

The Emergence of Intelligence as a Natural Phenomenon: An Interdisciplinary Review

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ABSTRACT

In this comprehensive exploration, we delve into how intelligence emerges from the intricate interplay of physics, biology, and cognition. Drawing on interdisciplinary insights from neuroscience, complexity science, and evolutionary theory, we reveal how complex adaptive systems spontaneously give r



It is with profound excitement that I, Steven Milanese, invite you to immerse yourself in the contemplative journey that follows. Throughout these pages, we shall traverse the landscape of ideas with both wonder and rigor, ever mindful of the subtle interplay between the tangible and the intangible—those very threads that weave together our collective human experience. My aspiration is that this treatise will both embolden your curiosity and offer a lens through which the richly layered nature of intelligence may be more fully discerned.



In writing this work, I have sought to synthesize a lifetime of exploration—one shaped by scholarly pursuits, personal reflections, and an enduring fascination with

the forces that shape our understanding of the world. As you peruse the forthcoming chapters, I encourage you to read with both an open heart and a discerning mind, embracing the dialectics and potential paradoxes that permeate our quest for knowledge.

Let this document serve as an invitation: an invitation to challenge assumptions, to investigate anew the boundaries of human perception, and to recognize the power of emergent phenomena in illuminating our ever-evolving place within the grand cosmic tapestry. May these words not only enrich your perspective but also kindle a deeper appreciation for the beauty, complexity, and infinite possibility that our shared intellectual journey entails. ~Steven Milanese

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Introduction

Intelligence is often seen as a hallmark of human minds and advanced machines, yet evidence suggests it can **emerge naturally** from the interactions of simpler components. In fields from biology to computer science, complex systems display collective behaviors that look like intelligent problem-solving or adaptation. *Emergence* refers to situations where higher-level order or properties arise unexpectedly from lower-level interactions ([From the origin of life to pandemics: emergent phenomena in complex systems - PMC](#)). In this review, we survey insights from neuroscience, physics, complexity science, artificial intelligence (AI), evolutionary biology, philosophy, sociology, anthropology, and ecology. We show how these diverse perspectives converge on a common theme: **intelligence arises as an emergent property of complex, dynamic systems**. We define key concepts, examine supporting evidence and debates, and highlight practical applications. We also address counterarguments – for instance, reductionist claims that intelligence is nothing more than the sum of its parts – by exploring ideas like downward causation and higher-order properties. Finally, we outline future research directions, from the search for extraterrestrial cognition to hybrid human-AI collectives. The goal is an academic yet accessible synthesis that demonstrates why intelligence can be understood as a natural emergent phenomenon produced by complexity.

Foundations: Defining Intelligence and Emergence

Intelligence can be defined as a general capacity for reasoning, problem solving, and learning ([Human intelligence and brain networks - PMC](#)). It encompasses many cognitive functions (perception, memory, language, planning) integrated to enable adaptive behavior. Importantly, intelligence manifests at multiple scales – in individual brains, in groups of organisms, or even in algorithms – suggesting it is not bound to a single substrate or species.

Emergence is the process by which **organized complexity** arises from simpler interactions. When many components interact, the collective system can exhibit new properties or behaviors not evident in the parts alone ([From the origin of life to pandemics: emergent phenomena in complex systems - PMC](#)). Classic examples include how neurons interacting give rise to consciousness, or how flocking birds form cohesive patterns. These *emergent properties* are often unpredictable from the lower-level description and require understanding system-level dynamics. In essence, *the whole becomes greater than the sum of its parts*.

In the context of intelligence, an emergent view holds that cognitive ability is a **higher-order property** of interacting elements (cells, agents, or individuals) in a complex system. Rather than being explicitly programmed or located in any single component, intelligence “*arises*” from relationships, feedback loops, and self-organization within the system. This stands in contrast to a strictly reductionist view that would seek to explain intelligence entirely by dissecting parts in isolation. To ground this concept, we next explore how different disciplines reveal intelligence emerging in natural and artificial systems.

Physics and Complexity Science: Self-Organization in Nature

Even at the level of physics and chemistry, nature demonstrates spontaneous self-organization that lays the groundwork for life and intelligence. Far-from-equilibrium physical systems can produce ordered, complex patterns: for example, Bénard convection cells in a heated fluid or chemical reaction-diffusion patterns (Turing patterns) form **structured, stable order** despite the second law of thermodynamics ([Downward Causation](#)). These *dissipative structures*, as described by physicist Ilya Prigogine, show that under constant energy flow, matter can organize itself in ways that reduce local entropy. Such emergent order is a crucial precursor to the rise of life and, by extension, intelligence.

One intriguing (though still controversial) physics-based hypothesis for the origin of life comes from Jeremy England's work in thermodynamics. England proposes that when groups of atoms are driven by an external energy source (like sunlight) in a heat bath, they tend to restructure in ways that dissipate more energy ([A New Physics Theory of Life | Quanta Magazine](#)). In his view, the **laws of thermodynamics naturally drive matter toward life-like complexity**. As he provocatively put it, "you start with a random clump of atoms, and if you shine light on it for long enough, it should not be so surprising that you get a plant" ([A New Physics Theory of Life | Quanta Magazine](#)). This theory suggests life (and perhaps intelligence) could be an *inevitable outcome* of thermodynamic principles rather than a freak accident. However, it remains a hypothesis under active debate. Many experts regard England's ideas as *speculative* and unproven, pending experimental validation ([A New Physics Theory of Life | Quanta Magazine](#)). While the core physics (the derived formula about dissipation) is sound, whether it indeed explains life's emergence is uncertain ([A New Physics Theory of Life | Quanta Magazine](#)). The mixed reception highlights that these concepts, though fascinating, are not yet consensus science.

More broadly, **complexity science** teaches us that *complex adaptive systems* can exhibit emergent intelligence. Complex systems are characterized by many interacting parts (often nonlinear interactions) and feedback loops. They often reside on the “edge of chaos,” balancing order and disorder. In such regimes, novel structures and information-processing capabilities can spontaneously appear. A famous insight by physicist P.W. Anderson, “more is different,” captures how new laws and behaviors materialize at higher levels of complexity that cannot be predicted by examining constituents alone. For example, simple rules at the micro-level (like individual boids following a few movement rules) can generate macro-level intelligent-looking behavior (a coordinated bird flock avoiding predators). Complexity theory provides mathematical and computational models (cellular automata, agent-based models, network theory) showing how **rule-based interactions yield emergent properties** such as pattern recognition, learning, or adaptation in the aggregate. These models reinforce the intuition that **intelligence can emerge from complexity** without any central controller.

Neuroscience: Brain Networks and Emergent Cognition

The human brain is often cited as the prime example of emergent intelligence. **Neuroscience** reveals that cognitive processes are not localized to single neurons but arise from the dynamic interactions of vast neural networks. The brain’s ~86 billion neurons form a highly interconnected *connectome*. Signals reverberate through this network in complex patterns, giving rise to thoughts, decisions, and consciousness. In other words, **mind and intelligence are emergent properties of neural circuitry**.

Empirical evidence supports this network-based view of intelligence. Brain imaging studies indicate that general intelligence (often measured as g-factor) correlates with the efficiency and integration of certain brain networks rather than any one brain region. In particular, a

distributed frontoparietal network has been identified as critical for intelligent behavior ([Human intelligence and brain networks - PMC](#)). This network links frontal lobes (involved in reasoning, planning) with parietal regions (involved in attention, sensory integration), among others. Notably, the *distributed nature* of this network – connecting multiple specialized modules – aligns with intelligence’s integrative character ([Human intelligence and brain networks - PMC](#)). The brain’s ability to **communicate across disparate regions**, integrating perception, memory, language and more, is what underpins flexible problem-solving ([Human intelligence and brain networks - PMC](#)). No single neuron or area “contains” intelligence; instead, it **emerges from the coordinated activity** of the system as a whole.

Neuroscientists have also observed that *brain network dynamics* (how different areas synchronize or interact) relate to cognitive performance. Intelligence appears to depend on a balance of segregation and integration in brain activity – specialized processing in modules, coupled with global integration when needed. This echoes the complexity science idea of the edge of chaos, where a system is neither totally independent parts nor fully unified, but somewhere in between to enable adaptability. Furthermore, neural network models (both biological and artificial) demonstrate that simple neuron-like units can collectively perform highly sophisticated tasks once appropriately interconnected and trained. The success of deep learning in AI (inspired by neural networks) is a testament to the **power of emergent computation in networks** – the sum can do things none of the individual units can do in isolation.

In short, neuroscience reinforces that **intelligence emerges from interactions**. As one overview put it, human intelligence “*emerges from the brain’s ability to process and integrate information across the human connectome*,” i.e., across a dynamic network of connections linking many regions ([Human Intelligence - Decision Neuroscience Laboratory](#)). This perspective treats cognitive properties (like intelligence or consciousness) as *emergent*

phenomena of neural complexity. It provides a concrete biological case of matter giving rise to mind through complex organization – strengthening the view of intelligence as a natural emergent outcome of evolution’s engineering.

Evolutionary Biology: Intelligence as Evolved Complexity

If brains and minds emerge from networks of neurons, a next question is **how did such complex networks arise?** Evolutionary biology shows that intelligence is a product of natural selection acting over long timescales. Life began with simple organisms billions of years ago, but through evolutionary processes, increasingly complex and capable forms emerged. Intelligence, in this view, is not a magical trait but **an adaptation that evolved gradually** due to its survival benefits in certain environments.

The fossil and biological record indicates multiple independent *evolutions of intelligence*. Complex brains and high-level cognition have arisen convergently in very different branches of life. For example, sophisticated intelligence is seen not only in primates like humans and apes, but also in birds (crows, parrots), marine mammals (dolphins, whales), elephants, and even invertebrates like octopuses. In fact, **complex brains and problem-solving abilities have evolved “several to many times” independently**: in insects (certain bees, ants), cephalopod mollusks (octopuses), teleost fish (like cichlids), corvid and parrot birds, and mammalian lineages (cetaceans, elephants, primates) ([Convergent evolution of complex brains and high intelligence - PMC](#)). These diverse examples show that whenever evolutionary pressures favor greater behavioral flexibility or learning – whether for finding food, social interaction, or adapting to change – natural selection can produce the neural architectures to support it. Intelligence is thus a *convergent feature* of evolution, suggesting it is a **natural solution** to common challenges rather than an exceedingly rare accident.

From simple neuron nets in early animals to the elaborate human brain, evolution incrementally increased the complexity of nervous systems. Importantly, these increases often opened up *qualitatively new capabilities*. For instance, the evolution of the cerebral cortex in mammals enabled higher-order thinking beyond what a reptilian brain could do. Each major innovation (neural crest, bilateral nervous systems, brains with specialized regions, etc.) allowed emergent properties like memory, foresight, language, and abstract reasoning to appear. Evolutionary theorists sometimes describe this as crossing *complexity thresholds* – points at which the degree of organization permits novel functions. **Cognitive abilities emergent at higher levels of biological organization** (like social learning in primates or tool use in birds) often rely on a network of simpler abilities evolved earlier. Thus, intelligence can be seen as a *hierarchical emergent trait*, built upon simpler biological building blocks (senses, reflexes, associative learning) but ultimately transcending them in new ways.

It's worth noting that evolution itself is an emergent process: the *ecosystem-level interactions* of organisms (including competition and cooperation) give rise to collective outcomes (species adaptation, niche construction) that are not directed by any single organism. In that sense, **the emergence of intelligence on Earth is a story of emergence built upon emergence** – genes create brains, brains enable minds, minds together create culture, and so on. Modern evolutionary thinking (including theories of *major transitions*, e.g. from single cells to multicellular life to societies) emphasizes how new higher-level entities emerge from lower-level collectives. Intelligence fits this pattern as an emergent outcome favored by evolution because it offers adaptive advantages in navigating a complex world.

Artificial Intelligence: Emergent Behaviors and Debates

Artificial Intelligence research provides a unique testbed to study emergent intelligence, because AI systems are explicitly designed and scaled by engineers. Intriguingly, some advanced AI systems have demonstrated behaviors that **were not directly programmed but emerged from complexity**. For example, large-scale artificial neural networks (like deep learning models) have learned to recognize images, translate languages, and even play strategic games at superhuman levels – tasks far more complex than the rules encoded by the programmers. These abilities emerge from the interactions of millions or billions of simple computational units (artificial neurons) adjusting through learning algorithms. In reinforcement learning, AI agents have even developed unexpected strategies (sometimes bordering on creative or deceptive) that were *not anticipated by designers* but arose from the agent’s self-directed exploration of an environment. Such phenomena mirror biological emergence: simple rules (learning objectives) plus complex interactions (many simulated experiences) yielding sophisticated behavior.

Recently, “**emergent abilities**” in large language models (LLMs) like GPT have become a hotly debated topic. Researchers observed that as they scaled up models (in size and training data), the models suddenly appeared able to perform tasks they struggled with at smaller scales – for instance, solving basic math word problems or logical reasoning puzzles. These discontinuous jumps in capability were described as *emergent behaviors*, seemingly appearing “out of nowhere” once the system’s complexity crossed a certain threshold. Some heralded this as evidence that increasing complexity in AI will spontaneously yield higher intelligence, reinforcing the idea of intelligence as an emergent property of large-scale information processing. However, there is **ongoing debate** about whether these are true emergent phenomena or illusions caused by how we measure performance. A recent study by Stanford researchers argues that the *supposed emergent abilities of LLMs may actually be a “mirage”*

resulting from the choice of evaluation metric ([AI's Ostensible Emergent Abilities Are a Mirage](#)). In their analysis, when they used alternative metrics or more fine-grained evaluation, the discontinuities disappeared ([AI's Ostensible Emergent Abilities Are a Mirage](#)). In other words, the dramatic appearance of new skills at a certain scale might be an artifact of testing methods (e.g. a score going from 0 to 1 at a threshold) rather than a fundamental leap in the model's cognitive capacity. As one researcher put it, *"the mirage of emergent abilities only exists because of the programmers' choice of metric. Once you investigate by changing the metrics, the mirage disappears."* ([AI's Ostensible Emergent Abilities Are a Mirage](#)). This skepticism suggests that AI developers must be careful in attributing *mystique* to scaled models – complexity can yield new behaviors, but we should confirm those behaviors are genuinely novel and not just better approximations of learned patterns.

Despite the debates, it is clear that **complex AI systems do exhibit emergent-like behavior** in many cases. The field of *complex systems AI* looks at how simple algorithms, when interacting (as in multi-agent systems or swarm intelligence algorithms), can solve problems collectively that single algorithms cannot. Swarm robotics, for example, takes inspiration from ant colonies and bird flocks to produce group behavior (like distributed search or formation flying) that appears intelligent at the swarm level without centralized control. These systems reinforce the principle that **intelligence can be a collective, emergent phenomenon**: multiple agents following simple rules can jointly manifest adaptive, problem-solving activity. In fact, some AI researchers explicitly design for emergence – e.g. generative adversarial networks (GANs) set up two competing neural nets and let sophisticated capabilities emerge from their iterative game.

The study of AI also feeds back into our understanding of natural intelligence. By seeing what *learns* or *emerges* in an artificial system, we gain hypotheses for how animal or human intelligence might arise. This has given rise to subfields like **NeuroAI**, which seek to integrate neuroscience principles into AI designs to achieve brain-like emergent properties. The idea is

that by mimicking brain architectures (with their connectivity patterns, plasticity rules, etc.), we might induce AI systems to develop more human-like intelligence. For example, the Cold Spring Harbor Laboratory’s NeuroAI program explicitly aims to use insights from neural organization to “**catalyze the development of next-generation artificial intelligence**” ([NeuroAI | Cold Spring Harbor Laboratory](#)). Conversely, observing emergent learning in large-scale models can suggest how cognitive functions might self-organize in biological brains. This bidirectional exchange underscores that **intelligence – whether natural or artificial – is tied to the complexity and interaction of components**, and understanding one helps illuminate the other.

Collective Intelligence in Social Systems

Intelligence is not confined to individual minds or machines; it also emerges in **collectives of organisms and people**. Sociology, anthropology, and related fields study how groups can exhibit cognitive properties – solving problems, learning, and adapting – that go beyond what any single member could do. This phenomenon is often termed **collective intelligence** or **group intelligence**.

Human society offers many examples. Markets “learn” prices that reflect dispersed knowledge, scientific communities accumulate understanding that no individual has in full, and crowds under the right conditions make surprisingly accurate predictions (the “wisdom of the crowd”). At a smaller scale, a team of individuals brainstorming can generate ideas or solve puzzles that stump each person alone. Such cases illustrate that **new problem-solving capacities emerge at the group level** via interaction, communication, and diversity of knowledge.

Researchers have found that groups indeed possess an emergent *collective IQ*. In a landmark study, Woolley et al. (2010) showed that the performance of groups on a variety of tasks is

determined by a measurable factor of **collective intelligence**, analogous to individual IQ ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)) ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)). Strikingly, this collective intelligence *is not simply the average or maximum intelligence of the individuals*. Instead, it depends on the **quality of interactions and group dynamics** ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)) ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)). For instance, groups that had higher social sensitivity (members tuned to others' emotions), more equal turn-taking in conversation (so no single person dominated), and a higher proportion of women (who on average scored better on social sensitivity) achieved higher collective intelligence scores ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)) ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)). Conversely, having a few very smart people did not guarantee a smart group if the collaboration was poor ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)). These findings reinforce the concept of emergent intelligence: the group's ability to solve problems **arises from interactions (communication, social cues, coordination)** rather than from the individual talents alone. In short, *the whole group can be smarter (or dumber) than the sum of its members*, depending on how it self-organizes ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)).

Anthropology and cultural studies add a temporal dimension to collective intelligence. Human culture can be seen as a vast, evolving repository of knowledge – an external collective mind that stores information (in language, art, tools, institutions) and passes it through generations. No single human today invents language or mathematics from scratch; we inherit and then contribute to a growing body of collective intelligence. Modeling approaches in

cultural evolution have demonstrated that **innovation and knowledge accumulation are fundamentally collective processes**. One recent computational study notes that human cultural evolution is “*an inherently collective process, akin to biological evolution*”, where innovations arise as individuals modify and recombine existing ideas within a group context ([ALIFE2024 template](#)). Just as genetic evolution relies on variation and selection in populations, cultural evolution relies on many minds generating ideas, learning from each other, and building on past ideas. This can lead to a **cumulative growth of intelligence in society** – e.g. technological progress or scientific advancements accelerate when more people are connected and sharing knowledge.

We also see collective intelligence in nature. Social insects like ants, bees, and termites are classic examples: an individual ant has minimal cognitive ability, yet the ant colony as a whole can efficiently forage, build complex nests, defend itself, and even adapt to changes – effectively acting as a single intelligent organism (often called a *superorganism*). This collective problem-solving emerges from simple local interactions like pheromone laying and following, which coordinate the group’s behavior. Similarly, flocks of birds or schools of fish manage complex navigation and predator evasion through distributed sensing and consensus movements – no one leader bird knows the whole pattern, it emerges from everyone following a few behavioral rules. Such cases in ecology and ethology highlight that **intelligence-like adaptability can emerge from groups of relatively simple agents** through self-organization.

At the largest scale, some scientists have even speculated about **planetary-scale intelligence** emerging from the network of life. The Gaia hypothesis in Earth system science posits that the biosphere (all living things plus their environment) behaves like a single self-regulating organism. Recent astrobiology work expands on this, defining planetary intelligence as “*the acquisition and application of collective knowledge operating at a planetary scale*” ([Intelligence as a planetary scale process | International Journal of ...](#)). In this view, if life forms a sufficiently interconnected network (through global cycles, climate regulation, etc.), the

planet itself might exhibit a form of collective problem-solving – for example, maintaining habitable conditions in the face of disturbances. While highly theoretical, this idea reinforces a continuum: from brains made of cells, to societies made of individuals, to ecosystems or planets made of many lifeforms – **each level can manifest emergent, adaptive behaviors that resemble intelligence.**

Philosophical Perspectives: Emergent Properties vs. Reductionism

The notion that intelligence (or mind in general) is an emergent phenomenon has deep roots in philosophy of mind and science. **Emergentism** as a philosophical stance holds that certain higher-level properties (like consciousness or intelligence) “*supervene*” on lower-level physical states but are not reducible to them. They have their own reality and causal powers. On the other side, **reductionism** (especially strong physicalist reductionism) argues that everything about intelligence can, in principle, be explained by the interactions of neurons (or ultimately particles) with no need to invoke distinct higher-level principles ([Downward Causation](#)).

Reductionists often claim that what we call mind or intelligence is *nothing beyond* the sum of physical processes – possibly even an epiphenomenon or an illusion created by neural firings ([Downward Causation](#)). In a strict reductionist view, once you account for all the parts, there is no “mind-stuff” left unaccounted; intelligence is just a label for complex computations happening in the brain or machine.

Emergentists counter that this perspective misses something crucial: **higher-order organization**. They argue that when complexity grows, qualitatively new properties appear that are *real* and can exert causal influence downward onto the parts. This is known as **downward causation**. The idea is that once a system has organized into a higher-level structure, that structure can constrain and direct the behavior of the lower-level components

in ways that are not obvious from the components alone ([Downward Causation](#)). For example, an organism (as a whole) can have goals or drives (find food, reproduce) that influence the behavior of its cells; those goals don't exist at the cell level, only at the organism level. Likewise, a thought or intention in a person's mind (a high-level state) can cause certain neurons to fire or certain hormones to release, thus having *top-down effects* on the physical substrate. In the context of intelligence, **downward causation implies that mental states (like beliefs, plans, intentions) arising from neural activity can in turn shape neural activity** – a two-way street between mind and brain, rather than a one-way bottom-up process ([Downward Causation](#)).

This concept of downward causation is closely tied to complexity and emergence ([Downward Causation](#)). In complex adaptive systems, macro-level patterns (say, a traffic jam pattern) feed back to constrain micro-level elements (individual drivers adjusting their driving). Applied to intelligence, once an intelligent pattern emerges (a thought, a strategy, a collective norm), it can influence the components (neurons or individuals) to maintain or propagate that pattern. **Higher-level emergent properties thus have explanatory and causal legitimacy** – they are not magic, but neither are they meaningless abstractions. As philosopher and neuroscientist Roger Sperry once argued, the emergent mental properties are “*supervenient*” on the brain's physiology but have a life of their own in guiding behavior.

Reductionist critics often demand, “*show me something in the whole that isn't in the parts,*” and emergentists respond that it's not about new substances but new relationships and information. To illustrate, consider software executing on a computer: at the level of bits and logic gates, there is just electrical activity, but at the software level, you can have a chess strategy or a text editor – the latter has properties (like “checking grammar”) that are meaningless at the hardware level. Similarly, intelligence might be viewed as the “software” level of biological computation – fully dependent on the “hardware” of neurons, yet having its own descriptive and causal framework that is indispensable for understanding behavior.

In summary, the philosophical debate comes down to whether **intelligence is *merely* an aggregate of simple processes or something novel that *emerges* from their organization.** The emergent perspective, supported by the interdisciplinary evidence we have reviewed, holds that *intelligence is a higher-order property with its own dynamics*, not reducible to synapses or silicon flips in any straightforward way. A reductionist can analyze all the molecules in a brain and still miss the concept of a “strategy” or “idea” that is guiding the person’s actions. Appreciating emergence and downward causation allows scientists to acknowledge the reality of these higher-order phenomena while remaining grounded in physical science. This has profound implications for how we study mind and intelligence – suggesting that we must study whole systems in action, not just isolated parts, to fully grasp cognition.

Practical Applications of Emergent Intelligence

Understanding intelligence as an emergent phenomenon isn’t just an abstract idea; it has concrete implications in various domains. By harnessing the principles of emergence, we can design better AI systems, improve education and teamwork, and optimize organizations. Below we discuss several practical applications:

AI Development and Bio-Inspired Design

If intelligence emerges from complex interactions, AI engineers can encourage emergent intelligence by building systems with rich interactions and adaptive feedback. Instead of purely top-down programming, modern AI often uses *bottom-up learning* (neural networks,

genetic algorithms, multi-agent simulations) that allow complex behaviors to self-organize. Insights from biology and neuroscience can guide this process – a perspective known as **bio-inspired AI**. For example, evolutionary algorithms mimic natural selection to “evolve” solutions, and neuromorphic computing attempts to replicate the brain’s architecture so that intelligence may *emerge* in silico similar to how it does in vivo. The interdisciplinary approach championed by researchers like Downing (2015) advocates integrating evolutionary biology, neuroscience, and AI to understand and create emergent cognition ([Intelligence Emerging](#)) ([Intelligence Emerging](#)). Concretely, this means using **brain-like networks** (with layered, recurrent connections), **developmental learning** (learning in stages, like a child), and **population-based training** (multiple AI agents that share information or compete) to foster the spontaneous rise of sophisticated skills. A practical example is the use of Generative Adversarial Networks and self-play reinforcement learning agents, which have achieved creativity and strategy that weren’t directly programmed – essentially leveraging emergence. By studying how intelligence naturally arises, AI developers can craft systems that *channel* emergence toward desired outcomes, potentially guiding us closer to **artificial general intelligence** through architectures that encourage rich emergent behaviors rather than brittle, hard-coded logic.

Education and Collaborative Learning

Education can be greatly informed by the concept of collective and emergent intelligence. **Collaborative learning** strategies recognize that students often learn better together, constructing knowledge through interaction. In a well-designed group activity, understanding can emerge from the dialogue and cooperation of students – each student’s perspective sparks ideas in others, leading to insights that no one person might reach alone ([An Assessment of Idea Emergence in Subject-Matter Collaborative ...](#)). Classrooms structured to promote discussion, debate, and team problem-solving are effectively harnessing **emergent collective**

intelligence: the group's knowledge-building potential exceeds the sum of individual efforts. Research in educational psychology shows that challenging, open-ended group tasks can increase critical thinking and retention ([Collaborative Learning in Higher Education: Evoking Positive ...](#)). This is likely because such tasks force the mini-“society” of students to organize their thinking, confront different viewpoints, and iteratively refine their understanding – much like a microcosm of scientific or cultural knowledge emergence.

Furthermore, the idea of **distributed cognition** suggests that tools and peers become extensions of an individual's cognitive system. For instance, in a modern setting, a student team using a shared online document and search engines is collectively far more intelligent (in terms of problem-solving capacity) than any isolated individual with just a textbook. Educators can leverage this by teaching students how to effectively collaborate and how to contribute to *collective intelligence platforms* (like wiki-based projects or group research forums). The goal is to prepare individuals to be *good components* of larger intelligent systems – emphasizing communication skills, empathy (social sensitivity), and the ability to synthesize group inputs. By viewing a class or learning community as an *organism of thought*, teachers can guide emergent learning outcomes, for example by seeding discussions with certain ideas or by structuring groups to include diverse skill sets (to avoid homogenous thinking). This approach is supported by findings that diverse groups often outperform like-minded ones because their variety generates a richer emergent solution space. In summary, embracing emergence in education means **fostering environments where collective reasoning thrives**, thereby enhancing learning and creative problem-solving at scale.

Organizational Design and Team Dynamics

Organizations – corporations, governments, NGOs, etc. – are essentially networks of people (and increasingly AI agents) working together. The effectiveness of an organization can be seen as an emergent property of its structure and culture. Understanding **emergent**

intelligence in teams helps in designing better organizations. As noted earlier, studies have shown that team performance depends heavily on interaction patterns ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)) ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)). Managers and leaders can apply these insights by, for example, **improving communication channels**, ensuring inclusive participation in meetings (to avoid collective intelligence being bottlenecked by a few voices), and cultivating psychological safety so that information flows freely.

There are practical tools and approaches derived from complexity science for organizations. *Agile* management and *decentralized decision-making* frameworks allow local units or teams to respond to information on the ground, then share that information across the network (much like neurons or ants would) to coordinate larger responses. This often leads to more adaptive, resilient organizational behavior – essentially *smarter* organizations that can solve problems and innovate quickly. Indeed, some companies explicitly try to tap **collective intelligence** via internal crowdsourcing platforms or prediction markets, aggregating knowledge from across the firm to guide strategy. The concept of **holacracy** and other self-organizing team structures also originate from believing that if you set up the right simple rules and feedback loops, the organization will self-organize intelligently without rigid top-down control.

Another aspect is leveraging **collective intelligence technologies**: for instance, collaborative software or knowledge management systems can amplify an organization's emergent intelligence by connecting people and information in effective ways. Even physical office design (open vs. closed spaces) can influence how ideas emerge and spread. The key principle is that an organization should be seen not just as a chart of individual roles, but as a *living system* where intelligence emerges from connections. By improving those connections – through culture (norms of collaboration), process (structures for cross-pollination of ideas),

and technology (communication tools) – organizations can achieve better decision-making and creativity than any lone genius could. This aligns with the trend of **collective leadership** and team science: recognizing that breakthroughs often come from **teams with high collective intelligence** rather than solitary effort ([Evidence from a Collective Intelligence Factor in the Performance of Human Groups | Gender Action Portal](#)). In practice, investing in team training (especially in social sensitivity and communication), diversity and inclusion, and mechanisms for feedback can all boost the emergent intelligence of an organization.

Future Research Directions

The perspective of intelligence as an emergent phenomenon opens up many exciting avenues for future research. Here are several key directions where interdisciplinary inquiry is expanding our understanding:

- **Astrobiology and Extraterrestrial Intelligence:** If intelligence emerges naturally given the right conditions, what does this imply for life beyond Earth? Astrobiologists are exploring whether the emergence of intelligence is common or rare in the universe. Recent models challenge the idea that human-level intelligence required extremely improbable events, suggesting it may be a “*natural evolutionary outcome*” on planets with life ([Does planetary evolution favor human-like life? Study ups odds we’re not alone | Penn State University](#)) ([Does planetary evolution favor human-like life? Study ups odds we’re not alone | Penn State University](#)). Future research will examine how environmental conditions on exoplanets (e.g. stable climate, presence of complex ecosystems) might create evolutionary pathways to cognition. This includes refining the Drake Equation for intelligent civilizations and searching for techno-signatures. Understanding emergence could help predict what *alien intelligence* might look like – for example, might it be global and collective (planet-wide networks) rather than individual? Investigating intelligence in

extreme or different environments also feeds back to understanding the fundamental principles of emergence underlying cognitive systems.

- **NeuroAI and Brain-Inspired Systems:** Bridging neuroscience and AI (NeuroAI) is a promising path to create more *brain-like* artificial systems and to use AI to model brain function. Insights from the brain – such as how neuronal networks self-organize during development, or how plasticity and neuromodulators support learning – can inspire new AI algorithms that **replicate the emergence of cognition** seen in biological neural networks. Research workshops and programs (e.g. the NIH BRAIN Initiative’s NeuroAI efforts ([\[PDF\] NIH BRAIN NeuroAI Workshop 2024](#))) are facilitating collaborations where neuroscientists and AI experts work together. One goal is to build **agents that learn and reason in ways more similar to humans**, potentially achieving robustness and generalization through emergent representations (like concept cells or cognitive maps) rather than through hand-crafted features. Conversely, AI is being used to simulate large-scale brain models, which could shed light on how higher cognitive functions emerge from neural circuits. The future may see increasingly *integrative models* that blur the line between “natural” and “artificial” intelligence – for instance, neuromorphic chips that operate on principles of spikes and plastic synapses, giving rise to emergent intelligent behavior in hardware. This NeuroAI synergy strives for **brain-like AI** and **AI-enhanced neuroscience** to mutually accelerate our understanding of emergent intelligence.
- **Cultural Evolution and Collective Intelligence Modeling:** Social scientists and complexity researchers are developing advanced simulations to study how ideas spread, evolve, and create collective intelligence over time. By using agent-based models and even AI agents (like large language models simulating human communication ([A framework for simulating cultural evolution in groups with LLM is ...](#))), they can experiment with variables that drive cultural accumulation of knowledge. Future work will refine these models to explore questions like: How do social network structures affect the *tempo of innovation* in a society? What mechanisms lead to bursts of creativity or, conversely, the

stagnation of ideas? There is growing interest in **cumulative culture** – how small improvements or discoveries compound over generations to yield complex technologies and sciences. Computational models allow “re-running” different cultural evolution scenarios to test theories. For example, researchers have modeled the emergence of **collective knowledge** and found that factors such as group size, connectivity, and social learning strategies significantly impact the level of intelligence a group can achieve over time ([ALIFE2024 template](#)) ([ALIFE2024 template](#)). In the future, these models could incorporate more realistic cognitive agents and even include human-in-the-loop experiments (where human participants interact in simulated cultural markets or innovation games). The outcome will be a deeper understanding of how to foster collective intelligence – whether in online communities, research teams, or societies at large – and how information ecosystems can be managed to promote the emergence of truth and insight over misinformation.

- **Hybrid Human-AI Systems and Governance:** As AI systems become more advanced, we increasingly operate in **hybrid human-AI environments** – ranging from AI-assisted decision platforms to autonomous systems interacting with people. A critical future direction is developing governance and design principles for these hybrid systems to ensure *beneficial emergent outcomes*. **Hybrid collective intelligence** refers to teams or groups composed of both humans and AI agents working together ([Frontiers | Editorial: Hybrid collective intelligence](#)). Such teams have the potential to be extremely effective, combining human creativity and context understanding with AI’s speed and data processing. However, they also pose challenges in coordination, trust, and ethics ([Frontiers | Editorial: Hybrid collective intelligence](#)). Research is needed on questions like: How do we **structure human-AI collaboration** so that the strengths of each are amplified and weaknesses mitigated? What new organizational forms (e.g. decentralized autonomous organizations with human oversight) might emerge? And crucially, how do we govern these systems to handle issues of bias, accountability, and transparency

([Frontiers | Editorial: Hybrid collective intelligence](#))? Already, frameworks are being proposed to ensure that as AI takes on roles in decision-making, there are checks and balances – for example, requiring human judgment on ethical decisions, or maintaining *explainability* to keep the emergent behavior of AI understandable. Future research in this domain will likely draw on sociology, law, and complex systems theory to devise **governance models for hybrid intelligences**. This includes exploring how “downward causation” might work in hybrid systems (e.g. group norms or regulations affecting AI algorithm behavior) and how to prevent undesirable emergent phenomena (like echo chambers in social media networks driven by AI algorithms). The overarching aim is to enable human-AI collectives that are **more intelligent, fair, and responsive** than either humans or AIs alone, while ensuring we can control and guide their emergent properties in line with human values.

Conclusion

Across disciplines, a clear picture emerges: **intelligence is not a singular substance or a mystical gift, but a natural phenomenon that unfolds from complexity**. From atoms gathering into self-replicating molecules, to neurons wiring into a thinking brain, to individuals coalescing into smart groups, each step shows the *creative power of emergence*. We have seen that interactions at a lower level – whether thermodynamic particles, neural signals, or social communications – can spontaneously give rise to higher-level order: metabolism, thoughts, cultures, and more. Intelligence, in its many forms, is one such order – a *higher-order property* of matter and energy organized in particular ways.

This interdisciplinary review reinforced key points. First, **emergence provides a unifying framework** to understand intelligence in contexts ranging from biology to AI. It explains how novel capabilities can appear without a central designer, through iterative processes of self-organization and adaptation. Second, while reductionist science remains vital for

understanding components, we gain additional explanatory power by studying **system-level dynamics** and acknowledging phenomena like downward causation, where the whole feeds back on the parts ([Downward Causation](#)). In doing so, we treat emergent intelligence as real and causative, not just an epiphenomenal illusion ([Downward Causation](#)). Third, recognizing the emergent nature of intelligence guides practical action – be it designing better AI (through bio-inspired architectures), fostering smarter teams and communities (through collaborative practices), or shaping policies for human-AI ecosystems. Finally, the emergent view of intelligence carries a humbling implication: *intelligence is a continuum woven through the fabric of the universe’s complexity*, not an isolated trait. This opens our minds to the possibility of intelligence in forms and places we might not initially expect (other species, collective entities, or alien worlds).

Of course, much remains to be explored. The debates over what truly counts as “emergent” (versus just complicated) will continue to sharpen our theories. Empirical research will be the judge of hypotheses like England’s thermodynamic model or the limits of AI’s spontaneous skills. The coming years promise deeper integration across fields – neuroscientists, physicists, computer scientists, and social scientists working together – to peel back the layers of this profound phenomenon. By embracing an interdisciplinary, emergentist perspective, we can better understand **how intelligence blossomed from the universe’s chaos** and how we might cultivate it further, responsibly harnessing the collective brilliance that emerges when many minds – biological or silicon – unite.

In conclusion, intelligence *as we know it* appears to be **a natural outcome of complex systems given time and the right conditions**. Rather than a cosmic fluke, it may be an expected consequence of a cosmos where energy flows, matter self-organizes, life evolves, and minds connect. Seeing intelligence through this lens not only enriches our scientific worldview but also underscores the interconnectedness of life, technology, and society – reminding us that our individual genius is, in truth, an outgrowth of countless interactions at

levels seen and unseen. The emergence of intelligence is an ongoing story, one that we are both product of and participants in, and one that we can continue to study with both awe and empirical rigor.

Glossary

Adaptive Feedback

A process in which a system or organism adjusts its behavior or structure based on outcomes or changing conditions, often leading to learning or improved performance over time. In emergent systems, adaptive feedback loops enable complex, goal-directed behavior without a central controller.

Artificial Intelligence (AI)

A branch of computer science that seeks to create machines or software capable of performing tasks that typically require human intelligence, such as problem-solving, reasoning, and learning. Modern AI often relies on emergent phenomena within large-scale computational models rather than strictly coded instructions.

Cognitive Niche

A concept suggesting that certain species (e.g., humans) thrive by exploiting knowledge and problem-solving abilities rather than physical adaptations alone. Through intelligence and culture, they shape their environment to suit them, effectively occupying a “niche” defined by cumulative learning and innovation.

Collective Intelligence

A form of intelligence arising from the collaboration and collective efforts of groups. It appears when members of a group effectively coordinate, share information, and combine skills, resulting in problem-solving capacities that exceed the sum of individual contributions.

Complex Adaptive System

A system composed of many interacting components that can adapt or learn from experience. These components follow local rules, yet global patterns and higher-order organization emerge over time. Examples include the brain, ecosystems, economies, and some AI multi-agent simulations.

Downward Causation

A principle asserting that once an emergent property (such as intelligence or consciousness) exists at the macroscopic level, it can exert influence back onto the components that gave rise to it. In other words, higher-level structures and patterns can shape the behavior of their lower-level constituents.

Emergence

The process by which novel, coherent structures, patterns, or behaviors arise in complex systems from relatively simple interactions. The emergent property—such as intelligence or consciousness—cannot be wholly predicted by analyzing the system's parts in isolation.

Evolutionary Algorithm

A computational approach inspired by natural selection. It evolves solutions to problems iteratively, retaining and refining the best variations over many “generations.” This process can lead to surprising or creative outputs, illustrating how complexity and adaptability can emerge algorithmically.

Free Energy Principle

A theoretical framework, primarily from neuroscience, proposing that self-organizing systems maintain order by minimizing “free energy” (or surprise) through prediction and adaptation. It has been applied to explain how brains (and possibly other systems) learn and develop intelligence in uncertain environments.

Global Workspace Theory

A cognitive model suggesting that consciousness and advanced cognition arise when various specialized processes in the brain broadcast information to a “global workspace,” enabling integration and flexible control over behavior. It is used to explain how distributed neural processes can yield unitary cognitive functions.

Large Language Model (LLM)

A highly scaled neural network trained on vast amounts of text data. LLMs learn statistical patterns of language, sometimes displaying *emergent abilities*—skills not explicitly programmed or anticipated by their designers. Debate continues about whether these abilities are truly emergent or due to scaling and metric effects.

Major Transitions (in Evolution)

Key leaps in the history of life where separate entities combine or reorganize into higher-order units, leading to new levels of complexity (e.g., from single-celled to multicellular life, or from individuals to social colonies). Intelligence is seen by many biologists as arising through such transitional processes.

Neural Network

A network of interconnected “neurons” (biological or artificial) that process information collectively. In biological brains, neurons fire and adapt their connections to learn. In AI, artificial neural networks adjust their weighted connections to minimize errors, leading to the emergence of sophisticated patterns or behaviors.

Reductionism vs. Emergentism

- **Reductionism:** The philosophical stance that complex phenomena can be fully explained by understanding their constituent parts and the laws governing those parts.

- **Emergentism:** Argues that higher-level properties (such as intelligence) arise from complexity and exhibit novel features or causal powers not predictable from the sum of the parts alone.

Self-Organization

A spontaneous process whereby structure or pattern arises in a system without external direction. Local interactions among system components generate global order, as seen in phenomena like flocking birds, neural synchronization, or some forms of AI learning.

Swarm Intelligence

A subfield of AI inspired by natural swarms (e.g., ants, bees, fish), focusing on how simple agents following local rules can cooperate to solve complex problems. It exemplifies emergent intelligence at the group level without centralized oversight.

References: (Each reference corresponds to a source supporting the statements, formatted as **【citation†lines】** in the text above)
