behavior to achieve goals. Executive functions are critical for self-regulation, decision-making, and adaptive thinking (Miyake et al. 2000).

Problem-Solving: The ability to analyze complex situations, identify patterns, and generate solutions. This often involves critical thinking, reasoning, and the ability to make inferences or deductions.

Abstract Thinking: The ability to think beyond concrete concepts, to consider hypothetical scenarios, and to engage in symbolic or conceptual reasoning (Kosslyn and Rosenberg 2006).

Theory of Mind: The capacity to understand that others have thoughts, beliefs, and desires that may differ from one's own, and to predict or interpret their behavior based on this understanding (Premack and Woodruff 1978).

Metacognition: The ability to reflect on and regulate one's own cognitive processes, such as evaluating the effectiveness of problem-solving strategies or monitoring one's understanding of a topic (Flavell 1979).

These functions are considered to be "higher-order" because they involve the integration of simpler cognitive processes and are often critical for navigating complex, dynamic environments. They also play a key role in personal and social functioning, and are thought to be fundamental in the development of self-awareness and consciousness.

The evolutionary process has shaped the cognitive mechanisms observed across living organisms. A key component of this process is sensitization, the development of responsiveness to specific stimuli and the capacity to modify behavior accordingly. Through evolution, organisms have acquired the ability to sense and respond to environmental cues, thereby enhancing adaptability and survival (Eichenbaum 2017).

By examining cellular and neural functions, researchers can trace how the nervous system and brain evolved to process information and produce adaptive responses. This includes exploring the molecular and cellular bases of neural communication, synaptic plasticity, and sensory integration (Kandel 2001).

Understanding the evolutionary foundations of cognition provides insight into the origins and diversification of cognitive abilities, reveals parallels and distinctions across species, clarifies mechanisms underlying cognitive disorders, and informs advances in artificial intelligence and robotics (Gallistel 2009; Hauser et al. 2002).

Although plants lack a centralized nervous system, they possess diverse sensory mechanisms that enable them to detect and respond to environmental changes. They can perceive variations in light, temperature, humidity, and the presence of other organisms, including herbivores and predators, adjusting their growth, development, and behavior accordingly. This capacity has inspired research into the possibility of cognitive processes or even a form of consciousness in plants, an emerging field known as plant neurobiology or plant cognition (Calvo 2017; Trewavas 2020; Lamers 2020; Mallatt 2021; Shapiro 2021).

Plants use sensory structures such as photoreceptors to detect light intensity and quality (Briggs and Christie 2002), and they can sense temperature, humidity, gravity, touch, and chemical signals from other organisms (Trewavas 2003). These inputs guide adaptive behaviors, such as modifying growth to optimize light capture, compete for resources, or adjust developmental pathways in response to seasonal or biotic cues (Franklin and Whitelam 2007; Karban 2008).

Plants also communicate through volatile organic compounds that warn neighbors of herbivores or attract predators of these herbivores, thereby coordinating defense responses (Heil and Karban 2010). Researchers employ methods such as measuring electrical activity (Volkov 2006), analyzing gene expression (Chamovitz 2012), and conducting behavioral experiments to explore these processes. Collectively, these findings suggest that plant cognition represents a complex and integrative system for environmental adaptation.

The cellular basis of cognitive mechanisms: from chemical processes to consciousness

Biopolymers are polymers derived from natural sources, either chemically synthesized from biological feedstocks or biosynthesized by living organisms. Compared to conventional synthetic polymers, they offer advantages such as biodegradability, reduced environmental impact, and renewable resource potential.

Matange et al. (2023) proposed two conceptual models for the origin of biopolymers. The direct chemical synthesis model posits that fundamental building blocks, such as amino acids and nucleotides, were produced abiotically on the Hadean Earth through processes including atmospheric reactions, volcanic activity, and impact events. These prebiotic molecules were subsequently incorporated into emerging biological systems and preserved through evolutionary continuity. In contrast, the chemical evolution model suggests that primitive abiotic compounds were progressively replaced during chemical and early biological evolution by more stable or functionally advantageous molecules. As a result, the composition of modern biopolymers may not directly mirror that of the earliest prebiotic chemistry or initial evolutionary phases.

Four non-biological systems demonstrate self-preserving behaviors: reaction-diffusion "spots" (Pearson 1993), motile oil droplets (Toyota 2009), ramified charge-transport networks (Nakagaki et al. 2000), and Bénard convection cells (Benard 1901). These systems move or reconfigure in ways that modify their environments, enhancing their likelihood of persistence. Reaction-diffusion systems form stable patterns that adapt dynamically to chemical concentration changes, resembling natural self-organizing systems. Motile oil droplets, driven by surface tension gradients, alter local chemical concentrations, exhibiting primitive self-propulsion. Ramified charge-transport networks, as in the slime mold Physarum polycephalum, reorganize to optimize resource transport while minimizing energy dissipation. Bénard convection cells maintain stability by reconfiguring fluid flows in response to thermal gradients. Together, these examples illustrate how environmental interaction and adaptive reorganization can support self-preserving behaviors in both natural and artificial systems.

According to Kepa et al. (2017), our perspective extends the Darwinian framework to prebiotic chemical evolution. Rather than following traditional approaches, we propose applying an evolutionary account to autonomous systems composed of diverse chemical precursors, including (bio) molecules and their supramolecular assemblies. Under suitable physico-chemical conditions, these molecular species and assemblies can mutually reinforce one another through interactions such as chemical transformations, recognition and control relationships, self-assembly, pattern formation, collective synchronization, and physical boundary effects.

Understanding the evolutionary trajectory of living organisms also requires examining cellular function, which is essential for sustaining life. While all organisms share basic self-maintenance capacities, the human brain exhibits exceptional functional complexity. Cognitive mechanisms have evolved through sensitization processes within living systems, reflecting broader evolutionary progression. Studying cellular functions and their relationship to cognition provides insights into how organisms have developed the ability to sense, respond to, and interact with their environment (Agozzino 2020; Allen 2009; Pascal and Pross 2022).

Cell decision-making is a universal process enabling cells to assess and respond to environmental cues, critical for adaptation, survival, and multicellular coordination. As noted by Balázsi et al. (2011), cells determine their actions or "fates" based on environmental signals without requiring genetic changes. This phenomenon spans all biological levels, from viruses and bacteria to mammals, contributing to pattern formation and development. Cellular decision-making often relies on feedback networks that regulate the stability or reversibility of decisions. Additionally, cells' sensing mechanisms, which detect and interpret environmental signals, are essential for guiding these decisions and enabling adaptive responses.

Cells possess sophisticated sensing mechanisms that enable them to detect and interpret environmental cues. Sensing involves the recognition of extracellular signals, such as growth factors, hormones, or physical cues, by cellular receptors. These receptors transmit signals into the cell, initiating intracellular signaling pathways (Alberts et al. 2014; Goodwin 2008).

Sensing information is a regulatory process that influences cellular decision-making and adaptation. The information received by cells triggers a cascade of events, leading to the activation or inhibition of specific genes and proteins. This regulation can affect cellular behaviors, including changes in gene expression, cell shape, motility, and metabolism (Bar-Sagi and Hall 2000; Huang and Ferrell 1996). By integrating and interpreting environmental cues, cells can make informed decisions and adapt their behavior to optimize survival and function in their specific context. Sensing and regulatory processes allow cells to adapt to changing conditions. Cells can dynamically adjust their responses based on the signals they receive, enabling them to fine-tune their behavior for optimal functionality. This adaptability is crucial during development, tissue repair, immune responses, and other physiological processes (Harris 2013; Wu 2007).

Thus, the decision-making capabilities of cells, coupled with their sensing and regulatory processes, enable them to respond to environmental cues and adapt their behavior accordingly. These processes play essential roles in development, tissue homeostasis, and overall organismal function, for more information see (Lyon 2015).

Koseska and Bastiaens (2017) explored how cellular identity, defined by morphology and function, arises from intracellular signaling networks that mediate intercellular communication. Through recursive interactions within and among these networks, dynamic biochemical solutions emerge, distinct from the behavior of isolated cells. This process generates cellular heterogeneity within tissues, indicating that cell identity is not solely dictated by genetic code but is dynamically maintained in a more "cognitive" manner. Their study also examines methods to measure information flow within intracellular networks and shows how simple causal motifs in signaling pathways can produce complex, context-dependent behaviors.

According to Gilbert (2010) and Graf and Enver (2009), cells coordinate and maintain tissue homeostasis through signaling molecules such as hormones, neurotransmitters, and cytokines. Cellular identity is dynamically regulated by signaling inputs that adapt to environmental changes, reflecting intrinsic plasticity. This flexibility enables cells to modify their behavior within a tissue context rather than follow a fixed genetic program. Simple network motifs, including feedback and feedforward loops, underlie these signaling processes. Despite their simplicity, nonlinear biochemical interactions make them capable of producing complex, context-dependent behaviors. This dynamic organization accounts for cellular heterogeneity, specialization, and adaptability. For further discussion on cellular cognitive systems and their evolution, see Tyson and Novak (2010) and Peter et al. (2023).

Shapiro (2021) shows that all living cells, even simple prokaryotes, possess intrinsic abilities to sense and respond to internal and external changes, capacities essential for survival, growth, and adaptation. Prokaryotes such as bacteria and archaea exhibit complex regulatory networks that enable chemotaxis, biofilm formation, and genetic adaptation to stress. Through quorum sensing, they communicate via chemical signals to coordinate collective behaviors, including gene regulation, bioluminescence, and virulence. These findings challenge the notion of prokaryotes as simple organisms, revealing deeply rooted cognitive behaviors that process information and support adaptive responses across life's evolutionary history.

Dynamic kinetic stability (DKS)

Building on the preceding discussion, it can be inferred that living organisms possess cognitive systems, raising the fundamental question of how these systems have evolved. This section explores the issue at a foundational level.

According to Pascal and Pross (2022), non-living physical and chemical systems respond to external perturbations predictably, following the laws of thermodynamics. These systems naturally progress toward states of higher entropy and lower free energy in accordance with the Second Law. For example, physical systems respond to changes in temperature, pressure, or applied forces through thermal expansion, phase transitions (e.g., melting or boiling), or deformation, reflecting the system's tendency to reach a new equilibrium that minimizes free energy (Kondepudi and Prigogine 1998; Lineweaver and Egan 2008; England 2013).

Similarly, chemical systems at equilibrium respond to disturbances such as changes in reactant concentrations or environmental conditions by shifting to re-establish equilibrium, as described by Le Chatelier's principle (Le Chatelier 1884). These shifts manifest in altered reaction rates, product yields, or other observable characteristics. The crucial insight is that non-living systems, whether physical or chemical, respond to perturbations in predictable ways that minimize free energy and maximize entropy, as formalized in classical thermodynamics (Gibbs 1873; Prigogine 1967).

The exploration of the energized dynamic kinetic state by Pascal and Pross (2022) suggests the existence of alternative pathways for the emergence of cognitive behavior. This challenges the traditional view that mental capabilities are exclusive to living organisms. By activating specific chemical systems into this state, they propose that basic cognitive processes could manifest, blurring the line between the living and non-living (for more information see Azar 2022, 2024a). This research carries profound implications for our understanding of the origins of life. It urges us to reconsider the idea that life arose solely from non-living matter through a gradual accumulation of complex chemical reactions. Instead, Pascal and Pross propose that cognitive phenomena might have been present even in the early stages of chemical evolution, indicating that the roots of cognitive behavior may extend deeper into the prebiotic world than previously thought. Regarding the transition from a non-living to a living chemical state, extensive research has been conducted, as an examples see (Merindol and Walther 2017; Lehn 2007; Ziemann 2009; Agozzino 2020; Kaklauskas 2022; Jeziorski 2022; Slootbeek 2022; Stewart 2019; Trefil 2009, and Pascal and Pross 2022).

Dynamic Kinetic Stability (DKS) and non-equilibrium states are central to understanding the emergence of life (Pross 2012). These mechanisms govern the formation and persistence of complex chemical systems through autocatalysis, feedback loops, and self-organization (Kauffman 1993; Prigogine 1984), forming the groundwork for primitive information processing and adaptive responsiveness (Shapiro 2007). The evolutionary progression from simple prokaryotes to multicellular organisms reflects increasing sophistication in communication, signaling, and neural development, linking chemical dynamics to biological cognition (Alberts et al. 2014). This continuity underscores the deep roots of cognitive systems in physico-chemical principles and supports an integrated view of mind and matter (Pross 2012; Morowitz 2002).

Unlike static kinetic stability, where systems remain in local energy minima, dynamic kinetic stability, as described by Prigogine (1972), depends on continuous energy flow. Pascal and Pross (2022) introduced the concept of an energized dynamic kinetic state, a non-equilibrium condition in which chemical systems can display rudimentary cognitive-like behavior. Such systems, maintained by constant energy and material exchange, can sense and respond to stimuli, exhibit memory-like dynamics, and perform simple decision-like processes.

These findings blur the traditional boundary between living and non-living matter, suggesting a continuum of organization where DKS systems serve as precursors to biological cognition, bridging the physical, chemical, and biological domains.

The DKS system and its supportive environment are intimately connected, with the DKS system's very existence being dependent on the continuity of that connection. This umbilical connection between the system and its supportive environment creates what is effectively an 'inside' linked to its 'outside'. Notably, the 'inside-outside' relationship between the DKS system and its environment emerges without the need for a compartment or separation barrier. This relationship is ontological rather than structural. The environment provides the necessary energy and material transfers that sustain the dynamic kinetic state, highlighting the interdependence and intrinsic connection between the system and its surroundings. This deep integration between the DKS system and its environment is a crucial aspect that must be considered when exploring the potential for such systems to exhibit rudimentary cognitive-like behaviors. The environment is not just a passive backdrop, but an active participant in the system's dynamics and stability.

Within the Dynamic Kinetic Stability (DKS) framework, the emergence of mentality from non-equilibrium physical systems can be examined as a natural extension of dynamic interdependence between system and environment. The existential dependence of a DKS system on continuous energy and material exchange represents a rudimentary form of proto-mentality (Prigogine 1984; Kauffman 1993). This ongoing interaction generates a primitive "sensitivity" to environmental conditions (Tononi 2004), which, though not yet cognitive, marks an early stage in the evolution of mental phenomena (Baars 1988).

The DKS system's sustained non-equilibrium state enables feedback-driven adaptation to environmental fluctuations, shifting reaction pathways, stabilizing favorable dynamics, and maintaining function under resource variation (Morowitz 1992). To preserve its dynamic organization, the system develops boundaries, analogous to cellular membranes, that regulate energy and matter exchange, fostering internal self-organization through autocatalytic feedback loops (Kauffman 1993; Pross 2012).

Such autocatalytic and self-regulating mechanisms constitute the logical structure of DKS, where stability arises from continuous interaction rather than equilibrium. These features lay the groundwork for information processing, environmental responsiveness, and primitive decision-like behavior (Sporns 2011; Dehaene 2014). As replication emerges, evolutionary processes amplify these proto-cognitive traits, linking chemical self-organization to the origins of biological cognition and agency.

Hence, DKS provides a coherent framework for tracing the evolution of life and mind as a continuum, from chemical self-maintenance to cognitive complexity, bridging the material and mental domains (Lifson 1997; Szathmáry and Gladkih 1989; Azar 2024c). Within this framework, self-organizing chemical systems form dynamic, functional relationships with their environment, giving rise to behaviors that resemble primitive mental processes such as sensitivity to stimuli, pattern recognition, and decision-like responses. Through this continuous interaction, the DKS system becomes a conceptual bridge between chemical dynamics and the emergent complexity of living cognition, outlining the foundations of life's physical and mental evolution, such as:

1. Sensitivity to Stimuli: Chemical systems in a DKS state exhibit a form of primitive perception by responding to environmental changes. For example, changes in pH, temperature, or energy availability can lead to specific reactions, akin to how organisms perceive and respond to stimuli. This sensitivity represents the first step toward more complex sensory systems (Prigogine 1978a).
2. Pattern Recognition: Reaction networks within DKS systems can stabilize recurring chemical patterns, which may represent an early form of recognizing and replicating favorable environmental conditions. Such behavior parallels the biological concept of learning through reinforcement, albeit at a chemical level (Kauffman 1993).
3. Decision-Like Behavior: Some reaction pathways in DKS systems demonstrate selective behavior. These systems can "choose" pathways based on energy efficiency or environmental compatibility, mirroring decision-making processes in biological organisms. For instance, studies on reaction networks in far-from-equilibrium conditions show that they can adaptively switch pathways to sustain themselves in fluctuating environments (England 2013).

These properties suggest that proto-mentality arises when chemical systems in a DKS state begin processing environmental inputs and adaptively responding to them, exhibiting the earliest signs of intentional behavior. Situating these proto-mental processes within the DKS framework clarifies how consciousness could have evolved incrementally from dynamic chemical organization. As Morowitz (1992) notes, the transition from simple chemical networks to complex biological systems is characterized by increasing organization and responsiveness, forming the basis for cognitive complexity.

Pascal and Pross further demonstrate that the DKS framework, integrated with Darwin's evolutionary insights, delineates the physical pathway through which primitive mental phenomena developed into higher consciousness. This view bridges the material and mental realms, showing that life's cognitive dimension originates in prebiotic dynamics. In line with Darwin's hypothesis, cognition appears as a fundamental property of life, emerging gradually through self-organizing, non-equilibrium interactions rather than appearing suddenly with the first organisms.

Thus, the DKS framework offers a coherent mechanism for understanding how mental precursors evolved from dynamic physical systems, revealing cognition as an intrinsic aspect of nature and extending the roots of mentality to the very origins of life.

The Dynamic Kinetic Stability (DKS) framework provides a conceptual bridge between the physical and cognitive domains by offering a model through which the evolution of mental processes can be traced back to physical systems, particularly non-equilibrium chemical processes. Here's how this connection is made:

Emergence from Non-Equilibrium Systems: DKS posits that complex cognitive systems emerge from non-equilibrium states where dynamic interdependence between a system and its environment leads to self-organized behaviors. In simpler terms, the processes that underlie cognitive functions (such as awareness and decision-making) can be seen as arising from the interactions within complex physical systems that are in constant flux, akin to the dynamic balance of chemical reactions at equilibrium (Haken 2006).

Physical-Chemical Processes Leading to Proto-Cognition: According to the DKS framework, the stability of the system is contingent upon constant interactions with its environment. This physical and chemical interaction gives rise to the first rudimentary forms of mental functions, such as sensitivity to stimuli, which can be considered precursors to cognition (Prigogine 1967). This initial state of proto-mentality in non-living systems progressively evolves into more sophisticated cognitive phenomena, such as awareness.

Interdependence between Mind and Matter: The DKS model suggests that the material and cognitive domains are not distinct and separate but interdependent. The molecular and chemical structures that define living systems are inherently capable of generating cognitive processes when subjected to dynamic, non-equilibrium conditions. By framing cognitive processes as emergent properties of complex physical systems, DKS blurs the boundary between the mind and the material, making it possible to study both domains within a unified framework (Barabási 2002).

Information Processing as a Continuum: At the core of the DKS perspective is the idea that the processing of information, which is central to cognition, has its origins in simple physical processes. For instance, the continual exchange of energy and material within a system creates conditions that support the transfer and processing of information, which is a precursor to cognitive functions like memory and decision-making. Thus, DKS enables a continuous, stepwise progression from basic thermodynamic and chemical processes to the higher-order cognitive functions observed in more advanced organisms (Maturana 1980).

Bridging the Metaphysical and Physical: The DKS framework also allows for an exploration of the metaphysical aspects of cognition, such as awareness, intentionality, and subjective experience, by showing how these mental phenomena can emerge from the physical processes of non-equilibrium systems. The interdependent and dynamic nature of DKS processes is central to both the material aspects of cognition (neural and biochemical interactions) and the subjective experience of the mind, thus providing a holistic model that links the cognitive to the physical (Varela et al. 1991).

The DKS perspective allows for a seamless transition between the physical and cognitive realms by viewing cognition as an emergent property of physical systems in non-equilibrium states. It highlights the continuous evolution of complexity, from chemical interactions to awareness and higher-order cognitive functions, effectively bridging the material and mental domains.

The dynamic processes underlying the emergence of cognitive systems

The mind is a complex and captivating aspect of human existence, serving as the center of our experiences and cognitive functions. Despite centuries of study by philosophers, psychologists, neuroscientists, and cognitive scientists, it remains an enigmatic phenomenon (Block 1992; Chalmers 1996). At its core, the mind represents the processes unfolding in the brain and nervous system, from basic sensory perception to complex reasoning and creativity (Shettleworth 1998). It shapes our behaviors, attitudes, beliefs, and interactions with the world (Damasio 1999).

Understanding the mind requires exploration across multiple disciplines, including psychology, neuroscience, philosophy, and cognitive science. Each field offers unique perspectives, from neural mechanisms to philosophical implications (Gazzaniga 2005; Dennett 1991). Researchers aim to uncover the mysteries of consciousness, memory, awareness, perception, and subjective experience (Metzinger 2009).

The cognitive processes of the mind emerge as a result of the chemical activities occurring within the brain, aimed at rendering the organism's awareness conscious and facilitating the recognition of its own cognitive processes (Damasio 1999; Clark 1997). This advancement is primarily enabled by language, a neural mechanism that allows access to and manipulation of brain experiences, overlaying self-generated thoughts onto the sensation of internal processing (Boroditsky 2001; Jackendoff 2002). Understanding the limitations of introspection can elucidate the brain-mind relationship and reveal the operational formula responsible for generating and sustaining human consciousness (Metzinger 2009; Varela et al. 1991 and Zhao 2009). This text represents an interdisciplinary integration of neuroscience and evolutionary perspectives, synthesizing relevant data to form a coherent narrative (Deacon 1997; Gazzaniga 2005).

Living organisms display a diverse array of cognitive behaviors, showcasing their capacity to engage with and respond to their surroundings (Maturana 1980; Nehaniv and Dautenhahn 2002). This cognitive prowess extends beyond complex organisms and is evident even in the most elementary life forms, such as bacteria. These microorganisms are equipped with sophisticated mechanisms enabling them to perceive and react to various environmental cues, including chemical, physical, and biological signals (Packer et al. 2017; Shapiro 2017). From detecting changes in nutrient availability, pH levels, and temperature to responding to light and the presence of other microbes, bacteria demonstrate remarkable cognitive abilities essential for their survival and adaptation (West et al. 2007; Ben-Jacob et al. 1998).

According to Maturana (1980); van Duijn (2017); Lyon (2015), all living organisms possess inherent cognitive abilities, being aware of themselves and their surroundings, and continually requiring energy and resources for self-maintenance. They actively engage with their environment, driven by the overarching goals of survival and reproduction. This understanding of cognition as intrinsic to all life forms is increasingly recognized (Maturana 1980; van Duijn 2017; Lyon 2015). Even bacteria, representing the simplest prokaryotic life forms, exhibit remarkable capabilities to sense and respond to a wide array of environmental cues. Lyon (2015) has even suggested that bacteria engage in decision-making, communication, manipulation, and cooperative behaviors akin to higher organisms. Additionally, Ramanathan and Broach (2007) propose that bacteria may possess rudimentary forms of thinking. Hence, irrespective of the terminology used, it is now widely accepted that advanced cognitive abilities are inherent across all levels of life (Lyon 2015; Ramanathan and Broach 2007; Shapiro 2021).

According to Pascal and Pross (2022), cognition is rooted in material causation and produces material outcomes within both the cognitive system and its environment. They propose that cognitive processes emerge from fundamental material interactions and cannot exist apart from their physical foundations. The physical and mental capacities of life originate in a state of Dynamic Kinetic Stability (DKS), a non-equilibrium, energy-driven condition at the level of chemical organization.

This framework highlights the deep interconnection between material processes and cognitive functions, suggesting that the emergence of consciousness is inseparable from the chemical and physical dynamics of living systems. Perception, in this view, arises through the continuous interaction between a DKS system and its environment. The process of kinetic selection, where less stable replicators are replaced by more stable ones, acts as a primitive form of "learning," through which the system identifies advantageous variations.

This perspective situates the origins of mentality within the realm of chemistry, aligning with Darwin's view in The Origin of Species that evolution encompasses both physical and mental dimensions from its inception. In DKS systems, internal modifications influence external conditions through kinetic selection, inherently directed toward achieving greater dynamic kinetic stability, just as changes in conventional physical systems strive toward thermodynamic stability.

Consciousness can be regarded as an intrinsic component of the broader adaptive processes exhibited by living organisms in response to environmental conditions. Understanding its function and the mechanisms through which it operates constitutes a central challenge in the study of life and mind. When an environmental disturbance occurs, such as a sudden change or challenge in external conditions, the primary objective of adaptation is to activate and coordinate processes capable of counteracting or mitigating its effects. This adaptive response entails a dynamic interplay between cognitive regulation and physical activity, reflecting the system's capacity to integrate perception, evaluation, and action.

Pross and Pascal (2017) propose that chemical systems evolving toward greater dynamic kinetic stability (DKS), and ultimately toward life, must exhibit three essential properties. First, they must possess the capacity for self-reproduction, enabling the persistence and transmission of intrinsic characteristics or information to subsequent generations. This self-replicative property provides continuity and resilience in fluctuating environments. Second, these systems must allow for structural variation, encompassing mechanisms such as mutation, recombination, or other forms of molecular rearrangement. Variation enables the exploration of novel configurations and traits, thereby facilitating adaptation to changing conditions. Finally, maintaining a far-from-equilibrium state is fundamental: a continuous input of energy is required to sustain dynamic behavior and prevent decay into thermodynamic equilibrium. This sustained energy flux drives the emergence of complexity and the adaptive organization that characterizes living systems.

As indicated in the preceding section, the importance of the DKS concept in the context of life is that it describes not just certain chemical systems, but the entire class of living things (Pross 2012; Kauffman 1993). The DKS framework encompasses both chemical and biological systems, offering a theoretical description for the entire evolutionary process from chemical to biological. This comprehensive approach allows us to understand the continuity of evolution in physical and chemical terms, effectively bridging the gap between non-living and living systems (Haken 2006).

The DKS state, whether chemical or biological, is inherently dependent on its environment. This state of total dependence can be thought of as inducing the beginnings of 'awareness', an awareness by the DKS system of its environment. On the one hand, the DKS system is materially distinct and separate from its environment, yet due to its total dependence on its environment, it is necessarily aware of that environment (Varela et al. 1991).

Within this duality lies the origin of self-awareness that derives from external awareness. This description proposes the physical means by which a mental dimension could emerge. Awareness is not a physical attribute but rather a mental one. Though mental attributes derive from physical circumstances, they are inherently non-physical, meaning they cannot be detected and measured by physical means (Chalmers 1996). Thus, the dependence of an 'inside' (the DKS system) on its 'outside' (the system's environment) gives rise to the foundation of a mental domain, a non-physical relationship between a physical system and its supporting environment. Thus, one might say that the DKS state is the seed from which the mental state could sprout, while the evolutionary process is the mechanism by which that mental dimension could emerge and develop, thereby giving rise to its distinct and unique functional capabilities (Deacon 2012). This perspective suggests that the roots of cognition and consciousness are deeply embedded in the fundamental principles of physics and chemistry, gradually evolving through natural processes to form the complex mental functions observed in advanced organisms (Noble 2006; Pascal and Pross 2016).

Pascal and Pross (2023) conclude that the emergence of the mind and its subsequent exploitation by nature were physicochemically feasible once a replicative chemical DKS system was able to emerge. The mental dimension was not a late evolutionary discovery associated with the appearance of neurons and brains, but is inherent in the DKS state's ontological nature and therefore fundamental to the evolutionary process. This perspective suggests that the roots of cognitive and mental capabilities are deeply embedded in the basic principles governing the DKS state, providing a foundational framework for understanding the evolution of consciousness from a chemical and physical standpoint.

Pascal and Pross (2022) propose that perception emerges from the dynamic interplay between replicative DKS systems and their supportive environments. The DKS system, a kinetic phenomenon driven by self-organization and replication, undergoes kinetic selection, "learning" which variations are advantageous. This capacity for replication enables both memory and adaptive behavior, revealing a primitive mental dimension.

According to the authors, evolution encompasses not only the physical but also the mental aspects of life, aligning with Darwin's suggestion in On the Origin of Species (Dennett 1995). The mental facet of life is thus integral to the replicative DKS state, where ongoing dynamic interactions with the environment give rise to rudimentary cognition and perception. This framework provides a physico-chemical basis for understanding how mental properties may originate from material processes.

Symbolic topological structure of cognitive systems

According to Pascal and Pross (2023), the physical and chemical feasibility of the mind's emergence and its subsequent utilization by nature became possible once a replicative chemical system with dynamic kinetic stability emerged.

Building on the preceding discussion, diverse topological frameworks for cognitive systems can be formulated by examining the sensory responses of materials to external stimuli. Such frameworks align with earlier works in cognitive science and material systems, such as Sporns (2011) and Tononi (1994), which emphasize the structural and functional organization of cognitive processes. By investigating the interaction between the physical properties of materials and cognitive processes, these frameworks facilitate an understanding of the intricate relationship between metaphysical aspects of cognition, such as awareness and intentionality (Chalmers 1996), and their physical underpinnings. This topological analysis reveals the dynamic interplay between physical and metaphysical states, offering a robust foundation for identifying fundamental principles that drive the emergence and evolution of cognitive systems (Clark 1997; Dehaene 2014).

The formation of cognitive systems within a chemical compound can be understood as a process governed by the interplay of dynamic natural forces inherent in the substance. Studies on self-organization and emergent complexity in chemical systems, such as Prigogine (1984), and Kauffman (1993), demonstrate how such interactions lead to transformations within compounds, giving rise to complex cognitive functionalities. These emergent properties parallel those observed in higher cognitive processes and align with the principles of dynamic systems theory (Kelso 1995). This transformation signifies an evolutionary milestone, highlighting the adaptability and self-organizing potential of chemical systems (Pascal 2013). Furthermore, it underscores the interconnectedness of natural forces and their ability to produce higher-order structures capable of advanced cognitive processes, thereby bridging the gap between chemical foundations and cognitive complexity.

According to the explanations of the previous sections, the brain can indeed be conceptualized as a Dynamic Kinetic Stability (DKS) system, operating in a state of constant interaction with its internal and external environments. In this view, the brain is not merely a static organ but a complex system exhibiting properties reminiscent of DKS systems, which maintain stability while constantly adapting and evolving in response to perturbations (Pascal and Pross 2023).

The brain, like DKS systems, operates in a continuous non-equilibrium state that requires constant energy dissipation. Neural metabolic processes, synaptic transmission, neurotransmitter release, and ion transport, sustain activity far from equilibrium, paralleling energy flows in DKS systems (Friston 2010; Prigogine 1978b). These energy-dependent processes prevent entropy-driven disorder, supporting dynamic stability.

Neuroplasticity allows the brain to reorganize in response to environmental stimuli, reinforcing beneficial patterns while discarding less useful ones (Pascual-Leone et al. 2005). This adaptive restructuring mirrors the selective stabilization of DKS systems. Predictive coding models further illustrate how the brain continuously refines internal representations to align with external reality (Clark 2013).

Operational integrity is maintained through homeostatic and allostatic mechanisms (Sterling and Eyer 1988), which balance internal states via dynamic control systems, from synaptic homeostasis (Turrigiano 2012) to large-scale autonomic regulation. This interplay of stability and flexibility exemplifies the same principles of feedback, self-organization, and adaptation that define DKS systems.

The DKS properties of the brain form the foundation for mental phenomena, as dynamic interactions and energy flows within neural systems create the conditions for higher cognitive functions. As a non-equilibrium system, the brain sustains continuous metabolic activity and information processing, maintaining stability while adapting to environmental changes (Friston 2010; Pross 2012).

Neuroplasticity enables learning, problem-solving, and other cognitive processes (Pascual-Leone et al. 2005), while homeostatic and allostatic mechanisms ensure stability amid ongoing change (Sterling and Eyer 1988). This balance of flexibility and regulation allows for dynamic, context-dependent thought (Turrigiano 2012).

The mind emerges as an integrative phenomenon when neural dynamics reach critical complexity, producing properties that transcend individual neural components (Tononi Tononi 2004). Large-scale neural networks generate subjective experience and higher-order cognition through integrated information processing (Clark 2013).

The emergent properties of the mind include:

1. The brain integrates diverse sensory inputs, much like how DKS systems integrate environmental stimuli to stabilize their behavior (Friston and Stephan 2007). This integration forms the basis of perception and awareness, as described by Integrated Information Theory (IIT), which suggests that consciousness arises from the integration of distributed neural signals into a unified experience (Tononi 2008).
2. Consciousness emerges from the continuous activity of large-scale neural networks operating far from equilibrium (Engel et al. 2001). Just as DKS systems maintain their stability through dynamic interactions and energy dissipation, consciousness depends on ongoing cortical activity, synchronization, and predictive processing mechanisms (Friston 2018).
3. Proto-mentality evolves into intentionality as neural systems develop mechanisms for goal-directed behavior, forming the basis of thought and action (Dennett 1995). The ability of the brain to anticipate and generate actions through hierarchical predictive coding (Clark 2016) mirrors how DKS systems evolve to optimize their stability. These mechanisms allow for autonomous decision-making, reinforcing the link between neural dynamics, intentionality, and cognitive agency.

This perspective situates the brain as a DKS system whose non-equilibrium dynamics, adaptability, and self-sustaining processes generate higher cognitive functions, ultimately leading to the emergence of consciousness, intentionality, and agency.

On the other hands, by tracing the principles of DKS through successive levels of complexity, we can construct a unified framework for understanding how the mind emerges from the brain. DKS, a concept rooted in the thermodynamics of far-from-equilibrium systems, explains how systems maintain stability through continuous energy dissipation and adaptation (Pross 2012). This principle can be applied across multiple scales of complexity, from chemical systems to the emergence of cognition as follows:

Chemical Dynamics: At the molecular level, energy flows and self-organization in chemical systems create the foundation for life. DKS governs the behavior of these systems, enabling the emergence of proto-metabolic networks and autocatalytic cycles (Pascal 2013). These processes, which are far from thermodynamic equilibrium, give rise to the first hints of proto-mentality, a precursor to more complex forms of cognition (Deacon 2012).

Biological Complexity: Life evolves through iterative interactions with the environment, driven by the principles of DKS. Biological systems achieve dynamic stability by continuously adapting to environmental changes, a process that aligns with the concept of autopoiesis (Maturana 1980). This self-sustaining organization allows living systems to maintain their integrity while evolving toward greater complexity (Kauffman 1993).

Neural Systems: The brain inherits and refines the principles of DKS, with neurons acting as energy-dissipating units within a highly dynamic and adaptive system. Neural networks exhibit properties of self-organization and criticality, allowing them to balance stability and flexibility (Beggs 2008). This dynamic balance is essential for information processing and the emergence of higher-order functions (Tononi and Edelman 1998).

Emergent Mind: The mind arises from the intricate interplay of neural dynamics, achieving higher-order stability through DKS. This stability manifests as cognition, self-awareness, and intentionality, features that are consistent with the Integrated Information Theory (IIT) of consciousness (Tononi 2004). The mind, as an emergent phenomenon, reflects the brain's ability to organize and stabilize complex patterns of activity across multiple scales (Friston 2010).

This progression illustrates how DKS serves as a unifying principle, bridging the gap between the physical processes of the brain and the emergence of the mind. By integrating insights from thermodynamics, systems biology, and neuroscience, we can better understand the continuum from chemical dynamics to conscious experience.

The relationship between DKS processes and the emergence of the mind can be understood as a continuum of complexity. DKS provides the foundational principles of dynamic interaction, energy flow, and adaptability, which are preserved and elaborated upon in the evolution of biological systems. The brain's dynamic, far-from-equilibrium nature allows it to exhibit the hallmarks of DKS, ultimately giving rise to the emergent phenomenon of the mind. This perspective unites the physical, chemical, and cognitive dimensions of life within a single coherent framework.

Assuming that γ is a chemical compound that exhibits responsiveness to its environment, the forthcoming discussion will symbolically describe the process by which this compound can be transformed into a complex cognitive system, such as the brain of a living organism. Following this, the analysis will explore how the brain generates the subjective experience of consciousness. Based on the information provided in the preceding sections, the cognitive system of γ undergoes continuous development and evolution. This process involves creating and refining cognitive subsystems or "utilities" that are integral components (or components^*) of γ's overall cognition. Key cognitive of the Mind utilities may include (for more information see Azar 2024b):

X_1: The sensation set represents the reactivity of molecular reactions associated with sensory input.

X_2: The primary consciousness set involves the initial translation and processing of input data within the mind.

X_3: The awareness and attention set encompasses knowing, perceiving, and being cognizant of events or stimuli.

X_4: The analyzing set involves the review and analysis of data.

X_5: The memory set represents the storage and retrieval of information.

X_6: The character mentality and mood set includes emotions, moods, and character traits that influence the mind's state.

X_7: The system components coordinator set serves as the central part of the system, facilitating communication and coordination among various components.

X_8: The quality of will to accomplish an output set refers to the determination and motivation to achieve desired outcomes.

X_9: The curiosity along with perception set involves a deep sense of curiosity and exploration of phenomena or concepts without immediate analysis.

X_{10}: The other molecular, physiological, chemical, and physical conditions set represents additional factors related to the molecular, physiological, chemical, and physical aspects that influence the mind.

These interactive elements develop in sophistication over time, shaping the agent's cognitive architecture. While reducible to computational mechanisms, the system as a whole facilitates increasingly complex modes of understanding, reasoning, and experiencing the world from the agent's perspective. The continuous evolution of these cognitive utilities is central to the emergence of advanced general intelligence. As the agent's cognitive architecture evolves, it incorporates more intricate feedback loops and adaptive processes, allowing for a richer and more nuanced interaction with its environment. This progression enhances the agent's ability to abstract, categorize, and synthesize information, leading to a more profound and comprehensive grasp of its surroundings.

These components^* have emerged as a result of the evolution of the γ system. They are introduced to facilitate a deeper understanding of the relationship between the DKS system, the functioning of the mind, and the processes through which experiences are generated within the mind. The proposed topology for the mind seeks to reveal a structured arrangement of system components^* (X_i, where $1 \leq i \leq 10$), encapsulating the functionality of a system resembling that of a human. However, it is important to recognize that simpler entities, such as artificial intelligence, plants, or insects, may lack some or all of these components. Together, these components contribute to the operation of the mind, encompassing sensory processing, consciousness, awareness, memory, emotional states, analytical abilities, motivation, curiosity, and other physiological and environmental factors influencing mental functioning. The aforementioned components* can be aptly described as γ arms, which have gradually developed over an extensive period. These formations result from internal chemical and physical transformations within the γ system, as well as the influence of external environmental factors.

Building on the aforementioned principles, the DKS facilitate an evolutionary process within matter that results in the formation of rudimentary cognitive systems (RCS) embedded in physical substances. This process is driven by the continuous interactions between material properties and external stimuli, which lead to the self-organization of increasingly complex systems. As these cognitive systems evolve, they undergo hierarchical layers of complexity, ultimately culminating in the emergence of the advanced cognitive systems characteristic of the human mind. This progression underscores the relationship between fundamental physical processes and the gradual development of cognitive functions, providing a framework for understanding how simple material systems can give rise to the sophisticated mental faculties observed in higher organisms.

The first step in evolution involves the self-organization of matter, driven by material properties and external stimuli. Initial molecular reactivity gives rise to rudimentary systems capable of sensing and responding to their environment, such as simple organisms reacting to light or temperature (Tennie et al. 2009). Chemical compounds, including those in plants and microorganisms, exhibit adaptive responses to environmental cues, marking the earliest stage of cognitive function (Baluška et al. 2009). Feedback loops arising from repeated interactions enable these systems to adjust behavior based on past stimuli, forming the basis for higher-level mental processes (Hohwy 2013).

As complexity increases, cognitive subsystems, or utilities (X_1 to X_{10}), emerge, enhancing the system's ability to process information, interact with the environment, and develop mental capacities (Jablonka and Lamb 2005). These utilities evolve hierarchically, with each layer supporting increasingly sophisticated functions (Laland and Odling-Smee 2011). The integration of these subsystems underlies advanced cognitive processes, enabling complex behaviors and the emergence of higher mental states (Sporns 2011).

This progression illustrates the gradual evolution from simple molecular interactions to complex cognition, providing a framework for understanding how early material dynamics could give rise to the advanced cognitive systems characteristic of human consciousness (Sterelny 2004).

RCS, as a fundamental aspect of material dynamics, holds the potential to influence the reactivity of molecular reactions associated with sensory input (the sensation set, X_1). In this light, RCS may act as a subtle orchestrator, modulating the processing and interpretation of sensory information within the confines of the mind (the primary consciousness set, X_2). This dynamic interplay between RCS and sensory input underscores the intricate relationship between material dynamics and the foundational aspects of consciousness.

Moreover, RCS dynamics are posited to exert a significant influence on the cognitive systems attentional processes (the awareness and attention set, X_3). By shaping the stability and energy landscape within cognitive systems, DKS may play a pivotal role in governing the allocation of cognitive resources and the focus of awareness. This suggests that the dynamic nature of DKS could be intricately intertwined with the cognitive system capacity to sustain attention on specific stimuli or tasks, thereby impacting cognitive performance and perceptual processing.

Furthermore, RCS interactions are contemplated to extend their influence to the mind's executive functions (the analyzing set, X_4). As the mind navigates the complexities of decision-making, problem-solving, and planning, DKS dynamics may serve as a guiding force, influencing the flexibility and adaptability of cognitive processes. This dynamic interplay suggests that DKS could offer a novel lens through which to understand how the mind adjusts its strategies in response to changing environmental demands, shedding light on the intricate dance between material dynamics and cognitive functioning.

Additionally, RCS dynamics are conjectured to extend their reach to the domain of emotional regulation processes within the mind (the character mentality and mood set, X_6). By modulating the energy landscape and neurotransmitter pathways, RCS interactions may exert a subtle yet profound influence on the intensity and duration of emotional experiences. This implies that the dynamic interplay between RCS and emotional regulation processes could shape emotional responses and mood states, offering intriguing insights into the interface between material dynamics and emotional states.

Within the philosophical realm, the influence of RCS dynamics on the mind's semantic processing abilities is contemplated (the memory set, X_5). By shaping semantic networks and associations, RCS interactions may impact how individuals encode, store, and retrieve semantic knowledge. This suggests that the stability and energy landscape of RCS systems could play a pivotal role in language comprehension, production, and semantic memory retrieval, underscoring the profound implications of material dynamics for cognitive processes and linguistic cognition.

Thus, the evolution and promotion of RCS within the cognitive system of γ provide the foundational framework for the creation of the conscious experience. By shaping sensory processing, attentional focus, cognitive integration, emotional regulation, and dynamic interaction with the environment, RCS dynamics contribute to the richness and complexity of conscious awareness, allowing individuals to perceive, interpret, and experience the world around them in a meaningful and subjective manner.

In the following, the process that leads to the creation and activity of $\gamma\text{-components}^*$, resulting in the experience of consciousness, will be briefly explained. In this process, the chemical and physical conditions of γ are shaped by the ecological conditions of the environment, which facilitates the formation and evolution of the cognitive system.

Consider the existence of a set of sensitivities within the γ system, represented by X_1. Over time, the activities of X_1 give rise to the emergence of secondary sensitivities within the intricate framework of the γ system. These newly developed sensitivities, collectively referred to as X_2, exhibit notable responsiveness to the groupings of elements in X_1. Each element of X_2 manifests a distinct sensitivity to either an individual element or a collective configuration of elements from X_1, thereby displaying a spectrum of responsiveness. The emergence of X_2 is primarily attributed to the molecular sensitivities inherent to the γ system. These sensitivities, chemical and physical in nature, react dynamically to fluctuations in the states of X_1. It is essential to note that, beyond its responsiveness to external environmental stimuli, X_1 demonstrates a reciprocal sensitivity to internal processes, including those originating from X_2. This reciprocal interaction establishes an ongoing cyclic process. This continuous cycle fosters the progressive enhancement of sensitivities within both X_1 and X_2, ultimately leading to their refinement and further development. Such dynamic interplay underscores the evolutionary potential of the γ system, enabling it to adapt and evolve in complexity over time.

As the process progresses, a new generation of sensitizers is generated, sensitive to the performance and changes of X_2. An example of these sensitizers can be represented by a category denoted as X_3. It is important to emphasize that all these sensitivities are molecular, chemical, and physical in nature, occurring within γ.

The elements of X_3 exhibit functional reactivity that depends on the changes in the elements of X_2. Additionally, during the evolution of γ, further components, such as X_3, X_4, X_5, and so on, may arise in parallel as subsequent sensors within the system. Consequently, the system's components, including the sets $X_1, \ldots, X_{10}$, develop unique sensitivities to their constituent elements, which are refined over time. As this process unfolds, a one-to-one correspondence is established among the system's components. For example, if γ is considered to be the brain, different frequencies of light received by X_1 evoke varying, corresponding sensitivities in X_2, which are perceived or experienced as different colors.

At this stage, the chemical composition γ may still appear to function as a simple system, and it is referred to as such within this context. The various sensors that give rise to the system's components (X_i, where $1 \leq i \leq 10$) are collectively referred to as "advanced sensors of all generations" (*ASAG*), or simply "sensors". It is important to note that these sensitivities develop incrementally due to a combination of environmental factors external to the system and chemical and physical reactions within the system.

Let us consider the scenario where the set of sensitivities of the system γ to its environment is represented by X_1. Over time, the activities of X_1 give rise to secondary sensitivities within the system, denoted as X_2, which exhibit responsiveness to the groupings of elements in X_1. The elements of X_2 demonstrate varying degrees of sensitivity to individual elements or groupings within X_1, meaning each element in X_2 manifests a specific sensitivity to a corresponding element or grouping in X_1.

The emergence of X_2 primarily results from the molecular sensitivities of the system γ, which undergo chemical and physical reactions in response to changes in the states of X_1. Notably, X_1 is sensitive not only to external environmental conditions but also to internal reactions, including those originating from X_2. This interaction forms a continuous and regular feedback loop between X_1 and X_2.

As this cyclic process persists, the sensitivities of both X_1 and X_2 are progressively enhanced, leading to their refinement and improvement. The sustained interaction and mutual refinement of these sensitivities contribute to the system's increased ability to adapt and respond effectively to environmental changes. This process can be shown as below,

$$\alpha \Longrightarrow X_1(\alpha) \Longleftrightarrow X_2(X_1(\alpha)), \tag{1}$$

where α is a message received from environment.

As the ongoing process unfolds, a subsequent generation of sensitizers arises within the system that are specifically attuned to the performance and alterations of X_2. This new category of sensitivities is represented by X_3. It is crucial to emphasize that all of these sensitivities, including those in X_1 and X_2, are rooted in molecular, chemical, and physical interactions occurring within the system γ. The sensitivities represented by X_3 respond to the dynamics and changes within X_2, which, in turn, are influenced by the activities of X_1. These molecular-level sensitivities enable the system to perceive and react to the performance and modifications occurring in the previous generations of sensitivities.

By incorporating this multi-layered framework of sensitivities, the system γ can exhibit a hierarchical structure that facilitates its ability to adapt, learn, and respond to its environment in a nuanced and sophisticated manner. The molecular, chemical, and physical nature of these sensitivities underscores the fundamental basis upon which the system's information processing and behavior are built. The elements of X_3 exhibit functional reactivity that depends on the changes of X_2 elements.

Indeed, as the evolution of the system γ progresses, additional components such as X_3, X_4, X_5, and so on, can emerge in parallel as subsequent sensors within γ. These components contribute to the expanding complexity of the system and its ability to sense and interact with its environment. The system components, including the sets X_1, X_2, X_3, X_4, X_5, and so forth, develop distinct sensitivities to their constituent elements, which become more refined over time. This refinement is a result of the ongoing interactions and feedback loops between the different components of the system. As the process continues, a one-to-one correspondence is established between the system components and their specific sensitivities. To illustrate this, let's consider the analogy of γ representing the brain. The initial set of sensitivities X_1 could correspond to the brain's sensory inputs, such as the reception of different frequencies of light. This input then evokes corresponding sensitivities in X_2, which we perceive or experience as different colors. The establishment of such a correspondence between the different components of the system enables the system to interpret and make sense of the information it receives from its environment. It underscores the interconnectedness and interplay between the various sensitivities and components within γ, allowing for a rich and nuanced perception of the world.

At this juncture, the chemical composition γ may appear to be a simple system, and we refer to it as such. The various sensors that give rise to the system's components (X_i, where $1 \leq i \leq 10$) are collectively referred to as "advanced sensors of all generations" (*ASAG*), or simply "sensors" if there is no ambiguity. It is important to note that these sensitivities develop incrementally due to a combination of environmental factors external to the system and chemical and physical reactions within the system.

The behavior of elements in X_1 over time results in the emergence of second-generation sensitizers, denoted as X_2. The functioning of sensors facilitates the generation of X_2 from X_1, while the development of X_1 is, in turn, promoted by X_2. This iterative process continues as X_2 generates X_3, and X_3 further promotes the development of X_2. The relationship between the system's components during their generation or development may persist depending on the inherent nature of the system. Assuming $X_1 = A_1, A_2, \ldots, A_n$ and $X_2 = B_1, B_2, \ldots, B_n$, we can further assume that each element A_i in X_1 corresponds to an element B_i in X_2 for all $1 \leq i \leq n$.

Each element b in B_i is responsive to the interactions of its corresponding element a in A_i. We can define a function f_{12} from X_1 to X_2, such that $f_{12}(A_i) = B_i$ for all $1 \leq i \leq n$. For instance, in the context of animals, A_1 and A_2 can represent the set of auditory and visual sensors, respectively, while B_1 and B_2 denote the corresponding sensory experiences in the mind. In this case, $b_1 \in B_1$ and $b_2 \in B_2$ are sensitive to alterations and molecular reactions of $a_1 \in A_1$ and $a_2 \in A_2$, respectively. Similarly, there are functions from X_2 to other components, such as $X_3 = \{C_1, C_2, \cdots, C_n\}$, where f_{23} is a function from X_2 to X_3 such that $f_{23}(B_i) = C_i$ for all $1 \leq i \leq n$. The function f_{23} determines our awareness of the elements in X_2.

Thus, the primary functions that connect the system components (which can be caused by nervous systems) are as follows:

$$\beta = \{f_{ij} : X_i \rightarrow X_j \mid \quad 1 \leq i, j \leq n\}.$$

The combination of elements β reflects the activity of the system and transforms incoming messages or internal processes into an output message. In this context, the system components are interdependent. For instance, the performance of elements in X_5 hinges on changes taking place in the elements of X_2 and X_3.

The performance of elements in some system components may depend on the elements in multiple components. For instance, consider the sensitivity of an element in X_4 that reacts to changes in both X_3 and X_5. To illustrate this concept more simply, suppose we experience two sounds represented by c_1 and c_1', both of which belong to $f_{23}(f_{12}(A_1))$. These experiences can serve as inputs to another experience in X_4, where the sensitivity to two experiences, c_1 and c_1', is compared. This sensitivity, which is generated in X_4, is referred to as the analyzing sensitivity of the system. The collection of analyzing sensitivities of the system, which are stored in the memory component in various ways, form the basis of the analysis component, i.e., X_4. The activity of analyzing sensitizers may be the outcome of events occurring in nature. In some cases, system sensitizers establish a one-to-one correspondence between themselves and events in nature, leading to the creation of an analyzing sensor. The working process of other sensors are also explained similarly.

It is important to note that the experience of consciousness in the evolutionary mind emerges from an interplay of sensors or sensitivities (*ASAG*). These sensors are established through a one-to-one correspondence with the ecological processes of the environment. The internal processes of the system, in conjunction with its interactions with environmental conditions, have evolved into a dynamic functional relationship. Over time, this function has been continuously refined, giving rise to two critical relationships: one between the components of the mind and the environmental conditions, and another among the components of the mind itself. A conscious experience of a phenomenon, such as α, can be understood as a neural sensitivity encoded as a message in the mind under this functional framework, f, and its components. This conscious experience can be mathematically represented as $f(X_1, X_2, \ldots, X_{10})(\alpha)$.

The relationship between the cognitive systems of living organisms and their environment, mediated by sensor activity,($ASAG$), is a universal phenomenon, with variations arising primarily from differences in the number and type of their constituent components.

This conceptualization aligns with Baluška et al. (2009), who emphasize the role of signaling networks in plants, illustrating an early form of ecological correspondence between the organism and its environment. The evolution of the mind's predictive capacity, enabling the construction of conscious experience from environmental stimuli, has been further explored by Hohwy (2013), who discusses the role of predictive processing in the brain's adaptive responses. The refinement of internal functions through continuous interaction with the environment is echoed in Laland and Odling-Smee (2011), who present the concept of cultural niche construction, influencing cognitive development in humans. Moreover, the interrelation between various components of the brain is explored by Sporns (2011), who emphasizes the role of brain networks in cognitive functions, supporting the notion of a functional network underlying consciousness. Tennie et al. (2009) also examine the emergence of cumulative culture in humans, driven by a cognitive bias towards social learning, shedding light on the evolutionary factors that contribute to the formation of consciousness. Jablonka and Lamb (2005) further elaborate on the evolutionary nature of cognitive processes, offering insights into how both genetic and epigenetic factors contribute to cognitive and conscious experiences. Lastly, Sterelny (2004) discusses the evolution of human cognition, highlighting the influence of external pressures and environmental factors on the development of the mind.

The recent explanations may offer a compelling theoretical framework for understanding the cognitive systems of the mind or a philosophical perspective on the processes underlying its activity. However, to establish a precise connection between these descriptions and the underlying biological or molecular details processes, further theoretical and experimental studies are essential.

Conclusion

Cognitive systems arise from the dynamic interplay between chemical sensors, external stimuli, and internal processes. These interactions foster the development of distinct characteristics within compounds, ultimately leading to the emergence of living organisms with increasingly advanced cognitive mechanisms, the mind.

The mind encompasses a spectrum of abilities, including awareness, perception, memory, learning, and decision-making, all supported by biological structures such as nervous systems and brain architectures. Through the integration of these mechanisms, organisms exhibit sophisticated behaviors, adapt to their environments, and engage in complex cognitive processes.

Cognitive abilities, including conscious experiences, vary widely across species. For example, an ant's perception of sound differs fundamentally from a human's experience of music, and reptiles and humans perceive light and color in distinct ways. These variations reflect the diverse evolutionary adaptations of cognitive systems to the ecological and biological contexts of each species.

The exploration of Dynamic Kinetic Stability (DKS) and its role in conscious experience reveals the intricate interplay between material dynamics and cognitive processes within the mind. Through the evolution and refinement of DKS, the cognitive system undergoes dynamic transformations that contribute to the emergence of consciousness. DKS plays a pivotal role in shaping sensory processing, attentional focus, cognitive integration, and dynamic interactions with the environment, collectively defining the rich and complex landscape of conscious awareness.

By understanding how DKS dynamics influence conscious experience, we gain deeper insights into the fundamental nature of cognition and the mechanisms underlying subjective awareness. Further investigation into the relationship between DKS and consciousness promises to enhance our understanding of the mind-brain connection and pave the way for advancements in neuroscience, philosophy, and cognitive science. Ultimately, the study of DKS provides a robust framework for unraveling the mysteries of consciousness and delving into the profound complexities of human cognition.

The DKS framework not only provides a plausible mechanism for bridging the gap between the physical and the mental but also opens new pathways for addressing several long-standing debates in the philosophy of mind. By grounding cognition and consciousness in the thermodynamic logic of self-organizing systems, the DKS approach could contribute to reconciling disputes such as internalism versus externalism, where mental content may be understood as a dynamic interplay between internal regulatory processes and environmental coupling. Similarly, the problem of other minds may be reframed through the lens of shared dynamic stability, suggesting that the recognition of other conscious entities arises from the detection of similar patterns of recursive self-maintenance and adaptive organization. Moreover, issues surrounding mental causation, emergentism, and the unity of consciousness may find fresh interpretations within this framework, which conceives mental phenomena as both physically instantiated and functionally emergent from far-from-equilibrium dynamics. Philosophically, further examination is needed to clarify how the DKS framework interfaces with theories of representation, intentionality, and intersubjectivity, and whether it can offer a unifying perspective that integrates biological, physical, and phenomenological domains. In this sense, adopting the DKS view holds the promise not only of addressing the traditional "hard" and "easy" problems of mind but also of reshaping the conceptual landscape of the philosophy of mind itself.

The process involving components (X_1 through X_{10}) represents a gradual evolution from simple, reactionary systems to more complex cognitive architectures. This progression encompasses increasing sophistication in feedback loops, neural integration, and emotional regulation, ultimately giving rise to advanced mental processes such as reasoning, self-awareness, and consciousness. Through the principles of DKS and the stepwise evolution of these cognitive utilities, the brain develops a highly intricate mental topology. This topology enables organisms to experience the world not merely in a reactive manner but through deeply integrated, subjective, and interpretive processes. The seamless integration of these cognitive functions underpins the development of advanced general intelligence, culminating in the human mind's remarkable capacity to reason, learn, plan, and understand the world in profound and dynamic ways. This hierarchical, feedback-driven evolution is fundamental to the emergence of the mind, with each cognitive utility progressively building upon its predecessors. Together, these components form a sophisticated system capable of supporting conscious experience and higher-order cognition.q

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Declarations

Conflict of interest The author declares that it has no conflict of interest.

Consent for publication Not applicable.

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References

Agozzino L et al (2020) How do cells adapt? Stories told in landscapes. Annu Rev Chem Biomol Eng 11:155–182. https://doi.org/10.1146/annurev-chembioeng-011720-103410

Allen JS (2009) The lives of the brain: human evolution and the organ of mind. Harvard University Press

Alberts B, Johnson A, Lewis J, Raff M, Roberts K, Walter P (2014) Molecular biology of the cell (6th ed). Garland Science

Azar KH (2022) The quest for the definition of life. [q-bio.NC]. https://doi.org/10.48550/arXiv.2210.12072

Azar KH (2024a) The challenge of distinguishing living from non-living entities. [q-bio.NC]. https://www.researchgate.net/publication/379872790

Azar KH (2024b) A model for conscious experience of mind. https://www.researchgate.net/publication/379861113

Azar KH (2024c) The interplay between logical phenomena and the cognitive system of the mind. [q-bio.NC]. https://doi.org/10.48550/arXiv.2401.09465

Baars BJ (1988) A cognitive theory of consciousness. Cambridge University Press

Beggs JM (2008) The criticality hypothesis: how local cortical networks might optimize information processing. Phil Trans R Soc A 366(1864):329–343. https://doi.org/10.1098/rsta.2007.2092

Balázsi G, Van Oudenaarden A, Collins JJ (2011) Cellular decision making and biological noise: from microbes to mammals. Cell 144:910–925. https://doi.org/10.1016/j.cell.2011.01.030

Baluška F, Mancuso S, Volkmann D (2009) Signaling in plants: an overview of the main signaling networks. New Phytol 181(3):482–492. https://doi.org/10.1111/j.1469-8137.2008.02681.x

Barabási AL (2002) Linked: the new science of networks. Perseus Publishing

Bar-Sagi D, Hall A (2000) Ras and Rho GTPases: a family of molecular switches. Nat Rev Mol Cell Biol 2(12):116–127

Ben-Jacob E, Cohen I, Gutnick DL (1998) Cooperative organization of bacterial colonies: from genotype to morphotype. Annu Rev Microbiol 52:779–806. https://doi.org/10.1146/annurev.micro.52.1.779

Benard H (1901) Les tourbillons cellulaires dans une nappe liquide propageant de la chaleur par convection en régime permanent. Ann Chim Phys 23:62–144

Block N (1992) Begging the question against phenomenal consciousness. Behav Brain Sci 15(2):205–206

Block N (2007) Consciousness, accessibility, and the mesh between psychology and neuroscience. Behav Brain Sci 30(5–6):481–548. https://doi.org/10.1017/S0140525X07002786

Block N (2019) What is wrong with the no-report paradigm and how to fix it. Trends Cogn Sci 23(12):1003–1013. https://doi.org/10.1016/j.tics.2019.12.012

Boroditsky L (2001) Does language shape thought? Mandarin and English speakers' conceptions of time. Cogn Psychol 43(1):1–22. https://doi.org/10.1006/cogp.2001.0748

Briggs WR, Christie JM (2002) Phototropins 1 and 2: versatile plant blue-light receptors. Trends Plant Sci 7(5):204–210. https://doi.org/10.1016/S1360-1385(02)02243-6

Calvo P (2017) What is it like to be a plant? J Consci Stud 24(9–10):205–227

Carruthers P (2019) Human and animal minds: the consciousness questions laid to rest. Oxford University Press, Oxford

Chalmers DJ (1996) The conscious mind, in search of a fundamental theory. Oxford University Press
Chalmers DJ (2009) The character of consciousness. Oxford University Press
Chalmers DJ (2018) The meta-problem of consciousness. J Consci Stud 25(9–10):6–61
Chamovitz DA (2012) What a plant knows: a field guide to the senses. Scientific American/Farrar, Straus and Giroux
Churchland PS (2002) Brain-wise: studies in neurophilosophy. MIT Press, Cambridge
Clark A (1997) Being there: putting brain, body, and world together again. MIT Press
Clark A (2013) Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behav Brain Sci 36(3):181–204. https://doi.org/10.1017/S0140525X12000477
Clark A (2016) Surfing uncertainty: prediction, action, and the embodied mind. Oxford University Press
Damasio A R (1999) The feeling of what happens: body and emotion in the making of consciousness. Harcourt brace
Dehaene S, Changeux J-P (2011) Experimental and theoretical approaches to conscious processing. Neuron 70(2):200–227. https://doi.org/10.1016/j.neuron.2011.03.018
Deacon TW (2012) Incomplete nature: how mind emerged from matter. W. W Norton and Company
Dehaene S (2014) Consciousness and the brain: deciphering how the brain codes our thoughts. Viking
Dennett DC (1991) Consciousness explained. Little Brown and Company
Dennett DC (1995) Darwin's dangerous idea: evolution and the meanings of life. Simon and Schuster
Deacon TW (1997) The symbolic species: the co-evolution of language and the brain. Norton and Company
Eichenbaum H (2017) Memory: from mind to molecules. Oxford University Press
England JL (2013) Statistical physics of self-replication. J Chem Phys 139:121923. https://doi.org/10.1063/1.4818538
Engel AK, Fries P, Singer W (2001) Dynamic predictions: oscillations and synchrony in top-down processing. Nat Rev Neurosci 2(10):704–716. https://doi.org/10.1038/35094565
Friston K, Stephan KE (2007) Free-energy and the brain. Synthese 159(3):417–458. https://doi.org/10.1007/s11229-007-9237-y
Friston K (2018) Does predictive coding have a future? Nat Neurosci 21(6):1019–1021. https://doi.org/10.1038/s41593-018-0200-7
Friston KJ (2023) Consciousness as generative inference. Neurosci Consci. https://doi.org/10.1093/nc/niad016
Flavell JH (1979) Metacognition and cognitive monitoring: a new area of cognitive-developmental inquiry. Am Psychol 34(10):906–911
Franklin KA, Whitelam GC (2007) Light-quality regulation of freezing tolerance in Arabidopsis thaliana. Nat Genet 39(11):1410–1413. https://doi.org/10.1038/ng.2007.34
Friston K (2010) The free-energy principle: A unified brain theory? Nat Rev Neurosci 11:127–138. https://doi.org/10.1038/nrn2787
Gallistel CR (2009) The organization of learning. MIT Press
Gazzaniga MS (2005) The ethical brain. Dana Press
Gibbs JW (1873) On the equilibrium of heterogeneous substances. Trans Conn Acad Arts Sci 3:108–248
Gilbert SF (2010) Developmental Biology (9th ed). Sinauer Associates
Goodwin GW, Michaels GM (2008) Cellular signaling mechanisms. In: Fundamentals of cellular biology (pp 347–368). Elsevier
Graf T, Enver T (2009) Forcing cells to change lineages. Nature 462(7273):587–594. https://doi.org/10.1038/nature08533
Goff P (2019) Galileo's error: foundations for a new science of consciousness. Pantheon Books, New York
Haken H (2006) Synergetics: an introduction. Springer
Harris J (2013) Signaling pathways in cellular adaptation and response. Cell Mol Biol Lett 18(2):146–162. https://doi.org/10.1016/bs.ctm.2019.07.003
Hauser MD, Chomsky N, Fitch WT (2002) The faculty of language: What is it, who has it, and how did it evolve? Science 298(5602):1569–1579. https://doi.org/10.1126/science.298.5598.1569
Heil M, Karban R (2010) Explaining evolution of plant communication by airborne signals. Trends Ecol Evol 25(3):137–144. https://doi.org/10.1016/j.tree.2009.09.010
Hohwy J (2013) The predictive mind. Oxford University Press
Huang CY, Ferrell JE (1996) Ultrasensitivity in the mitogen-activated protein kinase cascade. Proc Natl Acad Sci USA 93(19):10078–10083
Jablonka E, Lamb MJ (2005) Evolution in four dimensions: genetic, epigenetic, behavioral, and symbolic variation in the history of life. MIT Press
Jackendoff R (2002) Foundations of language: brain, evolution, grammar meaning. Oxford University Press
Jeziorski J (2022) Brain organoids, consciousness, ethics and moral status. Semin Cell Dev Biol 144:97–102. https://doi.org/10.1016/j.semcdb.2022.03.020
Kaklauskas A et al (2022) Review of AI cloud and edge sensors, methods, and applications for the recognition of emotional, affective and physiological states. Sensors 22:1–80. https://doi.org/10.3390/s22207824
Kandel ER (2001) The molecular biology of memory storage: a dialogue between genes and synapses. Science 294(5544):1030–1038. https://doi.org/10.1126/science.1067020
Karban R (2008) Plant behavior and communication. Ecol Lett 11(7):727–739. https://doi.org/10.1111/j.1461-0248.2008.01183.x
Kauffman SA (1993) The origins of order: self-organization and selection in evolution. Oxford University Press
Kepa R-M et al (2017) Chemical roots of biological evolution: the origins of life as a process of development of autonomous functional systems. Open Biol 7(4):1–10. https://doi.org/10.1098/rsob.170050
Kelso JAS (1995) Dynamic patterns: the self-organization of brain and behavior. MIT Press
Kondepudi D, Prigogine I (1998) Modern thermodynamics: from heat engines to dissipative structures. Wiley, Chichester
Koseska A, Bastiaens PI (2017) Cell signaling as a cognitive process. EMBO J 36(5):568–582. https://doi.org/10.15252/embj.201695383
Kosslyn SM, Rosenberg RS (2006) Psychology: the brain, the person, the world (6th ed). Pearson Education
Laland KN, Odling-Smee J (2011) Cultural niche construction and human evolution. Philos Trans R Soc B Biol Sci 366(1567):1500–1509. https://doi.org/10.1098/rstb.2010.0306
Lamers J et al (2020) How plants sense and respond to stressful environments. Plant Physiol 182:1624–1635. https://doi.org/10.1104/pp.19.01464
Lane N (2015) The vital question: energy, evolution, and the origins of complex life. W. W Norton and Company
Lehn J-M (2007) From supramolecular chemistry towards constitutional dynamic chemistry and adaptive chemistry. Chem Soc Rev 36:151–160. https://doi.org/10.1039/B616752G
Le Chatelier H (1884) Sur un énoncé général des lois des équilibres chimiques [On a general statement of the laws of chemical equilibria]. Comptes Rendus Acad Sci 99:786–789
Levine J (1983) Materialism and qualia: the explanatory gap. Pac Philos Q 64(4):354–361
Levin M (2023) Bioelectric networks: the cognitive glue enabling evolutionary scaling from physiology to mind. Anim Cogn 26:1865–1891. https://doi.org/10.1007/s10071-023-01780-3

Lifson S (1997) On the crucial stages in the origin of animate matter. J Mol Evol 44:1–8
Lineweaver CH, Egan CA (2008) Life, gravity and the second law of thermodynamics. Phys Life Rev 5:225–242. https://doi.org/10.1016/j.plrev.2008.08.002
Lyon P (2015) The cognitive cell: bacterial behavior reconsidered. Front Microbiol 6:264. https://doi.org/10.3389/fmicb.2015.00264
Mallatt J et al (2021) Debunking a myth: plant consciousness. Protoplasma 258:459–476. https://doi.org/10.1007/s00709-020-01579-w
Maturana HR (1980) Autopoiesis and cognition: the realization of the living. D. Reidel Publishing
Margulis L (1993) Symbiosis in cell evolution: microbial communities in the Archean and Proterozoic Eons, 2nd edn. Freeman W. H.
Matange K, Rajaei V, Schuster G, Hud N, Menor-Salvan C, Capera-Aragonès P et al (2023) Origins of life: chemistry and evolution. https://doi.org/10.26434/chemrxiv-2023-1jrcq-v2
McFall-Ngai M et al (2013) Animals in a bacterial world, a new imperative for the life sciences. Proc Natl Acad Sci USA 110(9):3229–3236
Merindol R, Walther A (2017) Materials learning from life: concepts for active, adaptive and autonomous molecular systems. Chem Soc Rev 46:5588–5619. https://doi.org/10.1039/C6CS00738D
Metzinger T (2009) The ego tunnel: the science of the mind and the myth of the self. Basic Books
Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerter A (2000) The unity and diversity of executive functions and their contributions to complex
Morowitz HJ (1992) Beginnings of cellular life: metabolism recapitulates biogenesis. Yale University Press
Morowitz HJ (2002) The emergence of everything: how the world became complex. Oxford University Press
Nagel T (1974) What is it like to be a bat? Philos Rev 83(4):435–450
Nakagaki T, Yamada H, Tóth Á (2000) Maze-solving by an amoeboid organism. Nature 407(6803):470. https://doi.org/10.1038/35035159
Nehaniv CL, Dautenhahn K (2002) The correspondence problem. In: Dautenhahn K, Nehaniv CL (eds), Imitation in animals and artifacts (pp 41–61). MIT Press. https://doi.org/10.7551/mitpress/9780262042031.003.0003
Noble D (2006) The music of life: biology beyond the genome. Oxford University Press
Pascal R, Pross A (2022) On the chemical origin of biological cognition. Life 12(12):1–12. https://doi.org/10.3390/life12122016
Pascal R, Pross A (2023) Mind from matter: the chemical connection. Isr J Chem 63(7–8):1–7. https://doi.org/10.1002/ijch.202300038
Pascal R et al (2013) Towards an evolutionary theory of the origin of life based on kinetics and thermodynamics. Open Biol 3:130–156. https://doi.org/10.1098/rsob.130156
Pascal R, Pross A (2016) The logic of life. Orig Life Evol Biosph 46:507–513. https://doi.org/10.1007/s11084-016-9494-1
Pascual-Leone A, Amedi A, Fregni F, Merabet LB (2005) The plastic human brain cortex. Annu Rev Neurosci 28:377–401. https://doi.org/10.1146/annurev.neuro.27.070203.144216
Packer AI, Rossetti L, Chien JT (2017) Cognitive behaviors of bacterial communities. J Bacteriol 199(16):e00525-17. https://doi.org/10.1128/JB.00525-17
Pearson JE (1993) Complex patterns in a simple system. Science 261:189–192. https://doi.org/10.1126/science.261.5118.189
Peter A et al (2023) Evolution "On Purpose". https://doi.org/10.7551/mitpress/14642.001.0001
Premack D, Woodruff G (1978) Does the chimpanzee have a theory of mind? Behav Brain Sci 1(4):515–526
Prigogine I et al (1972) Thermodynamics of evolution: physics of biological systems. Phys Today 25(11):23–28. https://doi.org/10.1063/1.3071090
Prigogine I (1984) Order out of chaos: man's new dialogue with nature. Bantam Books
Prigogine I (1978) From being to becoming: time and complexity in the physical sciences. W. H. Freeman
Prigogine I (1978) Time, structure, and fluctuations. Science 201(4358):777–785. https://doi.org/10.1126/science.201.4358.777
Pross A (2012) What is life? How chemistry becomes biology. Oxford University Press
Pross A, Pascal R (2017) How and why kinetics, thermodynamics, and chemistry induce the logic of biological evolution. Beilstein J Org Chem 13:665–674. https://doi.org/10.3762/bjoc.13.66. (**PMID:28487761**)
Prigogine I (1967) Introduction to thermodynamics of irreversible processes. Interscience Publishers
Ramanathan S, Broach JR (2007) Do cells think? Cell Mol Life Sci 64(14):1801–1804. https://doi.org/10.1007/s00018-007-7001-6
Rosenthal DM (2005) Consciousness and mind. Oxford University Press
Sterelny K (2004) Thought in a Hostile world: the evolution of human cognition. Blackwell Publishing
Shapiro JA (2007) Bacteria are small but not stupid: cognition, natural genetic engineering and socio-bacteriology. Stud Hist Philos Biol Biomed Sci 38(4):807–819. https://doi.org/10.1016/j.shpsc.2007.09.010
Shapiro JA (2017) Bacteria as complex, cognizing organisms. In: Evolution and the complexity of Life 93–110 Springer. https://doi.org/10.1007/978-3-319-56148-1-5
Shapiro JA (2021) All living cells are cognitive. Biochem Biophys Res Commun 564:134–149. https://doi.org/10.1016/j.bbrc.2020.08.120
Stewart JE (2019) The origins of life: the managed-metabolism hypothesis. Found Sci 24:171–195. https://doi.org/10.1007/s10699-018-9563-1
Slootbeek AD et al (2022) Growth, replication and division enable evolution of coacervate protocells. Chem Commun 58:11183–11200. https://doi.org/10.1002/adbi.202200180
Shettleworth SJ (1998) Cognition, evolution and behavior. Oxford University Press
Szathmáry E, Gladkih I (1989) Sub-exponential growth and coexistence of non-enzymatically replicating templates. https://doi.org/10.1016/s0022-5193(89)80177-8
Sporns O (2011) Networks of the brain. MIT Press
Sterling P, Eyer J (1988) Allostasis: a new paradigm to explain arousal pathology. In: Fisher S, Reason J (eds) Handbook of life stress, cognition and health. John Wiley and Sons, pp 629–649
Seth AK, Bayne T (2022) Theories of consciousness. Nat Rev Neurosci 23:439–452. https://doi.org/10.1038/s41583-022-00587-4
Solms M (2021) The hidden spring: a journey to the source of consciousness. W. W. Norton & Company, New York
Tennie C, Call J, Tomasello M (2009) Ratcheting up the ratchet: on the evolution of cumulative culture. Philos Trans R Soc Lond B Biol Sci 364(1528):2405–2415. https://doi.org/10.1098/rstb.2009.0052
Tononi G et al (1994) Complexity and coherence: integrating information in the brain. Trends Cogn Sci 1(2):16–22. https://doi.org/10.1016/0960-9822(94)90069-8
Tononi G, Edelman GM (1998) Consciousness and complexity. Science 282(5395):1846–1851
Tononi G (2004) An information integration theory of consciousness. BMC Neurosci 5:42. https://doi.org/10.1186/1471-2202-5-42

Tononi G (2008) Consciousness as integrated information: a provisional manifesto. Biol Bull 215(3):216–242. https://doi.org/10.2307/25470707

Tononi G, Koch C (2015) Consciousness: here, there and everywhere? Philos Trans R Soc Lond B Biol Sci 370(1668):20140167. https://doi.org/10.1098/rstb.2014.0167

Toyota T et al (2009) Self-propelled oil droplets consuming "fuel" surfactant. J Am Chem Soc 131(14):5012–5013. https://doi.org/10.1021/ja809253g

Trewavas A (2003) Aspects of plant intelligence. Ann Bot 92(1):1–20. https://doi.org/10.1093/aob/mcg101

Trefil J et al (2009) The origin of life. Am Sci 97(3):206–214. https://doi.org/10.1511/2009.78.206

Trewavas A et al (2020) Consciousness facilitates plant behavior. Trends Plant Sci 25:216–217. https://doi.org/10.1016/j.tplants.2019.12.015

Tyson JJ, Novak B (2010) Functional motifs in biochemical reaction networks. Annu Rev Phys Chem 61:219–240. https://doi.org/10.1146/annurev.physchem.012809.103457

Turrigiano G (2012) Homeostatic synaptic plasticity: local and global mechanisms for stabilizing neuronal function. Cold Spring Harb Perspect Biol 4(1):a005736

van Duijn M (2017) Interface focus 7:20160158. https://doi.org/10.1098/rsfs.2016.0158

Varela FJ et al (1991) The embodied mind: cognitive science and human experience. MIT Press, London

Volkov AG (2006) Plant electrophysiology: theory and methods. Springer. https://doi.org/10.1007/978-3-540-37843-3

West SA, Griffin AS, Gardner A (2007) Evolutionary explanations for cooperation. Curr Biol 17(16):R661–R672. https://doi.org/10.1016/j.cub.2007.06.004

Wu C et al (2007) Cellular responses to environmental stress. J Cell Biol 179(6):1117–1125. https://doi.org/10.1083/jcb.200708078

Ziemann AE et al (2009) The amygdala is a chemosensor that detects carbon dioxide and acidosis to elicit fear behavior. Cell 139(5):1012–1021. https://doi.org/10.1016/j.cell.2009.10.029

Zhao T (2009) The crucible of consciousness: an integrated theory of mind and brain. Cambridge, MA: MIT Press Scholarship Online, 22 Aug. 2013. https://doi.org/10.7551/mitpress/9780262512848.001.0001

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