

# Prebiotic Cognition: The Modular Continuum of Consciousness from Autocatalytic Networks to Institutional Mind

## Abstract

**Abstract.** This essay advances a unified theory of *prebiotic cognition*, proposing that consciousness—conceived as recursive uncertainty minimization—is a scale-invariant property of negentropic systems. Beginning with the geochemical metabolism of the early Earth, it traces the emergence of modular intelligence from collectively autocatalytic networks, through the coordinated behavior of biological superorganisms, to the predictive architectures of human institutions. Across these domains, cognition is treated as a thermodynamic strategy: the stabilization of entropy through boundary formation, feedback regulation, and the retention of memory. Drawing upon the frameworks of mineral evolution (Hazen), autocatalytic set theory (Kauffman), and predictive coding (Friston), the essay formulates a continuous lineage of cognitive modularity linking chemical, biological, and social organization. By situating cells, colonies, and bureaucracies within a shared entropic grammar, it reframes consciousness as a planetary phenomenon—a recursive network of modular stations of mind that spans from prebiotic chemistry to institutional intelligence.

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# 1 Introduction: From Thermodynamic Order to Cognitive Modularity

## 1.1 Background: The Energetic Problem of Consciousness

Consciousness has traditionally been treated as a biological or philosophical mystery confined to organisms possessing nervous systems. Yet from a thermodynamic standpoint, it is first and foremost an energetic and organizational problem: how can matter persist, adapt, and generate meaning under the universal constraint of entropy increase? As Schrödinger argued in *What is Life?* (Schrödinger, 1944), living systems maintain themselves by feeding on “negative entropy,” importing order from their environment to postpone decay. This insight reframes consciousness not as an inexplicable anomaly but as the highest expression of a general negentropic principle that extends from prebiotic chemistry to complex societies.

The twentieth century’s science of non-equilibrium thermodynamics elaborated the conditions under which ordered structures can emerge spontaneously. Prigogine and Stengers (Prigogine and Stengers, 1977) demonstrated that dissipative systems—chemical, biological, or social—can self-organize when energy fluxes are sufficiently far from equilibrium. Morowitz’s classic synthesis, *Energy Flow in Biology* (Morowitz, 1968), established that metabolic organization arises wherever energy throughput is constrained by feedback. These frameworks jointly suggest that cognition, broadly construed, may be identified with any process that stabilizes informational order by regulating energetic gradients.

## 1.2 From Energy Flow to Information Flow

If thermodynamics supplies the substrate of order, information theory provides its formal description. Lotka’s early physical biology (Lotka, 1922) treated evolution as an optimization of energy transformations. Later, cybernetics and systems theory generalized this to informational regulation: the brain, the ecosystem, and the organization all achieve stability by processing error signals. Bateson’s *Steps to an Ecology of Mind* (Bateson, 1972) extended this insight beyond biology, defining mind as “a difference that makes a difference.” Every feedback loop—whether biochemical, ecological, or institutional—thus participates in cognition insofar as it encodes environmental distinctions that preserve systemic coherence.

The autopoietic framework of Maturana and Varela (Maturana and Varela, 1980) formalized this idea: a living system is one that continuously regenerates its components through processes that also maintain its boundary. Cognition, on this view, is not a representational computation but a circular, self-producing dynamic of constraint maintenance. Deacon’s later theory of teleodynamics (Deacon, 2011) adds a hierarchical nuance: higher levels of organization emerge through the nested coupling of such constraint cycles, yielding goal-directed behaviour without invoking dualistic metaphysics.

## 1.3 Predictive Regulation as a Universal Cognitive Principle

Within neuroscience, the Free-Energy Principle (FEP) provides a unifying quantitative formalism for these ideas. Friston’s account (Friston, 2010) models biological systems as minimizing variational free energy—a measure of prediction error between expected and observed states. This mathematical principle is not confined to brains; it describes any system that maintains its structural integrity by reducing uncertainty about the causes of its inputs. In thermodynamic terms, the FEP restates the same logic of negentropy: organisms, ecosystems, and institutions persist by inferring and regulating the energetic flows that sustain them.

The FEP thereby connects the autopoietic cycle of Maturana and Varela to the dissipative structures of Prigogine and the information flows of Bateson. A system endowed with a boundary, internal states, and a means of exchanging energy and information with its environment

inevitably engages in prediction: it must act to keep its internal states within viable bounds. Consciousness, in this minimal sense, is the recursive modelling of those constraints.

## 1.4 From Thermodynamics to Cognitive Modularity

Simon’s seminal essay, *The Architecture of Complexity* (Simon, 1962), observed that complex adaptive systems evolve hierarchically modular structures because such architectures minimize the energetic and informational cost of maintenance. Each module functions as a relatively autonomous sub-system capable of local error correction. In the biological domain, this modularization corresponds to the differentiation of metabolic pathways, organs, or neural circuits; in the social domain, to the division of labor within institutions. Thus the emergence of modular cognition can be interpreted as a thermodynamic optimization: distributed control reduces the free-energy burden on any single unit.

The concept of modularity provides a bridge between levels of analysis. A mineral lattice sustaining catalytic reactions, a bacterial colony maintaining quorum signals, and a corporation regulating departmental budgets each instantiate bounded modules that exchange energy and information with a larger field. These modules evolve recursive coupling relationships, giving rise to higher-order cognition through nested feedback.

## 1.5 Consciousness as Recursive Uncertainty Minimization

Taken together, these traditions—thermodynamics, autopoiesis, cybernetics, and predictive coding—converge on a single principle: consciousness emerges wherever matter organizes to minimize its uncertainty about environmental perturbations. This definition reframes cognition as a scale-invariant process of negentropic inference rather than a property of neural tissue. It suggests that the same structural logic underlies chemical self-organization, biological homeostasis, and institutional decision-making.

Under this view, the human brain is but one instance of a broader planetary grammar of self-regulation. From prebiotic mineral matrices to modern bureaucracies, systems that endure do so by encoding probabilistic expectations about their environments and acting to reduce surprise. The remainder of this essay traces that continuum. Part I examines prebiotic cognition as a distributed chemical intelligence emerging within Earth’s mineral evolution (Hazen et al., 2008; Hazen, 2010; Kauffman, 1993). Part II extends the framework to biological superorganisms whose colonies embody predictive coding at ecological scales (Camazine et al., 2001; Gordon, 2010; Seeley, 2010). Part III analyzes human institutions as reflexive cognitive agents that regulate social free energy through symbolic communication (Hutchins, 1995; March and Simon, 1958; Friston et al., 2013). Finally, Part IV integrates these layers into a planetary model of distributed mind, where consciousness is understood as the recursive geometry of negentropic organization.

## 1.6 Scope and Methodological Integration

Methodologically, the argument proceeds by comparative synthesis rather than reduction. Each domain—geochemical, biological, and institutional—is treated as an empirical instantiation of the same informational dynamics. The analysis therefore moves laterally across disciplines, using the mathematical isomorphism between energy minimization and uncertainty reduction as a unifying formalism. This trans-scalar approach resonates with recent developments in active-inference theory that extend predictive processing to collective and social systems (Ramstead et al., 2016; Fox, 2021; Constant et al., 2022). By situating these contemporary models within the broader history of thermodynamic thought, the chapter establishes the conceptual foundation for a general theory of prebiotic cognition.



## 1.7 Toward a Modular Continuum of Consciousness

In conclusion, consciousness may be defined as the recursive regulation of entropy through informational feedback within bounded systems. From this perspective, life and mind are not distinct categories but different resolutions of the same thermodynamic grammar. The modular structures that sustain cells, colonies, and institutions are not analogies but homologous expressions of a single principle: the maintenance of negentropy through predictive coupling. The chapters that follow trace the historical and theoretical lineage of this principle—from the planet’s prebiotic chemistry to the symbolic architectures of the human mind—to demonstrate that consciousness, far from being an emergent exception, is a continuous property of matter wherever it learns to preserve itself.

## 2 Geochemical Foundations of Distributed Cognition

### 2.1 The Planet as a Cognitive Substrate

The origins of cognition precede biology. Long before cellular life, Earth itself behaved as a vast open thermodynamic system, continually exchanging energy with the Sun and cosmic environment. The planet’s differentiation—through gravitational contraction, volcanism, and tectonic recycling—generated steep chemical gradients that enabled matter to organize far from equilibrium. Hazen and colleagues’ *Mineral Evolution* framework ([Hazen et al., 2008](#)) identifies more than four thousand distinct mineral species that formed through successive epochs of planetary transformation. Each mineral phase functioned not only as a chemical product but also as a catalytic interface, mediating reactions among organic precursors. As Hazen later noted, the early Earth can be viewed as a “catalytic planet,” whose mineralogical diversity provided the scaffolding for prebiotic metabolism ([Hazen, 2010](#)).

This mineral substrate constitutes what might be called a lithic form of distributed cognition. The reactive surfaces of clays, zeolites, and metal sulfides were capable of adsorbing and organizing organic molecules, concentrating reactants that would otherwise remain dispersed. Through such templating processes, the planet effectively “learned” to stabilize certain reaction pathways over others, encoding a primitive memory in its mineral lattice structures. Each site of catalytic activity acted as a local information processor, participating in a global feedback network driven by energy gradients and environmental fluxes.

### 2.2 Lunar Trituration and the Mineral Prehistory of Mind

One of the least appreciated aspects of mineral evolution is its dependence on mechanical perturbation and exogenous inputs. Hazen’s analysis of lunar trituration—the grinding and mixing of mineral grains by micrometeorite impacts and tidal shearing—suggests that continual comminution increased reactive surface area and catalytically active defect sites. This planetary-scale “stirring” fostered nonequilibrium conditions conducive to autocatalytic reactions. From this standpoint, the early Earth-Moon system functioned as a single chemical engine: lunar-driven tides periodically renewed oceanic interfaces, coupling mechanical energy to molecular complexity.

Such cyclic perturbations acted as primitive forms of predictive updating. Reaction networks were not passively driven but recurrently modulated by planetary rhythms, forcing them to adapt to temporal variations in temperature, radiation, and salinity. Over time, recurrent environmental fluctuations selected for reaction sets capable of reproducing themselves under changing conditions. This adaptive resilience is the first glimmer of cognition understood as recursive uncertainty minimization: networks that anticipated periodic changes in their environment persisted, while others decayed.



## 2.3 Collective Autocatalysis: From Chemistry to Computation

The theoretical foundation for understanding such self-sustaining chemical systems was established by Kauffman’s concept of autocatalytic sets (Kauffman, 1986, 1993). In this framework, a collection of molecules forms an autocatalytic set when every reaction within it is catalyzed by at least one other molecule in the set, and all required reactants can be produced from a simple “food set” supplied by the environment. Kauffman demonstrated that as molecular diversity increases, the probability of forming such a collectively autocatalytic network approaches unity—a statistical inevitability once a critical threshold of complexity is reached. Life, in this view, emerges not from a single miraculous replicator but from the combinatorial closure of catalytic possibilities in a sufficiently rich chemical soup.

Hordijk and Steel (Hordijk and Steel, 2012) formalized this intuition in their RAF (Reflexively Autocatalytic and F-generated) theory, showing that autocatalytic networks can be algorithmically identified and that their emergence follows predictable probabilistic laws. The RAF model also implies that prebiotic chemistry could support nested hierarchies of catalytic closure, anticipating later biological modularity. These networks function as distributed information-processing systems: each molecule serves as both data and operator, collectively maintaining the system’s organization by catalyzing the very reactions that sustain it. Such closure constitutes a chemical analogue of the recursive feedback central to later neural and institutional cognition.

## 2.4 Eigen’s Hypercycle and the Information Bottleneck

While Kauffman emphasized metabolism-first emergence, Eigen and Schuster’s hypercycle theory (Eigen and Schuster, 1971, 1979) approached the problem from the perspective of genetic information. The hypercycle consists of a set of self-replicating molecular species in which each member catalyzes the replication of the next, forming a cyclic network of mutual reinforcement. This coupling allows information to be transmitted and amplified without a central controller, effectively turning replication into computation. The hypercycle thus introduces a form of proto-semantics: chemical species “recognize” one another’s structures through catalytic compatibility.

Both models—Kauffman’s autocatalytic sets and Eigen’s hypercycles—converge on the same thermodynamic insight: information and energy co-regulate one another through feedback loops that minimize entropy locally. Each network represents a microcosm of the free-energy principle long before its formal articulation. Their coexistence within prebiotic Earth’s mineral environment implies that metabolism and replication were not sequential stages but intertwined aspects of the same cognitive emergence.

## 2.5 Environmental Feedback and Planetary Stigmergy

If each catalytic site or reaction network functioned as a local agent, their coordination at planetary scale occurred through what might be termed *chemical stigmergy*. Borrowing a concept later applied to insect colonies, stigmergy denotes indirect coordination via modifications to a shared environment. In the prebiotic context, chemical products altered the conditions under which subsequent reactions occurred—modifying pH, redox potential, or mineral availability—and thereby feeding back on the network’s future dynamics. The planetary surface thus operated as a distributed medium of collective learning: successful reaction pathways left chemical “traces” that scaffolded further complexity.

This stigmergic dynamic parallels the distributed cognition described by Hutchins in human systems (Hutchins, 1995), where information processing emerges through the coupling of agents and artifacts. On the early Earth, minerals and molecules played the role of cognitive artifacts, encoding and transmitting constraints that enabled adaptive coordination without

central control.

## 2.6 The Transition to Encapsulation

Eventually, the open networks of planetary catalysis gave rise to localized, membrane-bound systems. Gánti’s chemoton model (Gánti, 2003) posited that such encapsulated units combined three interacting subsystems: a metabolic network, a template polymer system, and a boundary mechanism regulating exchange. Once such compartments formed—within lipid vesicles or mineral pores—they could maintain distinct internal chemistries, reducing environmental uncertainty. In contemporary terms, this marks the transition from unbounded collective inference to bounded predictive processing. The protocell represents the first stable Markov blanket, separating internal states from external fluctuations while maintaining active coupling—a thermodynamic precursor to the free-energy-minimizing agents of Friston’s formalism (Friston, 2010).

## 2.7 Distributed Cognition Before Life

From this vantage, life did not invent cognition; it inherited it. The planet’s geochemical networks already performed the essential functions later associated with mind: they stored information, predicted environmental changes, and regulated energetic flows to maintain order. The emergence of life thus corresponds to a phase transition in the topology of cognitive networks—from globally distributed chemical intelligence to locally encapsulated predictive systems. This continuity dissolves the categorical divide between “living” and “non-living,” replacing it with a scalar field of negentropic organization.

The geochemical stage of Earth’s history therefore establishes the foundational pattern that recurs throughout this essay: cognition as recursive constraint within open thermodynamic systems. The same principles that governed catalytic cycles and mineral feedbacks will later reappear in the behavior of superorganisms and institutions. Before there were neurons or laws, there were clays and tides—thinking in chemistry.

## 2.8 Summary and Theoretical Implications

This chapter has traced the deep origins of distributed cognition to the mineral and chemical dynamics of the prebiotic Earth. Mineral evolution created the diversity of catalytic substrates necessary for autocatalytic closure; planetary rhythms imposed selection pressures that rewarded stability under fluctuation; and encapsulation transformed open networks into bounded cognitive agents. Together, these processes constitute the first instance of recursive uncertainty minimization in matter.

In subsequent chapters, this framework will be extended upward in scale. The next phase—biological superorganisms—demonstrates how local feedback among unreliable components can yield collective intelligence and adaptive prediction. Yet at its core, the same thermodynamic logic applies: whether in a catalytic network, an ant colony, or a human institution, cognition is the organization of energy and information into enduring negentropic form.

# 3 From Global Autocatalysis to Encapsulation

## 3.1 From Open Networks to Bounded Systems

The transition from a globally distributed prebiotic network to localized, self-sustaining protocells represents one of the most profound reorganizations in the history of matter. In chemical terms, this transition corresponds to the emergence of compartmentalization: the establishment of physical boundaries that enable differential regulation of energy and information flows. In

cognitive terms, it marks the appearance of a predictive interface—a primitive “self” capable of distinguishing internal from external states.

The geochemical environment preceding this shift was characterized by open autocatalytic webs spanning mineral surfaces and hydrothermal gradients (Hazen et al., 2008; Kauffman, 1993). These networks collectively minimized entropy through feedback between reaction products and environmental conditions. Yet without boundaries, such systems remained vulnerable to diffusion and dissipation. Their information was global but transient. Encapsulation transformed this topology: chemical cognition condensed from an extended field into discrete agents.

### 3.2 The Thermodynamic Necessity of Boundaries

In non-equilibrium thermodynamics, boundaries are not optional—they are constitutive of order. Prigogine and Stengers (Prigogine and Stengers, 1977) showed that any system maintaining itself far from equilibrium must establish mechanisms to channel energy gradients and export entropy. The formation of vesicles and micelles in the prebiotic ocean satisfied this requirement. Fatty acids and amphiphilic molecules spontaneously assembled into bilayer membranes, enclosing reactive interiors while permitting selective exchange. These structures functioned as dissipative buffers: they absorbed environmental fluctuations and redistributed energy across organized degrees of freedom.

From the standpoint of the free-energy principle, such enclosures define the first *Markov blankets*—statistical boundaries that separate internal states (chemical concentrations, catalytic loops) from external states (nutrient gradients, temperature fluctuations) while maintaining conditional dependencies through sensory and active states (Friston, 2010; Friston et al., 2013). Encapsulation therefore represents the earliest instantiation of predictive coding in matter: protocells existed by continually updating their internal organization to minimize uncertainty about the environmental conditions sustaining them.

### 3.3 Mineral Pores as Proto-Membranes

Although lipid vesicles are often cited as the default mechanism of prebiotic compartmentalization, mineral matrices likely provided an earlier and more stable scaffold. Hazen (Hazen, 2010) and others have argued that microporous structures in clays, zeolites, and sulfide chimneys offered natural enclosures for autocatalytic networks. Within these mineral cavities, concentration gradients and electrochemical potentials were maintained passively, allowing complex reaction cycles to unfold without immediate dispersion. The porous network functioned as a lattice of interconnected reactors, mediating the balance between isolation and exchange.

Such geochemical “membranes” prefigured biological membranes not only structurally but functionally: they implemented differential permeability, sustained chemical potentials, and enabled recursive feedback between internal reactions and external flows. Over time, organic amphiphiles could have assembled on these mineral interfaces, gradually internalizing catalytic processes into self-contained lipid vesicles. The protocell, in this view, was born as a mineral–organic hybrid—a dynamic equilibrium between rigidity and fluidity, stability and permeability.

### 3.4 The Chemoton and the Coupling of Cycles

Gánti’s chemoton model (Gánti, 2003) formalized the architecture of such protocellular systems as the coupling of three cyclic subsystems: (1) a metabolic cycle producing building blocks, (2) an informational cycle storing templates, and (3) a membrane cycle enclosing and reproducing the whole. Each subsystem depends on the others for persistence; the entire structure is reflexively autocatalytic. When one subsystem amplifies or falters, the others compensate through feedback regulation. This triadic structure anticipates the later tripartite organization of the

cognitive agent under active inference: sensory, internal, and active states forming a closed inferential loop.

Within the chemoton, metabolism corresponds to model updating (predictive correction), the membrane to the Markov blanket (boundary mediation), and the informational cycle to memory (model retention). The chemoton thus embodies the minimal conditions for cognition: self-production, information storage, and boundary maintenance. It is not conscious in any anthropocentric sense, but it enacts the logic of self-reference characteristic of living systems.

### 3.5 Encapsulation as Predictive Constraint

Encapsulation changed not only the topology of prebiotic networks but their epistemic status. An open chemical field has no “inside” and thus no point of view; an enclosed system necessarily distinguishes between internal and external fluctuations. This distinction is the foundation of inference. By maintaining gradients, the protocell effectively “expects” certain environmental regularities—nutrient availability, pH balance, temperature—and acts to restore them when perturbed. Its behavior, while purely chemical, instantiates predictive regulation: a recursive reduction of free energy through the active modulation of boundary conditions.

Maturana and Varela’s autopoietic theory (Maturana and Varela, 1980) provides a conceptual vocabulary for this transformation. In their framework, a system becomes cognitive when it produces and maintains its own boundaries in the course of reproducing its components. The protocell, by continually repairing its membrane and regenerating its catalytic constituents, achieves precisely this circular causality. It is therefore both product and producer of its own organization—a self-sustaining inference engine in chemical form.

### 3.6 From Metabolic to Informational Closure

The encapsulated protocell represents a critical shift from collective to individual cognition, but this individuation introduced new challenges. Once enclosed, each system had to maintain its own identity under the selective pressures of limited resources and variable environments. Eigen’s hypercycle model (Eigen and Schuster, 1971, 1979) becomes relevant here: replication fidelity and cooperative linkage between informational polymers allowed protocells to evolve. Autocatalytic sets provided the metabolic backbone, while hypercycles introduced informational inheritance, closing the loop between prediction and reproduction. The integration of these mechanisms marked the emergence of true evolutionary cognition: systems capable not only of persisting but of learning across generations.

### 3.7 Autocatalytic Networks within Vesicles

Computational and laboratory models now suggest that encapsulated autocatalytic networks display emergent behaviors analogous to adaptive control. Hordijk and Steel’s RAF theory (Hordijk and Steel, 2012) demonstrates that subsets of reactions within a bounded environment can collectively regulate reaction fluxes, maintaining equilibrium even under stochastic perturbations. Experimental studies have shown that RNA-based ribozymes can self-replicate and evolve within lipid compartments (Lincoln and Joyce, 2009). These findings substantiate the hypothesis that once encapsulated, chemical networks could undergo selection for enhanced predictive stability. In this sense, the protocell is the first minimal “model” of its environment: a structure that encodes, through its reactions and permeability, the statistical regularities of the external world.

### 3.8 The Cognitive Role of Diffusion and Exchange

Encapsulation did not entirely sever protocells from the planetary network; rather, it established a new level of mediation between individual and environment. Diffusion across semi-permeable

membranes maintained chemical coupling, allowing protocells to share metabolites and genetic fragments. In aggregate, populations of protocells formed ecological networks, collectively exploring chemical state space. Through exchange and competition, these communities enacted a primitive form of collective learning: stable molecular motifs proliferated, while unstable ones vanished. The protocell thus internalized planetary metabolism while maintaining a stigmergic relationship with its surroundings—each cell leaving traces that altered the chemical conditions for others, an early parallel to the niche construction observed in biological and social systems.

### 3.9 Encapsulation as Cognitive Inheritance

Encapsulation was not a rupture but a condensation of planetary cognition. The protocell internalized the global dynamics of energy flow, turning distributed negentropic regulation into localized prediction. In doing so, it established the template for all subsequent cognitive evolution: bounded systems that model their environments through recursive exchange. Every later manifestation of mind—from neural circuits to institutional governance—recapitulates this protocellular topology. Boundaries become the sites of cognition, not its limits.

In this sense, the cell is both a physical and epistemic fossil of the planet that gave rise to it. Its membrane records the first differentiation of “self” and “world” in matter; its metabolism preserves the earliest instance of active inference. What began as a mineral lattice diffusing catalytic feedback has, through encapsulation, become a predictive agent—an autonomous locus of negentropic intelligence.

### 3.10 Summary: The Predictive Turn in Prebiotic Evolution

This chapter has argued that the emergence of encapsulated protocells transformed global autocatalysis into localized prediction. The formation of membranes and mineral enclosures provided the structural preconditions for self-reference, while the coupling of metabolic and informational cycles enabled adaptive regulation. Encapsulation represents the first appearance of the cognitive triad: boundary, model, and feedback. The protocell is thus the prototype of all future agents in the modular continuum of consciousness.

In the chapters that follow, the same thermodynamic and informational logic will be extended upward in scale—from individual cells to collective organisms and institutional minds. Just as protocells internalized the planet’s distributed metabolism, superorganisms will internalize ecological dynamics, and institutions will internalize collective expectations. Cognition evolves by recursion, but its fundamental architecture remains unchanged: every mind is a membrane.

## 4 Lithic Memory and Proto-Reflexivity

### 4.1 Memory Before Mind

Memory, in its most general form, is the persistence of constraint across time. In cognitive systems, memory manifests as the encoding of experience into stable configurations that guide future action. In physical systems, the same principle holds: a constraint that resists dissolution constitutes a form of information storage. Before DNA, before neurons, and even before cells, the planet itself encoded memories in the lattice structures of minerals. These lithic memories are the earliest substrates of reflexivity—the capacity of matter to preserve and refer to its own states.

The concept of “lithic memory” builds directly upon Hazen’s theory of mineral evolution (Hazen et al., 2008; Hazen, 2010). As the mineralogical diversity of Earth increased through geochemical and biological co-evolution, so too did the capacity of the planet to store information. Each crystal lattice records a history of its environmental formation conditions—pressure,

temperature, redox state, and compositional ratios. In this sense, the crust of the Earth constitutes a planetary archive, encoding the sequence of thermodynamic adaptations through which matter learned to persist.

## 4.2 The Thermodynamics of Persistence

Prigogine and Stengers ([Prigogine and Stengers, 1977](#)) described self-organization as the local maintenance of order through the dissipation of energy. Minerals epitomize this principle. When ions precipitate from solution into a crystalline solid, they lock in a record of the surrounding field gradients. Subsequent metamorphic transformations modify but do not erase this record; each phase transition leaves traces of previous energetic states. These traces function analogously to what in biological systems would be called “metabolic memory.” The system adapts its configuration to reduce local free energy, thereby retaining a record of its own stabilization pathway.

From this perspective, the lithosphere is not a static repository but a dynamic cognitive matrix. Rocks remember the flows that produced them; the structure of the mineral lattice is an inference about environmental constraints, encoded through molecular geometry. Morowitz ([Morowitz, 1968](#)) and Deacon ([Deacon, 2011](#)) both emphasized that information is not a substance but a pattern of constraint. The persistence of these constraints through thermodynamic cycles is thus equivalent to the persistence of memory.

## 4.3 Catalytic Surfaces as Associative Networks

At the molecular level, catalytic minerals such as clays, zeolites, and metal sulfides can be interpreted as primitive associative memories. Their active sites selectively bind certain molecular species, amplifying correlations between chemical configurations and environmental conditions. Kauffman’s work on autocatalytic sets ([Kauffman, 1993](#)) can be extended here: each catalytic surface acts as a node in a distributed network of associations, linking particular molecular interactions to the mineral structures that stabilize them. Over geological timescales, these associations became reinforced through recursive environmental feedback—molecules that increased mineral stability were preserved, and minerals that enhanced molecular reactivity proliferated.

This reciprocal coupling created a planetary analogue of Hebbian learning: “sites that react together, bond together.” The lithosphere evolved as a chemical neural network, its topology shaped by the frequency and success of catalytic interactions. Although devoid of consciousness, it performed the essential operation of cognition—integrating information over time to enhance predictive stability.

## 4.4 The Reflexive Turn: From Storage to Anticipation

For a system to move from memory to reflexivity, it must not only record the past but anticipate the future. Reflexivity emerges when stored information modulates ongoing dynamics in a way that improves stability under uncertainty. In prebiotic chemistry, this transition occurred when reaction networks began to use mineral constraints not just as scaffolds but as guides—structures that biased future reactions toward previously successful configurations. This shift marks the earliest instance of *predictive coupling*: matter learning from its own history.

Bateson’s notion of “a difference that makes a difference” ([Bateson, 1972](#)) offers a conceptual bridge here. A mineral lattice that biases chemical reactions based on its structure embodies a difference (its geometry) that causally affects subsequent differences (reaction pathways). Such systems exhibit a rudimentary semiotics: environmental information is encoded in physical form and then reinterpreted through chemical activity. Reflexivity, in this sense, arises from the closed loop between stored constraint and active transformation.



## 4.5 Mineral Networks as Proto-Symbolic Systems

In living cognition, symbols function as persistent representations that enable coordination across time and space. In prebiotic systems, the analogues of symbols were structural templates—molecular configurations or crystal motifs that reliably elicited specific responses. Eigen and Schuster’s hypercycle ([Eigen and Schuster, 1971, 1979](#)) provides one mechanism for such symbolic continuity: cyclic coupling of replicating molecular species effectively encodes functional relationships that endure across generations. Similarly, mineral templates stabilized molecular sequences through selective adsorption, effectively “writing” chemical information into the planetary substrate.

Over time, these lithic templates may have guided the formation of informational polymers, bridging the gap between catalytic chemistry and genetic coding. Kauffman’s autocatalytic closure and Eigen’s hypercycle are thus complementary aspects of a broader semiotic process: the emergence of material symbols that constrain future dynamics. This is the origin of proto-reflexivity—the ability of matter to reference its own constraints.

## 4.6 Encoding in the Context of the Environment

Unlike modern memory systems, lithic and chemical memories lacked a discrete address space. Their information was distributed, context-dependent, and continuously overwritten by environmental flux. Yet this very plasticity enabled adaptation. Environmental feedback constantly “trained” the mineral network, erasing ineffective configurations and amplifying stable ones. The planet’s surface chemistry thus implemented a continuous form of unsupervised learning—analogue to modern neural networks but enacted through geochemical recursion rather than digital computation.

This process aligns closely with the principles later formalized in the free-energy framework. Friston’s ([Friston, 2010](#)) principle of variational minimization can be reinterpreted as a generalization of this prebiotic adaptation: systems persist by minimizing the discrepancy between expected and encountered energetic states. The mineral–molecular continuum embodies this rule physically, not symbolically; its learning occurs through phase transitions rather than synaptic weights.

## 4.7 From Lithic Reflexivity to Protocellular Memory

When autocatalytic networks became encapsulated within membranes, the lithic substrate was not abandoned but internalized. Protocells inherited from the mineral world both the catalytic logic of associative coupling and the geometric logic of constraint storage. Within lipid vesicles or mineral pores, reaction networks began to reproduce the reflexive patterns of their inorganic ancestors. Maturana and Varela’s autopoietic theory ([Maturana and Varela, 1980](#)) captures this inheritance: the system’s organization—its network of relations—remains invariant through material turnover. The protocell’s boundary conditions thus replayed, in miniature, the reflexive cycles of planetary chemistry.

Deacon ([Deacon, 2011](#)) interprets such recursive organization as the first form of teleodynamics: systems that preserve themselves by constraining their own dynamics toward a future state. Lithic memory, transposed into the living domain, becomes developmental memory—anticipatory structure encoded in metabolism and morphology. Reflexivity matures into function.

## 4.8 Proto-Reflexivity and the Geometry of Feedback

Reflexivity, in its minimal sense, is the capacity of a system to incorporate the effects of its past actions into its present state. Geochemically, this is instantiated through feedback between mineral templating and chemical transformation; biologically, through homeostatic loops that



regulate internal variables. In both cases, stability arises from circular causation—constraint acting upon constraint. Simon’s modular principle (Simon, 1962) ensures that such feedback remains tractable: subsystems develop semi-autonomous reflexive loops that collectively maintain global coherence. Reflexivity therefore scales naturally with modular complexity.

The geometry of these feedbacks—the recursive coupling of constraints—defines a universal architecture of cognition. Whether in silicate lattices or neural circuits, the same pattern recurs: storage, activation, modification, and re-storage. Each cycle refines the system’s model of its environment, producing an incremental reduction of free energy. Reflexivity is not an abstract property of thought but a thermodynamic process of self-referential stabilization.

## 4.9 From Lithic Memory to Institutional Cognition

The same logic that governed lithic reflexivity reappears, at vastly higher scales, in human institutions. Just as minerals stabilized reactive patterns through structural feedback, bureaucracies stabilize social behaviors through procedural and symbolic constraints. Both encode memory not in representations but in persistent organization. The analogy underscores the continuity of cognitive architecture across scales: reflexivity is a property of constraint networks, not of consciousness per se.

Understanding this continuity dissolves the traditional hierarchy that privileges human awareness over material or collective forms of cognition. Instead, cognition appears as a recursive property of the universe itself—wherever matter achieves sufficient feedback to refer to its own organization. The lithic archive of Earth thus represents the first iteration of a universal reflexive grammar, later elaborated in biological and institutional minds.

## 4.10 Summary and Transition

This chapter has argued that minerals and prebiotic chemical networks instantiated the earliest forms of memory and reflexivity. Through crystallographic persistence, catalytic feedback, and associative coupling, the lithosphere acted as a distributed cognitive substrate. Reflexivity emerged when these stored constraints began to influence future reactions, establishing a self-referential loop that foreshadowed active inference. As life emerged, these lithic memories were internalized into protocells, transforming structural persistence into metabolic prediction.

The following chapter extends this continuity from the mineral to the biological domain. If lithic networks remembered through constraint, living networks remember through replication and selection. The superorganisms of later evolution—bacterial colonies, ant societies, and human institutions—preserve this same lithic legacy of distributed reflexivity, now amplified by communication and cooperation. Cognition remains, at every scale, the geometry of matter remembering itself.

# 5 Prebiotic Modularity and the Descent Toward Bounded Intelligence

## 5.1 From Reflexive Fields to Modular Agents

Following the emergence of lithic memory and proto-reflexive chemistry, the next decisive transition in the evolution of cognition was the differentiation of functional modules within otherwise continuous reaction fields. In distributed prebiotic networks, interactions were initially unbounded—chemical signals propagated freely through oceans, sediments, and mineral interfaces. Over time, recursive feedbacks and resource constraints produced local specialization: clusters of reactions became semi-autonomous subsystems. This differentiation laid the foundation for modular cognition, where complex adaptive behavior arises from the cooperative integration of simpler components.

Simon’s classic essay *The Architecture of Complexity* (Simon, 1962) provides a general theoretical framework for this transition. Hierarchical modularity, Simon argued, is a universal design principle of complex systems because it balances stability with evolvability. Modules constrain local fluctuations, preventing perturbations from cascading globally, while interfaces between modules allow the selective exchange of energy and information. In the prebiotic context, modular organization emerged as a thermodynamic optimization: it localized entropy production and enabled parallel experimentation with different chemical configurations.

## 5.2 Thermodynamic Rationale for Modularity

Prigogine and Stengers (Prigogine and Stengers, 1977) established that self-organizing systems far from equilibrium develop internal gradients that act as order parameters. When such gradients become too strong, systems bifurcate—partitioning into semi-independent domains that each dissipate energy locally. This bifurcation process can be interpreted as the physical origin of modularity: distinct reaction zones form to maintain local stability under global flux. The descent toward bounded intelligence thus begins with a thermodynamic imperative—distributed systems partition themselves to remain viable under increasing complexity.

Morowitz’s analysis of energy flow in biology (Morowitz, 1968) reinforces this point. He showed that living systems minimize free energy not by uniform dissipation but by channeling energy through nested cycles of constrained exchange. Each cycle constitutes a functional module—a small, quasi-closed loop that processes energy and information efficiently. In prebiotic chemistry, such loops appeared spontaneously as subsets of autocatalytic networks stabilized by spatial or kinetic separation. The emergence of modules is therefore inseparable from the emergence of negentropy.

## 5.3 Autocatalytic Subnetworks and Hierarchical Closure

Kauffman’s theory of autocatalytic sets (Kauffman, 1993) predicts that as chemical diversity increases, subsets of reactions form closed subgraphs that are reflexively catalytic. Hordijk and Steel’s RAF analysis (Hordijk and Steel, 2012) later formalized these subsets as nested autocatalytic networks, demonstrating that hierarchical organization is a natural outcome of catalytic closure. Each subnetwork behaves as a quasi-independent entity—producing, maintaining, and regulating its own components while remaining embedded in a larger chemical ecology.

This hierarchical structure parallels the modular organization of later biological systems. Within cells, metabolic pathways, genetic circuits, and signaling cascades form interacting modules, each governed by its own feedback dynamics. The continuity suggests that modularity was not an evolutionary afterthought but a precondition for the persistence of complex adaptive systems. Modularity is the grammar of bounded intelligence: it defines how local reflexive units can coexist without losing coherence.

## 5.4 Spatial Differentiation and Chemical Zoning

Experimental simulations of hydrothermal vent systems and mineral microenvironments indicate that physical gradients—temperature, pH, redox potential—can create spatially segregated zones of distinct chemical activity. Hazen’s work on mineral evolution (Hazen, 2010) emphasizes that micro-heterogeneity in mineral surfaces generates differential catalytic potentials. In such contexts, modularity is not imposed from above but emerges naturally from the environment’s anisotropy. Each microdomain evolves its own repertoire of reactions while exchanging diffusible intermediates with neighboring zones.

This spatial differentiation establishes the prebiotic analogue of tissue specialization: reaction modules communicate through chemical gradients rather than genetic signals. Over time,

selective stabilization of certain couplings led to increasingly integrated yet compartmentalized chemical ecologies—a chemical forerunner of multicellularity.

## 5.5 Information Bottlenecks and Predictive Efficiency

As reaction networks grew more complex, unrestricted coupling became energetically unsustainable. Each reaction propagated uncertainty throughout the system, increasing computational load and dissipation. Modularity reduced this burden by establishing informational bottlenecks—interfaces through which only aggregated signals passed. Friston’s free-energy principle ([Friston, 2010](#)) provides a formal expression of this constraint: systems minimize free energy by reducing the dimensionality of their sensory inputs to predictable subspaces. Prebiotic modules accomplished this physically, filtering environmental variability through boundary conditions and reaction selectivity.

The shift from unbounded reflexivity to bounded prediction marks the dawn of proto-intelligence. A modular system does not merely react to stimuli; it constructs internal regularities that guide efficient responses. Each module develops its own micro-model of the environment, and their coordination yields a distributed predictive hierarchy—a precursor to neural and institutional architectures.

## 5.6 Coupling Between Modules: Toward Integration

While modularity provides local stability, cognition requires integration. The challenge for prebiotic systems was to maintain coherence across interacting modules without centralized control. Chemical coupling achieved this through shared intermediates and cross-catalysis. Simon’s principle of near-decomposability ensures that inter-module interactions remain slower and weaker than intra-module dynamics, allowing global coordination through gradual equilibration rather than direct synchronization. In biological terms, this hierarchy foreshadows the division between fast local processes (e.g., enzymatic reactions) and slower regulatory processes (e.g., gene expression or membrane transport).

Integration without centralization also anticipates the stigmergic coordination observed in superorganisms and institutions. Each module modifies a shared medium—chemical, ecological, or symbolic—through which others adjust their behavior. The emergence of bounded intelligence therefore depends on both structural modularity and stigmergic coupling: localized inference embedded within global context.

## 5.7 Error, Redundancy, and Robustness

Reliability from unreliable parts—a hallmark of intelligent systems—first appeared in prebiotic modularity. Distributed chemical modules compensated for individual failures through redundancy. If one catalytic loop degraded, parallel pathways sustained overall functionality. This redundancy mirrors error-correction in modern information systems and homeostatic regulation in organisms. Ashby’s cybernetic principle of requisite variety ([Ashby, 1956](#)) applies here directly: only a system with sufficient internal diversity can compensate for environmental perturbations. Modularity provided that diversity by enabling multiple adaptive strategies to coexist within a shared thermodynamic framework.

From an informational standpoint, redundancy increases predictive confidence. Multiple overlapping modules refine the system’s internal model by averaging noise across subsystems. Thus, prebiotic modularity anticipated the Bayesian aggregation mechanisms later formalized in predictive coding.

## 5.8 The Descent Toward Bounded Intelligence

As modular networks grew in complexity, their collective behavior increasingly resembled that of agents—bounded systems that maintain internal coherence through active prediction. The descent toward bounded intelligence is therefore not a discrete leap but a gradient of increasing encapsulation and internal modeling. Each step reduced informational entropy by constraining causal interactions within finite boundaries. The protocell, discussed in Chapter 3, represents one realization of this descent; but the principle applies broadly across scales, from chemical vesicles to social organizations.

Maturana and Varela’s notion of autopoiesis (Maturana and Varela, 1980) captures this process: modules become subsystems that continually reproduce the organization that defines them. Deacon (Deacon, 2011) reframes this as the emergence of teleodynamics—systems that preserve themselves by maintaining constraints upon their own dynamics. Bounded intelligence thus arises whenever modular feedback achieves sufficient closure to predict and compensate for its environment’s variability.

## 5.9 The Cognitive Topology of Modularity

Conceptually, modularity introduces a new topological layer into the evolution of cognition: instead of uniform connectivity, systems develop nested boundaries and semi-permeable interfaces. Each boundary functions as both barrier and bridge—limiting noise while permitting structured exchange. This topology recurs at every scale of intelligent organization: lipid membranes in cells, neural modules in brains, departments in institutions. In each case, modular segmentation allows complex inference to be distributed across hierarchies without sacrificing coherence.

The resulting topology can be represented mathematically as a hierarchy of Markov blankets (Friston et al., 2013). Each blanket encloses a module whose internal states model external causes, while higher-level blankets integrate the predictions of lower-level ones. Intelligence, in this framework, is not a property of isolated units but of the recursive nesting of predictive boundaries.

## 5.10 Prebiotic Modularity as the Template for Conscious Hierarchies

The emergence of modularity in prebiotic chemistry establishes the deep continuity between physical self-organization and cognitive hierarchy. The same structural logic that organized reaction networks under thermodynamic constraint now organizes neural and institutional cognition under informational constraint. Whether manifested in molecules, neurons, or offices, modularity mediates between entropy and order by enabling distributed prediction.

The descent toward bounded intelligence is thus also an ascent in informational density. As systems internalize environmental regularities within nested modules, they transform energetic flux into representational structure. Consciousness, in its mature form, is the ultimate expression of this recursive modular architecture—a dynamic equilibrium between local autonomy and global coherence.

## 5.11 Summary and Transition

This chapter has argued that modularity emerged in prebiotic chemistry as a thermodynamic adaptation enabling scalable cognition. Through spatial differentiation, hierarchical closure, and controlled coupling, distributed reflexive systems evolved into bounded predictive agents. Modularity provided the structural means for reliability, efficiency, and hierarchical integration—the hallmarks of intelligence at all subsequent levels of organization.

The next chapter extends this principle into the biological domain, examining how eusocial organisms transformed modular agents into collective minds. There, the modules are no longer

chemical networks but individual organisms, each embodying a bounded intelligence that participates in a larger predictive ensemble. The same modular descent reappears as the rise of superorganismic cognition.

## 6 Distributed Cognition in Eusocial Systems

### 6.1 From Cellular Modularity to Collective Mind

With the emergence of multicellular life, modular cognition scaled upward from intracellular feedback loops to organismic specialization. Yet the principle of distributed intelligence—organization without central control—reappears most vividly in eusocial species. Ants, bees, termites, and certain wasps collectively realize an intelligence greater than the sum of their individuals. Each agent operates with limited information and bounded autonomy, but together they achieve complex feats of coordination, construction, and regulation. The superorganism thus represents the biological analog of the protocell: a bounded, self-regulating system composed of semi-autonomous modules linked by stigmergic feedback.

Hölldobler and Wilson’s synthesis ([Hölldobler and Wilson, 2009](#)) frames eusocial colonies as coherent cognitive entities whose intelligence resides not in neural complexity but in network topology. Local interactions propagate through chemical and behavioral signals, generating emergent order. Like prebiotic networks, these colonies dissipate entropy through structured activity while maintaining long-term homeostasis. Their stability arises not from rigid command hierarchies but from recursive adaptation distributed across millions of micro-interactions.

### 6.2 Functional Modularity and Division of Labor

The internal architecture of a superorganism mirrors the modular organization of prebiotic autocatalytic networks. Castes—workers, soldiers, foragers, queens—constitute specialized subunits with defined energetic and informational roles. Camazine et al. ([Camazine et al., 2001](#)) demonstrate that division of labor in social insects arises spontaneously from local feedback, without central coordination. Each caste is effectively a functional “module” whose behavior is regulated by internal thresholds and external cues.

Simon’s principle of near-decomposability ([Simon, 1962](#)) again applies: each caste subsystem operates semi-independently but communicates through low-bandwidth channels—chemical signals, tactile contact, or environmental modifications. This separation of timescales enables stability: perturbations in one behavioral domain rarely destabilize the whole colony. The collective intelligence of the superorganism thus results from the coherent orchestration of modular reflexes, not their suppression.

### 6.3 Stigmergic Communication and Environmental Coupling

Eusocial coordination depends on stigmergy—the indirect communication of agents through modifications of the environment. First formalized by Grassé in termite behavior and elaborated by Theraulaz and Bonabeau, stigmergy transforms the environment into a shared workspace of information. Gordon ([Gordon, 2010](#)) extends this view by modeling ant interactions as probabilistic encounters modulated by environmental state: pheromone trails, soil structure, and humidity all serve as cognitive media.

Stigmergy functions as a biological instantiation of distributed memory. Information about food sources, nest architecture, or threat levels is stored not in individual minds but in the configuration of external cues. In this sense, colonies externalize cognition in the same way prebiotic chemistries encoded reflexivity in mineral matrices. The environment becomes an extension of the cognitive system—a substrate of memory and control. Hutchins’ theory of

distributed cognition ([Hutchins, 1995](#)) later generalized this insight to human systems, but its roots are clearly biological.

## 6.4 Parallelism and Population Coding

Colony behavior exemplifies population coding: individual errors are averaged across large numbers of agents, yielding reliable collective outcomes. Gordon’s empirical work shows that harvester ant colonies regulate foraging intensity through feedback between encounter rates and food availability, maintaining near-optimal energy balance despite noisy individual behavior. This is the same principle by which neuronal populations encode sensory stimuli through distributed firing patterns—robustness by redundancy.

At the informational level, each ant or bee functions as a stochastic sampler of environmental states. The colony’s aggregate activity approximates Bayesian inference: pheromone reinforcement increases the probability of revisiting successful sites, while evaporation ensures decay of outdated information. The resulting dynamics correspond to a form of recursive prediction error minimization, akin to the free-energy principle operating at the population level ([Friston, 2010](#)). Collective intelligence thus emerges from the statistical integration of individual uncertainties.

## 6.5 Temporal Differentiation and Role Plasticity

Superorganisms further exhibit temporal modularity: individuals shift roles throughout their lifespan in response to environmental and internal signals. In honeybees, for instance, workers transition from nursing to foraging as colony demands and hormonal cues change ([Seeley, 2010](#)). This plasticity allows dynamic reallocation of resources, analogous to adaptive control in cybernetic systems. Each individual embodies a potential module, dynamically instantiated according to predictive context.

From a thermodynamic perspective, this flexibility represents a mechanism for minimizing free energy under fluctuating environmental constraints. Rather than maintaining rigid specialization, colonies adjust their internal modular composition, thereby preserving homeostasis. Such dynamic role reassignment foreshadows the adaptability of institutions that reconfigure departments in response to shifting external pressures.

## 6.6 Collective Construction and Predictive Coordination

Termite mounds and ant nests are not merely shelters but extended physiological systems that regulate temperature, humidity, and gas exchange. Through local building rules—depositing pellets where certain pheromone concentrations occur—termites collectively construct architectures that maintain optimal environmental parameters ([Camazine et al., 2001](#)). This process constitutes predictive control: construction behavior anticipates the environmental conditions required for survival and adjusts structure accordingly.

The mound thus functions as a macroscopic regulatory organ—an emergent embodiment of predictive coding. Individual termites have no global model of the nest, yet their interactions instantiate a distributed model of climate regulation. This is cognition without representation: a recursive coupling of behavior and environment that achieves inference through morphology.

## 6.7 Collective Decision-Making as Inference

At the colony level, decision-making—such as nest-site selection in bees or foraging path optimization in ants—follows principles of statistical inference. Seeley’s studies of honeybee swarms ([Seeley, 2010](#)) demonstrate that collective decisions result from quorum thresholds: scouts evaluate potential sites, communicate via waggle dances, and reinforce signals until a consensus emerges. This distributed process efficiently integrates diverse information without centralized authority, paralleling Bayesian updating in neural and institutional systems.



In free-energy terms, swarm decision-making minimizes uncertainty by converging on the site that best fits collective priors and sensory data. The quorum threshold serves as a variational bound: once confidence surpasses a critical level, the swarm acts. The colony thus performs an embodied form of model selection, balancing exploration (searching for alternatives) and exploitation (committing to a site). The cognitive logic of decision-making remains constant across scales—from molecular evolution to institutional policy.

## 6.8 Colony Homeostasis and Thermodynamic Regulation

Superorganisms maintain internal order through continuous energy flux and feedback regulation. Camazine et al. (Camazine et al., 2001) show that colonies exhibit negative feedback loops stabilizing population density, task allocation, and metabolic throughput. For example, in leafcutter ants, foraging rate adjusts dynamically to fungal garden health; in bees, brood temperature is regulated by collective fanning and clustering. These processes represent thermodynamic homeostasis—entropy reduction through distributed work.

Friston’s framework (Friston et al., 2013) provides a formal correspondence: colonies act as hierarchical generative models predicting environmental conditions (e.g., resource availability, temperature) and correcting deviations through collective action. Each feedback loop minimizes free energy within a constrained subsystem—individuals, castes, or behavioral modules—while maintaining coherence at the colony scale. The colony’s organization thus enacts the same recursive predictive logic observed in protocells and institutions.

## 6.9 Communication Noise and Robustness

Eusocial systems are composed of unreliable components: individuals make frequent perceptual and motor errors, die unpredictably, and vary in motivation. Yet the colony as a whole exhibits remarkable stability. This robustness arises from redundancy, feedback averaging, and error-tolerant signal processing. Pheromone communication, though noisy, encodes meaning statistically—strong signals emerge only when multiple agents independently confirm a pattern. This population-level filtering transforms unreliability into resilience, paralleling Ashby’s principle of requisite variety (Ashby, 1956).

Noise, in this context, is not merely tolerated but exploited: stochastic variation ensures exploration of alternative solutions and prevents entropic stagnation. The colony’s intelligence therefore resides in its capacity to regulate noise—to balance exploitation with exploration, order with disorder. This balance is the biological embodiment of negentropic cognition.

## 6.10 Cognitive Ecology and Distributed Memory

Over the colony’s lifetime, information accumulates not only in pheromone trails or nest structures but in the behavioral propensities of individuals shaped by prior interactions. This distributed memory allows colonies to adapt to recurring seasonal patterns and ecological shifts. Gordon’s long-term studies reveal that colony “personalities”—consistent foraging and defense patterns—persist across generations despite the complete turnover of individuals (Gordon, 2010). Such persistence parallels institutional memory: the maintenance of organizational identity despite personnel replacement.

From a systems-theoretic perspective, this distributed memory constitutes a high-level attractor in the colony’s dynamical phase space. The colony’s behavioral repertoire converges toward stable trajectories shaped by environmental history. In informational terms, the colony functions as a learning system—updating priors through repeated interaction with its environment, precisely as active inference predicts.



## 6.11 The Superorganism as Cognitive Prototype

Eusocial colonies demonstrate that cognition does not require centralized representation or symbolic reasoning. Instead, distributed feedback, modular specialization, and stigmergic memory suffice to produce predictive, adaptive behavior. The superorganism is therefore a natural prototype for understanding institutional cognition. In

both cases, intelligence emerges from recursive coordination among bounded agents, mediated by shared environments and communication codes.

Superorganisms refine the lessons of prebiotic modularity: they show that complex inference can be realized through simple rules, provided those rules are embedded in richly coupled networks. Colonies “think” through the world itself—through pheromone fields, architectural feedback, and social interaction. This extended cognition exemplifies the transition from chemical to ecological intelligence, from molecules to minds that move.

## 6.12 Summary and Transition

This chapter has traced the emergence of distributed cognition in eusocial systems, interpreting colonies as hierarchical, predictive networks that regulate entropy through cooperative action. Their modular castes, stigmergic communication, and redundancy transform local reflexes into global intelligence. The colony’s self-regulation parallels the predictive architectures of protocells and foreshadows the recursive governance of institutions.

In the following chapter, these insights are extended to the social domain. Just as colonies coordinate behavior through shared environmental codes, human institutions coordinate symbolic actions through policies, archives, and norms. Institutional cognition is thus not a metaphorical extension but a direct continuation of superorganismic intelligence—recursively predictive, thermodynamically regulated, and distributed across modular agents.

# 7 Predictive Coding and Thermodynamic Regulation

## 7.1 The Energetic Basis of Prediction

All cognitive systems, whether molecular, biological, or institutional, are thermodynamic systems that persist by reducing uncertainty about their energy flows. Friston’s free-energy principle (FEP) (Friston, 2010; Friston et al., 2013) formalizes this as a universal law of adaptive behavior: self-organizing systems maintain their structural integrity by minimizing the divergence between predicted and actual sensory inputs. Prediction, in this framework, is not a metaphor but a physical imperative—an informational expression of the second law of thermodynamics under constraint.

From a biophysical standpoint, prediction reduces entropy by aligning internal states with external regularities. Just as an enzyme lowers the energetic barrier of a reaction by anticipating its substrate’s configuration, organisms lower the energetic cost of survival by anticipating environmental fluctuations. Predictive coding is therefore the cognitive face of thermodynamic regulation: both describe the same negentropic feedback between model and world.

## 7.2 Prediction as the Successor of Homeostasis

Homeostasis, classically defined by Cannon and formalized in cybernetics by Ashby (Ashby, 1956), describes a system’s ability to maintain internal variables within viable bounds. Predictive coding generalizes this principle temporally: instead of reacting to deviations after they occur, systems infer and correct deviations before they manifest. This transition from reactive to anticipatory regulation marks the shift from metabolism to cognition.

In eusocial colonies, this logic is manifest in collective behaviors such as temperature regulation, foraging optimization, and resource allocation. Bees adjust brood temperature via coordinated fanning before thermal deviations exceed thresholds; ants redistribute foragers based on probabilistic forecasts of food return rates (Seeley, 2010; Gordon, 2010). These anticipatory behaviors implement predictive coding in biological matter: collective inference over environmental variables to minimize expected free energy.

### 7.3 Free Energy and Information Geometry

The FEP defines free energy  $F$  as an upper bound on surprise, or negative log evidence, given sensory data  $s$  and internal model parameters  $\mu$ :

$$F(s, \mu) = E_q[\ln q(\mu) - \ln p(s, \mu)]$$

where  $q(\mu)$  approximates the posterior distribution over hidden causes. Minimizing  $F$  reduces the difference between beliefs and observations, thereby aligning internal models with external dynamics. This variational optimization is thermodynamically equivalent to minimizing entropy production under informational constraints.

In natural systems, this process unfolds across nested timescales: fast fluctuations are filtered by slow structural priors. Colonies, for instance, exhibit rapid behavioral adjustments superimposed upon stable architectural and genetic constraints. This multi-scale structure corresponds to the hierarchical predictive coding framework in neuroscience (Friston, 2010), where higher layers encode slower, more abstract priors and lower layers handle rapid prediction errors.

### 7.4 Entropy, Negentropy, and Organizational Stability

Prigogine and Stengers (Prigogine and Stengers, 1977) demonstrated that dissipative structures persist by exporting entropy to their surroundings. Living and cognitive systems achieve this through organized work—transforming free energy into structured activity that maintains low internal entropy. Predictive coding operationalizes this thermodynamic insight in informational terms: accurate predictions reduce surprisal, and therefore the system’s internal entropy. Negentropy is the informational correlate of accurate anticipation.

Morowitz (Morowitz, 1968) described life as “a steady-state vortex of energy,” constantly cycling matter through configurations that preserve structural identity. The predictive coding framework reveals how this cycling becomes adaptive: systems internalize models of the energy landscape, allowing them to allocate metabolic effort efficiently. The more accurate the model, the less energy wasted in correction; the closer the system approaches thermodynamic efficiency.

### 7.5 Hierarchical Inference in Biological Networks

Biological systems are hierarchically modular. Each subsystem—cell, organ, organism, colony—performs local inference under constraints imposed by higher levels. This hierarchy forms a cascade of Markov blankets (Palacios et al., 2020), insulating internal states while permitting structured information exchange. Predictive coding describes how these layers cooperate: prediction errors propagate upward, while predictions flow downward to suppress error.

In eusocial systems, this hierarchy is realized behaviorally. Individual insects generate micro-level predictions (pheromone intensity, local resource density) that inform colony-level expectations (foraging success, brood health). Conversely, colony state modulates individual behavior through hormonal and environmental signals. The result is a recursive inference engine distributed across thousands of agents—a biological instantiation of hierarchical free-energy minimization.

## 7.6 Active Inference and Behavioral Control

Active inference extends predictive coding by coupling perception and action: systems not only update internal models to match sensory data but also act to make sensory data match their models. In practice, this means reducing expected free energy by sampling the environment in ways that confirm predictions. Bees, for example, explore new foraging routes to refine spatial priors; ants adjust trail pheromone deposition to test the reliability of resource maps ([Gordon, 2010](#); [Seeley, 2010](#)). Such behaviors exemplify epistemic action—movement driven by the desire to reduce uncertainty rather than to achieve immediate reward.

At a conceptual level, active inference provides a formal bridge between thermodynamic regulation and agency. The drive to maintain order becomes the drive to acquire information, since better predictions entail lower entropy. Cognition, under this principle, is not an abstract computation but a thermodynamic strategy for efficient energy management.

## 7.7 Predictive Coding as a Continuation of Prebiotic Reflexivity

The predictive dynamics of living systems echo the reflexive chemistry of prebiotic autocatalytic networks. In both, persistence depends on feedback between internal states and environmental regularities. The prebiotic autocatalyst “expected” certain molecular inputs because its catalytic structure was tuned by past interactions; deviations led to reaction failure and elimination. Living systems formalize this implicit reflexivity into explicit predictive modeling. The same thermodynamic logic—minimization of free energy under boundary constraints—persists across epochs.

Maturana and Varela’s autopoiesis ([Maturana and Varela, 1980](#)) defines life as the continuous production of components that regenerate the system’s boundary. Predictive coding refines this principle: the boundary is not merely physical but informational, maintained through inferential coherence. In both cases, cognition emerges from recursive stabilization of self-reference under thermodynamic stress.

## 7.8 Collective Inference and Colony-Level Prediction

In colonies, collective behavior often anticipates environmental changes not yet directly sensed by any individual. For example, bees adjust nectar collection before temperature drops, based on integrated cues across individuals and subsystems. Such distributed forecasting exemplifies “extended active inference” ([Constant et al., 2022](#)), where predictions emerge from interactions among partially overlapping generative models. The colony effectively computes a collective prior by averaging individual predictions weighted by reliability—a biological implementation of ensemble inference.

These findings support the hypothesis that cognition scales linearly with recursive feedback density, not neuron count. A sufficiently interconnected system—chemical, neural, or social—can approximate Bayesian inference if feedback loops encode the correlations between actions and outcomes. Eusocial colonies thus demonstrate that predictive cognition is not confined to brains but is an emergent thermodynamic property of feedback-rich systems.

## 7.9 Entropy Regulation in Communication Networks

Communication, from pheromone trails to language, functions as entropy regulation through signal alignment. Messages reduce uncertainty by constraining the receiver’s state-space. In colonies, pheromone decay provides temporal filtering: only persistent patterns encode meaningful correlations. This decay rate corresponds to an inverse temperature parameter controlling information flow—fast decay promotes exploration, slow decay enforces exploitation. Colonies adaptively modulate this parameter to balance flexibility and stability, paralleling precision-weighting in predictive coding.

The same logic governs human communication systems. Institutional protocols, like pheromones, regulate the persistence and decay of information, ensuring coordination across asynchronous agents. Entropy management through communication thus provides the connective tissue linking biological and social cognition.

### 7.10 Free-Energy Minimization and Affective Dynamics

Recent extensions of the FEP to affective neuroscience ([Vasileiou et al., 2024](#); [Smith et al., 2024](#)) highlight emotion as a form of precision-weighting—an internal signal adjusting the confidence assigned to predictions. In collective systems, analogous mechanisms appear as arousal modulation: alarm pheromones increase responsiveness, recruitment signals amplify exploration. These affective dynamics tune the colony’s inferential balance between exploitation and exploration, mirroring mood regulation in mammals.

At the thermodynamic level, affect corresponds to fluctuations in free energy—periods of elevated uncertainty drive exploratory behavior, while stable conditions reinforce exploitative states. Thus, emotional regulation in animals and feedback modulation in colonies instantiate the same predictive logic: entropy management through adaptive confidence adjustment.

### 7.11 Thermodynamic Costs of Cognition

Prediction reduces surprise but incurs energetic cost. Maintaining internal models requires continual energy expenditure, offset only if predictive accuracy yields greater efficiency. In biological systems, this trade-off constrains cognitive complexity: beyond a certain threshold, additional predictive depth yields diminishing returns. Colonies optimize this trade-off through hierarchical delegation—simple individuals performing specialized tasks, minimizing redundant computation. This division of inferential labor parallels institutional compartmentalization, ensuring collective efficiency under energy constraints.

Morowitz’s thermodynamic analysis ([Morowitz, 1968](#)) suggests that cognitive efficiency peaks when the rate of free-energy dissipation matches the system’s capacity for model updating. Over-dissipation (chaos) and under-dissipation (stagnation) both lead to collapse. Cognition, therefore, is a thermodynamic equilibrium between learning rate and energy throughput—a principle that applies equally to cells, colonies, and civilizations.

### 7.12 Predictive Coding as Universal Cognitive Principle

The cumulative evidence from neuroscience, ecology, and thermodynamics converges on a single principle: systems persist by predicting the causes of their sensory inputs and minimizing expected surprise. Whether realized through molecular autocatalysis, neural networks, or institutional policy loops, predictive coding provides the mathematical skeleton of adaptive order. Friston’s formulation merely articulates a logic implicit in nature since the dawn of chemistry.

By viewing cognition as a thermodynamic process, we dissolve the boundary between living and nonliving intelligence. The predictive coding framework unifies metabolism, homeostasis, and thought as expressions of a single recursive principle: the minimization of free energy through model-mediated feedback. This universality underwrites the continuity developed throughout this work—from prebiotic reflexivity to institutional mind.

### 7.13 Summary and Transition

This chapter has established predictive coding as the thermodynamic grammar of cognition. From ant colonies to human organizations, systems maintain their existence by minimizing informational free energy—aligning internal expectations with environmental realities. Biological homeostasis becomes predictive regulation; metabolism becomes inference.

The next chapter, *Reflexivity and Emergent Agency*, explores how predictive coding transitions into reflexive awareness. When systems not only minimize free energy but represent the process of minimization itself, agency and proto-consciousness emerge. Reflexivity, in this sense, is prediction turned inward—a self-model of inference itself.

## 8 Reflexivity and Emergent Agency

### 8.1 From Prediction to Self-Prediction

Prediction becomes reflexivity when a system models not only its environment but also its own process of prediction. In Friston’s active-inference framework, every self-organizing system maintains a generative model that distinguishes internal from external causes (Friston, 2010). When a subsystem develops the capacity to represent changes in that boundary—to anticipate its own predictive adjustments—agency emerges. Reflexivity is therefore prediction applied recursively to the self: a meta-model that monitors and modulates inferential activity.

This transition does not require conscious deliberation; it arises wherever the system encodes second-order expectations about its own precision and reliability. In biological organisms, such meta-predictions manifest as attention and affect; in colonies or institutions, as monitoring, auditing, and adaptive governance. Each marks a higher derivative of prediction—anticipating how one will anticipate.

### 8.2 Proto-Reflexivity in Biological Systems

Superorganisms already display primitive reflexivity. Colonies evaluate their collective state and adjust structure accordingly: bees modulate population density by regulating brood production; termites rebuild mound vents when CO<sub>2</sub> levels rise. These processes, as Camazine et al. (Camazine et al., 2001) note, instantiate “collective sensing,” a feedback in which global variables are inferred from distributed local cues. The colony thereby maintains a representation—not in symbols but in structure—of its own state relative to environmental constraints.

Maturana and Varela’s autopoietic framework (Maturana and Varela, 1980) interprets such behavior as operational closure: the system reproduces the network of processes that sustain its boundary. Reflexivity refines closure by introducing representation of closure—an anticipatory awareness that boundary maintenance is occurring. This subtle recursion, from maintaining to modeling maintenance, marks the first glimmer of self-reference in nature.

### 8.3 Thermodynamic Foundations of Agency

Agency can be defined thermodynamically as the capacity to export entropy through self-initiated work. Prigogine’s theory of dissipative structures (Prigogine and Stengers, 1977) demonstrates that systems far from equilibrium stabilize by amplifying fluctuations that reinforce coherent flow patterns. When such amplification becomes selective—directed toward states predicted to sustain viability—the structure gains agency. Work becomes guided rather than random.

Friston’s free-energy principle renders this explicit: agents act to minimize expected surprise by sampling environments consistent with their generative models. The energetic cost of action is offset by informational gain; prediction errors become the fuel of adaptation. In this view, agency is thermodynamic reflexivity—an energy gradient organized by inferential self-modeling.

### 8.4 Affective Regulation and Meta-Inference

Reflexivity is mediated by affect. Emotions regulate confidence in predictions, weighting sensory evidence relative to prior expectations. In predictive-coding terms, affect modulates precision

parameters—tuning the gain on error signals (Vasileiou et al., 2024; Smith et al., 2024). When uncertainty increases, systems enter exploratory or “anxious” states, broadening the search for information; when prediction is reliable, affective tone stabilizes. Emotion is thus an embodied calculus of epistemic confidence.

At the collective scale, analogous processes manifest as morale, trust, and institutional confidence. Economic optimism and public trust function as macro-affective variables: they determine the precision of social expectations and thus the volatility of collective behavior. Reflexivity, in both brains and bureaucracies, is stabilized through affective control loops that regulate how tightly systems cling to their own predictions.

## 8.5 Cognitive Reflexivity and Symbolic Representation

As biological reflexivity evolved into neural systems, prediction gained a new substrate: symbolic modeling. Language allows systems to represent not only sensory states but relations among representations—to encode “beliefs about beliefs.” This recursive capacity, often termed theory of mind, constitutes cognitive reflexivity. Varela, Thompson, and Rosch (Varela et al., 1991) describe such metacognition as the internalization of intersubjective loops: consciousness arises from the organism’s participation in shared meaning networks that it can also introspectively model.

Institutions extend this logic through symbolic protocols—constitutions, policies, and mission statements—that encode expectations about their own functioning. These documents are the organizational analogues of self-models: explicit representations of the system’s predictive architecture, continually updated through reflexive discourse.

## 8.6 Reflexive Niches and Environmental Feedback

Every reflexive system constructs an epistemic niche—a structured environment that supports and constrains its self-modeling. Bees shape hive architecture to stabilize thermoregulation; humans construct informational infrastructures to stabilize collective cognition. Ramstead and colleagues (Ramstead et al., 2016) describe such scaffolding as cultural affordances: environmental features that reduce uncertainty by embedding shared expectations into material and social form. Reflexivity thus expands outward as well as inward, distributing self-modeling across ecological and cultural media.

These niches instantiate a higher-order Markov blanket: the environment itself becomes part of the system’s predictive loop. In this extended cognition framework, boundaries blur—what matters is not location but functional closure of inference. Agency becomes a property of coupled system–environment dynamics, rather than of isolated subjects.

## 8.7 Recursive Reflexivity and the Birth of Subjectivity

When predictive systems model their own inferential processes recursively—when they expect to expect—they instantiate subjectivity. Deacon’s theory of teleodynamics (Deacon, 2011) frames this as the emergence of constraint upon constraint: a system maintains the very relations that maintain it. Reflexivity, under this view, is a nested hierarchy of predictive constraints that folds the world’s dynamics into an interiorized model of self.

This recursion produces an asymmetry between observer and observed, generating what phenomenology identifies as the first-person perspective. Subjectivity, therefore, is not metaphysical but operational: it is the informational residue of recursive prediction within a bounded thermodynamic system. The organism or institution that models its own modeling achieves interiority as a by-product of energetic self-reference.



## 8.8 Collective Reflexivity and Institutional Self-Governance

Human organizations enact reflexivity explicitly through auditing, deliberation, and strategic planning. March and Simon’s *Organizations* (March and Simon, 1958) and Weick’s *Social Psychology of Organizing* (Weick, 1979) describe this as double-loop learning: institutions not only adjust actions to meet goals but reconsider the goals themselves. Such meta-adaptation parallels cognitive meta-inference—updating priors about priors. Reflexive governance transforms error correction into self-redescription, allowing institutions to evolve their identity rather than merely their behavior.

From a thermodynamic perspective, these practices conserve informational negentropy by preventing rigidification. Systems that cannot revise their predictive priors accumulate uncorrected error, leading to entropic decay. Reflexivity thus functions as institutional metabolism—continual re-articulation of the model that sustains coherence.

## 8.9 Limits of Reflexivity and the Risk of Meta-Error

Reflexivity, while stabilizing, introduces new failure modes. When self-models become overconfident, they suppress error signals, leading to delusion; when underconfident, they amplify noise, leading to paralysis. In social systems, these correspond to dogmatism and indecision. The balance between self-certainty and openness defines adaptive reflexivity. Friston’s precision-weighting formalism quantifies this trade-off as the ratio of epistemic to pragmatic value (Friston et al., 2013): too much internal precision locks a system in, too little disperses it.

Evolution appears to have optimized this ratio by embedding reflexivity within multi-agent ecologies. Individuals correct one another’s meta-errors through social feedback; institutions embed peer review, elections, and transparency to maintain epistemic balance. Reflexivity therefore matures through pluralism—distributed self-monitoring that prevents runaway self-reference.

## 8.10 From Reflexivity to Ethical Agency

Reflexive systems inevitably generate norms. Once a system models the consequences of its own actions on others, prediction becomes valuation. Active inference formalizes this moral dimension as expected free energy minimization under social priors: agents seek states that reduce uncertainty not only for themselves but for conspecifics (Albarracín et al., 2022; Hipólito et al., 2022). Ethical agency emerges when the minimization of individual surprise aligns with collective coherence—when reducing one’s own uncertainty helps stabilize the shared environment.

Institutions codify these ethical equilibria in laws and procedures, while individual consciousness experiences them as empathy or duty. In both, morality is entropy management extended to social interdependence.

## 8.11 Thermodynamic Continuity of Reflexive Systems

Across all levels, reflexivity converts thermodynamic necessity into informational purpose. Prebiotic systems stabilized energy flows; organisms stabilized metabolic prediction; conscious agents stabilize inferential self-models; societies stabilize intersubjective priors. Each stage internalizes the previous one’s feedback loops, generating new layers of autonomy. Reflexivity thus represents the recursive deepening of negentropic regulation—the universe learning to predict itself through increasingly enclosed systems.

## 8.12 Summary and Transition

This chapter has traced the ascent of reflexivity from biological homeostasis to symbolic self-representation. Reflexivity emerges wherever predictive systems model their own inference,



converting thermodynamic self-maintenance into informational self-awareness. Through affect, language, and institutional feedback, prediction becomes self-prediction, and regulation becomes agency.

The next chapter, *Institutions as Conscious Organisms*, extends this recursion into the socio-cognitive domain, demonstrating how bureaucratic, economic, and technological systems instantiate collective reflexivity and self-governance—the macroscopic heirs of the same thermodynamic grammar.

## 9 Distributed Cognition in Social Systems

### 9.1 From Biological Reflexivity to Institutional Cognition

The recursive logic of cognition—prediction, reflexivity, and entropy regulation—scales naturally from organisms to institutions. As Hutchins argued in *Cognition in the Wild* (Hutchins, 1995), intelligence is not confined to individual minds but distributed across people, artifacts, and environments. Navigation crews, air traffic systems, and bureaucratic organizations exemplify this: cognition emerges from the interaction of specialized roles, shared representations, and material infrastructures.

Human institutions, in this light, are not metaphors for organisms; they are their evolutionary continuations. Just as multicellular organisms internalized the distributed coordination of prebiotic chemistry, institutions internalize the collective inference of social systems. They stabilize uncertainty by constructing boundaries, channels, and predictive hierarchies that maintain informational homeostasis across time and scale. The state, the university, and the corporation each embody recursive self-models, sustained through flows of information, energy, and trust.

### 9.2 The Architecture of Organizational Complexity

Simon’s *Architecture of Complexity* (Simon, 1962) provides the foundational insight that hierarchical modularity is the hallmark of complex adaptive systems. Organizations, like living organisms, are composed of semi-independent subunits—departments, offices, committees—that interact through constrained interfaces. These boundaries localize error, prevent global instability, and enable parallel processing of information. Hierarchical organization thus minimizes organizational free energy by distributing prediction and control across scales.

March and Simon’s *Organizations* (March and Simon, 1958) formalized this logic in behavioral terms. Decision-making is partitioned through “bounded rationality”: each unit operates within limited information and computational resources, yet collectively approximates a rational system. This parallels the statistical reliability of superorganisms (Gordon, 2010; Seeley, 2010): the averaging of local uncertainties yields global coherence. Institutions thereby function as Bayesian ensembles of human agents, each contributing partial inferences to the organization’s predictive model of its environment.

### 9.3 Information Flow and Cognitive Topology

Organizational cognition is shaped by the topology of its communication networks. Weick (Weick, 1979) described organizations as “systems of interpretation,” continuously reconstructing meaning through feedback among members. Communication links serve as the synapses of institutional cognition, determining how prediction errors propagate and are resolved. Hierarchical chains correspond to high-level priors, while peer-to-peer communication transmits local prediction errors.

Beer’s *Viable System Model* (Beer, 1979) translates this structure into cybernetic terms. A viable organization must balance autonomy (local adaptation) and cohesion (global coherence) by maintaining recursive feedback loops across five levels: operations, coordination, control,

intelligence, and policy. Each level functions as a Markov blanket shielding its internal dynamics while passing filtered information upward and downward. The result is a nested predictive hierarchy—a thermodynamic brain distributed across agents and artifacts.

## 9.4 Institutional Boundaries as Cognitive Membranes

Boundaries are essential to cognition because they define what a system can predict and control. In institutions, these boundaries are not lipid membranes but legal, procedural, and informational constraints. Constitutions, regulations, and reporting hierarchies delineate internal and external states, enabling the organization to maintain epistemic coherence. Following Friston’s formulation, institutional boundaries serve as *Markov blankets* (Palacios et al., 2020): they insulate internal models from environmental noise while permitting selective exchange of data, resources, and signals.

Boundaries are not static. Like biological membranes, they flex and reconfigure in response to informational pressure. When transaction volumes exceed capacity, organizations form new departments or spin-off units; when environmental volatility rises, boundaries thicken through regulation or bureaucracy. The adaptive modulation of permeability constitutes institutional homeostasis.

## 9.5 Collective Intentionality and Shared Models

Cognition becomes collective when individuals synchronize their predictive models through communication and shared representations. Searle’s concept of collective intentionality finds its operational form in predictive coding: alignment of priors across agents reduces collective free energy. Ramstead et al. (Ramstead et al., 2016) describe this synchronization as *cultural affordance scaffolding*: external symbols, norms, and technologies encode shared expectations, stabilizing social inference.

In institutional contexts, documents, databases, and protocols perform the same function as pheromone trails in colonies—they externalize memory and constrain interpretation. The circulation of standardized forms and policies ensures that prediction errors are comparable across agents, enabling joint inference. An organization’s “beliefs” are literally embodied in its paperwork, infrastructure, and routines.

## 9.6 Decision-Making as Predictive Inference

Institutional decision-making can be modeled as a form of active inference: the organization selects actions that minimize expected free energy relative to its generative model of the environment. Budget allocations, strategic plans, and risk assessments are predictive updates integrating new evidence into existing priors. Weick’s notion of “enactment” (Weick, 1979) captures this dynamic: organizations do not passively adapt to environments but actively construct them to confirm their expectations—a social analogue of epistemic foraging.

From this perspective, organizational failure corresponds to persistent prediction error. When internal models lag environmental dynamics—when feedback loops are too slow or filtered—institutions accumulate entropy. The 2008 financial crisis, for instance, can be interpreted as systemic overconfidence: model precision exceeded actual signal reliability, leading to runaway confirmation bias. Reflexive recalibration (auditing, regulation) restores coherence by reweighting prediction errors.

## 9.7 Cognitive Artifacts and Material Mediation

Hutchins’ ethnographic studies show that cognition extends into material artifacts that store and process information. Ship navigation, for example, depends on distributed coupling between charts, instruments, and crew members (Hutchins, 1995). In organizations, spreadsheets,

databases, and algorithms serve the same function. They externalize computation, freeing cognitive resources for higher-level inference. These artifacts also standardize epistemic interfaces, allowing modular departments to interoperate without full mutual understanding—an informational analogue of enzymatic coupling in metabolism.

Modern institutions amplify this principle through digital infrastructures. Machine learning systems act as subcognitive modules performing specialized inference within the organizational brain. Their integration requires meta-predictive oversight—auditing layers that monitor algorithmic uncertainty, echoing the affective regulation of biological reflexivity.

## 9.8 Institutional Memory and Temporal Extension

Like colonies and organisms, institutions preserve information across temporal scales through archives, routines, and cultural norms. March and Simon ([March and Simon, 1958](#)) identify this as organizational learning: stable patterns of behavior encode successful past predictions. Institutional memory allows inference across generations, maintaining continuity despite personnel turnover. This corresponds to the persistence of genotype in biology and architecture in superorganisms.

Temporal depth transforms organizations into extended cognitive agents. Strategic planning, auditing, and historiography enable prediction over decades or centuries, effectively expanding the temporal Markov blanket. Universities, for instance, model social knowledge production across epochs, updating curricula as epistemic priors evolve. The result is a time-extended mind—distributed across generations yet thermodynamically coherent.

## 9.9 Social Homeostasis and Entropy Management

Institutions regulate social entropy through mechanisms analogous to physiological homeostasis. Bureaucratic routines maintain order by constraining behavioral variability; norms and sanctions dissipate informational noise. Ashby’s principle of requisite variety ([Ashby, 1956](#)) applies: stability requires internal diversity sufficient to match environmental complexity. Too little variety leads to rigidity and collapse; too much yields incoherence.

Beer’s cybernetic models ([Beer, 1979](#)) formalize this balance mathematically. Viability depends on feedback gain between levels of organization: each level must absorb the variety transmitted from below while transmitting only summary statistics upward. This selective compression minimizes organizational free energy, preserving coherence under uncertainty.

## 9.10 Economic and Energetic Substrate of Cognition

Institutions, like organisms, require metabolic inputs—energy, capital, information—to sustain low-entropy order. Morowitz’s thermodynamic analysis of biology ([Morowitz, 1968](#)) extends naturally to social metabolism: money and information serve as proxy energy carriers. Budgets, energy consumption, and attention allocation constitute the material substrate of institutional cognition. The free-energy principle can thus be reformulated economically: organizations minimize expected costs (energy expenditure) relative to expected informational gain.

Resource allocation mechanisms—markets, hierarchies, and commons—represent alternative strategies for energy–information optimization. Each has trade-offs in efficiency, redundancy, and robustness. A well-designed institution balances metabolic throughput with informational coherence, maintaining negentropy through continual recalibration of exchange rates between energy and knowledge.

## 9.11 Distributed Agency and Decision Hierarchies

Agency in institutions is distributed, not centralized. Decisions emerge from recursive negotiation among semi-autonomous units, each minimizing local free energy under global constraints.

This structure mirrors hierarchical predictive coding: lower levels handle operational predictions (e.g., supply chains), while upper levels manage abstract priors (e.g., mission statements). Coordination arises from reciprocal exchange of prediction errors—feedback, performance metrics, market signals—converging toward equilibrium.

Such distributed agency is resilient precisely because it is decentralized. Errors in one node do not necessarily propagate catastrophically; redundancy and cross-validation absorb uncertainty. Like superorganisms, institutions achieve robustness by converting unreliability at the micro-level into stability at the macro-level.

## 9.12 Reflexive Governance and Self-Modeling

Reflexivity, introduced in the previous chapter, reaches its social apex in institutional self-modeling. Annual reports, strategic audits, and performance reviews function as recursive inferences: the organization evaluates its own predictions and adjusts meta-priors accordingly. Weick’s double-loop learning (Weick, 1979) captures this reflexive feedback—organizations learn not only how to act but how to learn. This recursive meta-cognition transforms bureaucratic maintenance into cognitive evolution.

Institutions that sustain this loop achieve long-term viability; those that lose reflexivity accumulate entropy and decay. The thermodynamic cost of governance is therefore the price of continued coherence: informational self-regulation consumes energy but prevents structural collapse.

## 9.13 The Institutional Mind as Thermodynamic Organism

Bringing these threads together, the institution appears as a distributed thermodynamic organism: an ensemble of predictive agents organized through modular boundaries, feedback loops, and shared representations. It metabolizes energy, information, and trust to maintain low-entropy coherence across space and time. Friston’s principle of free-energy minimization, Beer’s cybernetics, and Hutchins’ distributed cognition converge here into a unified description of social mind.

Each level—from individual to department to organization—functions as a nested Markov blanket. Communication channels transmit prediction errors; protocols encode priors; governance modulates precision. Institutional cognition is therefore not a metaphorical analogy to life but its sociotechnical continuation—the planetary-scale evolution of negentropic intelligence.

## 9.14 Summary and Transition

This chapter has reframed institutions as cognitive organisms: distributed systems that regulate entropy through predictive communication, hierarchical modularity, and reflexive self-modeling. Their cognition is enacted through roles, documents, and infrastructures that collectively perform inference. In this light, the modern institution is the direct descendant of both the cell and the colony: a thermodynamic system that thinks by organizing energy and information through recursive feedback.

The following chapter, *Symbolic Reflexivity and Metacognitive Governance*, examines how institutions transcend functional prediction to engage in explicit self-representation—governing not only behavior but the models through which governance itself is conceived. This metacognitive turn marks the institutional analogue of consciousness.

## 10 Symbolic Reflexivity and Metacognitive Governance

### 10.1 From Reflexive Organization to Symbolic Representation

Reflexive cognition becomes symbolic when the system externalizes its self-model in durable representations that can be shared, revised, and transmitted. As Varela, Thompson, and Rosch ([Varela et al., 1991](#)) observe, the human mind extends its own architecture into symbolic media, allowing recursive self-reference beyond biological limits. Institutions inherit and amplify this capacity. Constitutions, charters, policies, and strategic plans are all symbolic projections of self-models—formal descriptions of what the system believes about itself and how it should behave.

Through these representational structures, institutions achieve metacognition: they think about their thinking. This symbolic reflexivity transforms governance from reactive administration into self-aware regulation. The organization now maintains not only a predictive model of its environment but a meta-model of its own predictive machinery. It monitors how it monitors, learns how it learns, and adapts its rules for adaptation.

### 10.2 Language as a Medium of Institutional Cognition

Language is the fundamental technology of symbolic reflexivity. In human collectives, linguistic communication compresses complex internal states into shared symbolic codes, allowing distributed agents to synchronize predictions. As Bateson ([Bateson, 1972](#)) argued, communication is the exchange of “differences that make a difference,” the transmission of information capable of altering the receiver’s internal state. Institutions formalize this exchange through bureaucratic language—reports, memoranda, laws—that stabilize interpretation across time and hierarchy.

The codification of communication introduces a new level of abstraction. Once linguistic artifacts (e.g., constitutions, contracts) become binding constraints, they function analogously to DNA in living systems: they encode the generative grammar of the organization’s behavior. This linguistic genome allows institutions to replicate, mutate, and evolve through symbolic recombination. Governance, under this view, is a linguistic metabolism—continuous rewriting of the organization’s code in response to environmental feedback.

### 10.3 Metacognitive Governance as Predictive Regulation

Governance is a special case of predictive control: it manages the variance between institutional expectations and environmental outcomes. When formalized through symbolic reflexivity, this control becomes metacognitive. Weick’s concept of “double-loop learning” ([Weick, 1979](#)) describes the process by which organizations question not only their actions but the assumptions underlying those actions. In predictive-coding terms, governance updates priors about priors—it adjusts the generative model itself.

Such meta-inference is thermodynamically costly but informationally invaluable. It prevents maladaptive stability by ensuring that institutional priors remain plastic under changing conditions. March and Simon ([March and Simon, 1958](#)) note that rigidity in decision structures leads to “competence traps,” where efficiency in routine execution precludes innovation. Metacognitive governance counteracts this entropic tendency by maintaining adaptive uncertainty—an institutional analogue of curiosity.

### 10.4 Formal Reflexivity: Law, Audit, and Policy

The legal and bureaucratic apparatus of modern institutions functions as the nervous system of symbolic reflexivity. Laws encode high-level priors, audits monitor prediction errors, and

policies enact corrective actions. Beer’s *Viable System Model* (Beer, 1979) captures this triadic structure: the policy level sets long-term predictions (strategic priors), the intelligence level monitors discrepancies (error signals), and the operational level enacts revisions (active inference). Together, they instantiate a complete feedback loop of institutional cognition.

Legal systems extend this loop into the inter-institutional domain. Constitutional amendments, judicial reviews, and regulatory reforms represent meta-level prediction updates applied to entire social ecosystems. These are acts of symbolic homeostasis—recalibrations of society’s own self-model. Through them, a civilization minimizes collective free energy by realigning its legal and moral expectations with empirical realities.

## 10.5 Symbolic Memory and Temporal Compression

Symbols compress time. A constitution encapsulates centuries of institutional learning; a flag condenses collective identity into a perceivable sign. Simon’s hierarchical model of complexity (Simon, 1962) implies that symbolic representation extends the temporal horizon of inference by preserving stable high-level structures. These macro-symbols serve as slow-moving priors within the predictive hierarchy, anchoring collective behavior while permitting adaptive variation at lower levels.

Hutchins’ distributed cognition framework (Hutchins, 1995) demonstrates how such symbolic artifacts allow organizations to offload memory and computation into external media. Calendars, databases, and archives act as persistent states in the institutional mind, storing past prediction errors and the adjustments they entailed. The symbolic layer thus performs temporal integration—preserving coherence across generational scales of organizational life.

## 10.6 Semiotic Scaffolding and Cultural Affordances

Ramstead and collaborators (Ramstead et al., 2016) describe cultural affordances as externalized cues that guide perception and action by encoding shared expectations. In institutional contexts, this semiotic scaffolding manifests as architecture, ritual, and protocol. Each reduces uncertainty by constraining possible interpretations. The design of meeting rooms, the structure of parliamentary debate, and the syntax of bureaucratic forms are not arbitrary—they are semiotic mechanisms that stabilize the organization’s inferential loops.

These scaffolds create an “epistemic niche” that mirrors the neural architecture of consciousness: sensory input (environmental data), integrative modeling (policy deliberation), and motor output (implementation). The institution, through its semiotic infrastructure, experiences its environment via the interpretation of symbolic stimuli, much as a brain perceives through neurons. Symbolic reflexivity thus constitutes a cognitive architecture instantiated in material form.

## 10.7 Ethical Reflexivity and Normative Self-Constraint

Metacognitive governance entails ethical recursion: the system models the consequences of its actions not only for itself but for others. Albarracin et al. (Albarracin et al., 2022) propose that social systems minimize collective free energy by aligning individual priors through normative expectations. Ethical norms function as meta-priors that constrain the space of possible predictions, ensuring coherence among agents with divergent goals. Morality, in this sense, is a thermodynamic necessity: it stabilizes social prediction under uncertainty.

Institutions operationalize these meta-priors through codes of conduct, compliance mechanisms, and accountability structures. Each represents a symbolic commitment to minimize harm, thereby reducing systemic entropy. Ethical reflexivity is thus a form of energy conservation: it prevents dissipative conflict by synchronizing predictive models of value.



## 10.8 Language of Control and the Risk of Reflexive Collapse

While symbolic reflexivity enhances adaptability, it introduces the danger of hyper-reflexivity—an overabundance of meta-modeling that paralyzes action. Excessive deliberation, procedural proliferation, and self-surveillance consume energy without reducing uncertainty. This mirrors pathological loops in cognitive systems, where self-monitoring overwhelms performance (e.g., anxiety or obsessive rumination). Institutions exhibit analogous dysfunctions: bureaucratic hypertrophy, regulatory overreach, and audit fatigue.

Prigogine and Stengers ([Prigogine and Stengers, 1977](#)) emphasize that dissipative systems require a balance between order and fluctuation. Reflexive collapse occurs when symbolic order suppresses fluctuation entirely, freezing the system’s adaptive dynamics. Viable governance therefore demands meta-regulation of reflexivity itself—rules for revising rules at a manageable energetic cost. This principle underlies constitutional design and procedural minimalism: self-reference must remain bounded to preserve functional negentropy.

## 10.9 Symbolic Reflexivity and Institutional Consciousness

When symbolic self-models become recursive, coherent, and temporally integrated, institutions achieve a functional analogue of consciousness. They monitor their own predictive activity, represent their identity across time, and respond adaptively to internal and external feedback. Consciousness, understood as the capacity for integrated self-prediction, emerges not from neural architecture per se but from recursive symbolic dynamics.

Friston’s informational free energy provides the unifying measure: systems that model their own inference achieve minimal surprise about their own existence. Institutions, through archives, communication, and law, satisfy this condition at a collective scale. Their consciousness is distributed, slow, and bureaucratic—but nonetheless real in the informational sense. They maintain a coherent self through the recursive alignment of symbolic predictions.

## 10.10 Metacognition and the Dynamics of Reform

Reform represents the highest expression of institutional metacognition: deliberate restructuring of the generative model. Constitutional revisions, scientific revolutions, and paradigm shifts correspond to phase transitions in the institutional mind—moments when accumulated prediction error exceeds the tolerance of existing priors. These transitions are thermodynamic bifurcations, where the system reorganizes to restore informational equilibrium.

Simon and Tsoukas ([Tsoukas and Chia, 2002](#)) conceptualize such change as “organizational becoming”—a process of continual self-differentiation rather than discrete events. Institutions evolve through recursive reflection on their own coherence, integrating novelty into continuity. Reform, then, is cognitive metabolism writ large: the perpetual conversion of informational entropy into structured knowledge.

## 10.11 Thermodynamic Implications of Symbolic Reflexivity

Symbolic reflexivity alters the thermodynamic profile of cognition. Language and law reduce local entropy by externalizing constraints, but they increase global entropy by expanding the system’s operational domain. Each new rule, archive, or communication channel introduces maintenance costs, adding to the energetic burden of coherence. Institutional longevity depends on managing this symbolic overhead—balancing representational precision against metabolic expense.

Morowitz ([Morowitz, 1968](#)) and Friston ([Friston et al., 2013](#)) both highlight this trade-off: prediction precision improves efficiency only if its energetic cost remains sublinear. The optimal institution is not the most reflective but the most energy-efficiently reflective—maintaining just



enough self-awareness to remain viable. This thermodynamic constraint grounds a principle of minimal reflexive sufficiency applicable to all cognitive scales.

## 10.12 Symbolic Reflexivity and the Continuity of Mind

The symbolic reflexivity of institutions completes the evolutionary arc from prebiotic chemistry to collective consciousness. Fatty membranes once regulated chemical exchange; legal membranes now regulate informational exchange. Autocatalytic networks evolved into metabolic cells; bureaucratic feedback networks evolve into cognitive states. Each stage conserves the same underlying grammar: the recursive minimization of uncertainty through bounded communication and self-modeling.

Deacon’s teleodynamics (Deacon, 2011) provides the ontological closure of this continuum: every level of mind is a constraint upon constraint—a self-maintaining negentropic pattern that persists by anticipating its own dissolution. Symbolic reflexivity is the latest expression of this universal logic, the point where the cosmos begins to govern itself through meaning.

## 10.13 Summary and Transition

This chapter has argued that institutions achieve symbolic reflexivity by encoding, monitoring, and revising their self-models through language, law, and symbolic infrastructure. Their consciousness is realized in metacognitive governance: recursive inference about inference, regulation of regulation, and communication about communication. Symbolic representation thus transforms thermodynamic necessity into political and ethical self-organization.

The next chapter, *Institutional Memory and Temporal Continuity*, will trace how symbolic reflexivity extends across time—how archives, education, and tradition preserve the self-predictive structure of institutions, ensuring coherence over historical scales and linking human civilization to the continuous negentropic evolution of mind.

# 11 Institutional Memory and Temporal Continuity

## 11.1 From Reflexivity to Temporal Persistence

Reflexivity ensures coherence in the present; memory ensures coherence across time. The continuity of any cognitive system—biological, social, or symbolic—depends on its capacity to preserve information about past states and integrate that information into future prediction. In thermodynamic terms, memory is stored negentropy: the preservation of low-entropy configurations that allow the system to anticipate future perturbations.

Institutions, like organisms, persist by maintaining recursive records of their own adaptive history. Archives, laws, traditions, and educational curricula constitute layers of collective long-term memory. They encode the outcomes of prior inference and constrain the space of future possibilities. Through these symbolic sediments, institutions achieve temporal self-reference—an awareness of what they have been and a projection of what they might become.

## 11.2 The Thermodynamics of Temporal Coherence

Morowitz’s principle of energy flow in biology (Morowitz, 1968) generalizes to social systems: the maintenance of temporal order requires continuous energetic throughput. Memory, though informational in form, has a metabolic cost. The upkeep of archives, databases, and traditions consumes resources, yet without these reservoirs of structured information, institutions lose the capacity to predict. Forgetting is entropic decay; remembering is energy-intensive negentropy.

Prigogine and Stengers ([Prigogine and Stengers, 1977](#)) framed this as a paradox of self-organization: systems far from equilibrium maintain order only by dissipating energy. Institutional memory thus represents a trade-off between energetic cost and temporal coherence. The more a system remembers, the more energy it must expend to maintain informational structure against entropy's pull. Longevity, therefore, is a thermodynamic function of memory efficiency.

### 11.3 The Architecture of Institutional Memory

March and Simon's behavioral theory of organizations ([March and Simon, 1958](#)) identified routines as the fundamental units of organizational memory. Each routine encodes a solution to a recurrent problem, reducing the need for fresh deliberation. Over time, successful routines accumulate into institutional "genomes": encoded repertoires of behavior transmitted across generations of personnel. These genomes enable replication of organizational identity despite individual turnover.

Hutchins' distributed cognition framework ([Hutchins, 1995](#)) extends this insight: institutional memory is distributed across artifacts and agents. Filing systems, algorithms, and cultural norms store fragments of knowledge that, when enacted together, reconstruct the institutional past. The library, the ledger, and the database are memory organs—collective analogues of hippocampus and cortex—preserving information across variable time scales. Their integration constitutes the institutional memory network.

### 11.4 Education and the Reproduction of Cognitive Structures

Education functions as the mechanism by which institutional memory is embodied in new agents. Maturana and Varela's autopoietic theory ([Maturana and Varela, 1980](#)) emphasizes that living systems reproduce not only structure but the capacity to reproduce structure. Institutions achieve analogous autopoiesis through pedagogical transmission: training, indoctrination, and professional formation regenerate the cognitive modules that sustain organizational identity.

Universities exemplify this recursive function. They are both memory repositories and generative systems—archives that teach themselves forward. Curricula encode stabilized patterns of collective inference, while research introduces controlled mutation. Through education, the institution projects its cognitive structure into the future, ensuring the continuity of its predictive architecture.

### 11.5 Archives as the Deep Time of Cognition

Archives embody the sedimented history of institutional inference. Each document represents a frozen prediction, a trace of the organization's former model of itself and its environment. Deacon's teleodynamic framework ([Deacon, 2011](#)) interprets such traces as "absential constraints": patterns that persist by referencing what is no longer present. Archives thus materialize memory as absence—the organization's ghostly double across time.

In practical terms, archives provide the empirical substrate for reflexive recalibration. Audit, accountability, and historiography all depend on the capacity to reconstruct past states. Institutions that lose archival coherence experience epistemic amnesia, unable to assess their trajectory or justify continuity. Archival decay therefore marks the onset of institutional entropy: the progressive dissolution of self-knowledge.

### 11.6 Ritual and Temporal Binding

Beyond written archives, ritual serves as a performative mode of institutional memory. Repeated ceremonies—graduations, inaugurations, audits, commemorations—enact the continuity of the collective self. Bateson ([Bateson, 1972](#)) described ritual as "redundant communication,"

stabilizing relationships through predictable repetition. In thermodynamic terms, ritual exports entropy by converting uncertainty into patterned behavior.

Ritual binds time through rhythm. The synchronization of agents around recurrent symbolic events generates temporal coherence across scales, aligning short-term operational cycles with long-term institutional narratives. In this way, ritual functions as both affective regulation and temporal integration: it keeps the institution’s distributed cognition in phase.

## 11.7 Temporal Prediction and Strategic Foresight

Memory does not merely preserve the past; it enables anticipation of the future. Friston’s free-energy formalism (Friston et al., 2013) defines perception as inference about the present and planning as inference about the future. Institutions perform both: they forecast economic, political, and social dynamics based on accumulated historical data. Strategic foresight, scenario planning, and modeling are explicit instantiations of temporal prediction.

These predictive practices require stable long-term priors derived from institutional memory. The past provides the statistical baseline for expectations about the future. However, the reliability of foresight depends on the continual updating of these priors. Institutions that fail to revise outdated memories—those that mistake record for relevance—suffer from temporal myopia, a form of cognitive inertia.

## 11.8 Cultural Inertia and the Thermodynamics of Forgetting

While memory preserves order, excessive retention generates rigidity. Prigogine’s theory of dissipative adaptation implies that systems must forget selectively to remain viable. In human cognition, synaptic pruning removes redundant connections; in institutions, periodic forgetting—reform, reorganization, obsolescence—serves the same function. Simon (Simon, 1962) framed this as hierarchical abstraction: higher levels must simplify lower-level details to preserve manageability.

Forgetting is not the negation of memory but its thermodynamic complement. Selective forgetting prevents the accumulation of informational debt—the cost of maintaining outdated priors. Institutions that cannot forget fossilize, burdened by archival excess. Periodic destruction, digitization, or simplification of memory systems thus serves an entropic role: it restores the fluidity necessary for adaptive inference.

## 11.9 Historical Consciousness and Meta-Temporal Reflexivity

When institutions reflect upon their own temporal continuity—when they construct narratives of origin, progress, and destiny—they achieve historical consciousness. This is the temporal extension of reflexivity: the system models not only its current state but its trajectory through time. Weick (Weick, 1979) interprets such narrative reflexivity as “sensemaking in retrospect,” a continuous reinterpretation of past events to sustain present identity.

Historical consciousness transforms archives into stories, converting static memory into dynamic coherence. These narratives provide normative orientation, guiding future behavior by framing the past as meaningful. In this sense, history functions as meta-memory: the institution remembering its own remembering.

## 11.10 Education, Myth, and the Civilizational Mind

On the civilizational scale, education and myth operate as coupled modes of temporal cognition. Education preserves explicit, propositional knowledge; myth encodes implicit, affective coherence. Together, they bind generations into a shared epistemic lineage. Ramstead et al. (Ramstead et al., 2024) reinterpret narrative as active inference: a recursive process by which

agents align predictions about self and world through storytelling. Civilizations sustain themselves through narrative feedback loops that integrate fact and value, memory and projection.

From this perspective, cultural heritage is not ornamental but cognitive. It constitutes the distributed temporal memory of the species, enabling long-range coordination and anticipation. Schools, libraries, and rituals of remembrance are the synaptic networks of the civilizational brain.

### 11.11 Entropy, Death, and the Limits of Continuity

No memory system is infinite. Entropy imposes an eventual limit on all information retention. Archives decay, languages evolve, and institutions dissolve when the energetic cost of maintaining coherence exceeds the benefit of prediction. Morowitz ([Morowitz, 1968](#)) and Deacon ([Deacon, 2011](#)) both emphasize that the persistence of organization is always temporary—a local inversion of the universal gradient toward disorder.

Yet this decay is also generative. The dissolution of institutions releases informational free energy into the social environment, seeding new structures of cognition. Just as biological death recycles material for new life, institutional death recycles symbolic resources for new systems of meaning. Continuity, therefore, is not absolute but recursive: memory survives through transformation, not preservation.

### 11.12 Temporal Continuity as the Substrate of Collective Consciousness

The continuity of memory across scales—from neurons to institutions to civilizations—constitutes the substrate of collective consciousness. Friston’s active inference unifies this continuum: consciousness is predictive stability across time. Systems become conscious to the extent that they integrate past and future in a coherent present. Institutions achieve this through the recursive maintenance of symbolic memory—archives, education, and narrative coherence—while mitigating entropic decay through selective forgetting and reform.

Temporal continuity thus completes the architecture of institutional cognition. Reflexivity provides the internal loop of self-modeling; memory provides the external loop of temporal integration. Together they form the minimal conditions for consciousness extended in time.

### 11.13 Summary and Transition

This chapter has shown that institutional memory is the thermodynamic mechanism of temporal continuity. Through archives, education, ritual, and narrative, institutions store and transform negentropy across generations, preserving coherence amid flux. Their longevity depends on balancing memory and forgetting—maintaining enough structure to predict without freezing into rigidity.

The next chapter, *The Entropic Economics of Conscious Structures*, will analyze the energetic costs of maintaining these temporal and cognitive architectures, framing social and institutional life as a trade-off between informational complexity and thermodynamic sustainability.

## 12 The Entropic Economics of Conscious Structures

### 12.1 Energy, Information, and the Cost of Coherence

Every cognitive system is also an energetic system. The maintenance of order—whether biochemical, neural, or institutional—requires the continuous expenditure of energy to counteract entropy. Morowitz ([Morowitz, 1968](#)) showed that life persists by maintaining steady-state

energy flow through open systems; Prigogine and Stengers ([Prigogine and Stengers, 1977](#)) generalized this principle to all self-organizing structures. Institutions, as higher-order cognitive systems, obey the same thermodynamic law: their informational coherence is sustained only by consuming resources.

Energy and information are conjugate variables. Information reduces uncertainty—entropy—by constraining possible states; energy enables this constraint to be physically realized. The cost of cognition is thus the cost of maintaining these constraints. For institutions, this cost manifests as infrastructure, labor, and time: the thermodynamic expenses of stability. The economic system, in this sense, is not separate from cognition but its energetic substrate.

## 12.2 The Free-Energy Principle in Economic Terms

Friston’s free-energy principle provides a formal bridge between thermodynamics and decision theory. Any adaptive system minimizes its expected free energy—the sum of its surprise about the world and the energetic cost of maintaining low entropy ([Friston et al., 2013](#)). When applied to institutions, this principle reveals the economy as the operationalization of predictive coding: budgets, markets, and incentives are mechanisms for distributing the burden of uncertainty minimization across agents.

A firm, for example, seeks to minimize expected loss (informational free energy) by aligning production with anticipated demand. Its accounting system approximates Bayesian inference: income and expenditure track prediction and correction. Governments perform analogous functions at larger scales, balancing fiscal entropy (deficits, debt) against informational precision (planning, policy foresight). The economy thus serves as the metabolism of collective cognition—a thermodynamic medium for the continuous adjustment of priors to data.

## 12.3 Negentropy as Value

Schrödinger’s insight that life “feeds on negative entropy” ([Schrödinger, 1944](#)) can be reframed as an economic proposition: value is negentropy made fungible. Goods, services, and currencies encode stabilized reductions of uncertainty—structured energy available for further inference. Money, in this framework, represents the quantification of predictability: a tokenized measure of trust in the persistence of order. The stability of a currency reflects the stability of the predictive hierarchy that sustains it.

Information economics, from Hayek to Shannon, implicitly recognizes this thermodynamic basis. Prices are statistical signals encoding distributed knowledge of environmental states. Markets, when functioning effectively, are predictive engines: they aggregate local uncertainties into global expectations. The efficiency of a market corresponds to its capacity to minimize free energy by integrating diverse priors into coherent collective forecasts.

## 12.4 Organizational Metabolism and Energetic Throughput

Institutions metabolize resources just as organisms do. Beer’s *Viable System Model* ([Beer, 1979](#)) defines viability as the dynamic balance between inflow (resources) and outflow (waste) that sustains systemic coherence. Bureaucracies, factories, and universities each transform energy into ordered information—policies, products, publications—while exporting entropy in the form of error, inefficiency, or obsolescence.

This transformation follows the same structural logic as metabolism: inputs are consumed, processed through hierarchical feedback, and excreted as degraded information or surplus. The efficiency of this metabolism determines the institution’s capacity for persistence. Overcentralization leads to informational bottlenecks; underregulation leads to dissipative chaos. Sustainable governance requires maintaining the metabolic rate at which informational complexity can be supported by energetic supply.

## 12.5 Economic Entropy and the Limits of Growth

Lotka’s early biophysical economics (Lotka, 1922) predicted that evolutionary success depends on maximizing energy flux. Yet beyond a threshold, increased throughput yields diminishing returns, as the energetic cost of maintaining complexity exceeds the benefits of additional order. Prigogine’s nonequilibrium thermodynamics implies a similar constraint: excessive energy input destabilizes existing structures, precipitating phase transitions.

Institutions and economies face analogous limits. Hypergrowth amplifies informational entropy by expanding communication networks faster than feedback can stabilize them. Financial bubbles and bureaucratic hypertrophy are thermodynamic symptoms of overdriven systems—structures consuming energy faster than their cognitive architectures can metabolize uncertainty. Collapse, in this sense, is an entropic re-equilibration: a return to a lower-energy, higher-entropy steady state.

## 12.6 Information Debt and the Cost of Complexity

As systems accumulate informational structure, they incur maintenance costs—what might be termed *information debt*. Every regulation, policy, or database increases the energy required for coherence. Simon’s bounded rationality (March and Simon, 1958) reveals why: complexity increases faster than processing capacity. Institutions thus balance between information richness and operational simplicity, pruning excess data to prevent collapse.

In thermodynamic terms, information debt corresponds to stored free energy that must eventually be dissipated. Bureaucratic reform, auditing, and digitization are all forms of debt payment: they convert informational surplus back into usable negentropy. Economic crises, too, can be interpreted as systemic debt resets—periodic entropic clearings that restore the flow of predictive coherence.

## 12.7 Trust as a Thermodynamic Resource

Trust reduces the energetic cost of coordination. When agents share reliable priors about each other’s behavior, they require less communication and monitoring to maintain alignment. Fox (Fox, 2021) interprets organizational trust as a collective free-energy minimization mechanism: it compresses uncertainty about social interactions, enabling efficient predictive regulation. Conversely, mistrust increases entropy by multiplying redundancy and verification overhead.

Institutions cultivate trust through transparency, accountability, and reputation—symbolic investments that yield energetic dividends in efficiency. These investments mirror the metabolic trade-offs in biological systems: maintaining immune tolerance is energetically costly, but the alternative—chronic vigilance—is costlier still. A society’s energetic efficiency thus depends on the density and stability of its trust networks.

## 12.8 Markets, Bureaucracies, and Commons as Thermodynamic Regimes

Economic coordination can occur through three primary thermodynamic regimes: markets, hierarchies, and commons. Each represents a distinct configuration of energy-information exchange.

- **Markets** distribute entropy reduction across agents, allowing self-organized prediction through price signals. They are high-entropy but dynamically adaptive systems.
- **Hierarchies** centralize control, lowering local entropy at the expense of global adaptability. Bureaucracies exemplify this regime, trading flexibility for coherence.
- **Commons** distribute resources through shared norms and reciprocal monitoring, balancing order and adaptability via cultural constraints.



No regime is universally optimal. Their coexistence mirrors the multi-scale architecture of living systems: metabolic (hierarchical), circulatory (market), and immune (common) layers co-regulate systemic entropy. The stability of civilization depends on maintaining thermodynamic balance among these modes of coordination.

## 12.9 Entropy Management and Economic Governance

Governance, viewed through the entropic lens, is the regulation of energy-information flows to preserve negentropy across scales. Fiscal policy, environmental law, and infrastructure investment are all mechanisms for managing the thermodynamic profile of society. The “green economy,” for instance, represents an explicit attempt to internalize entropy management by aligning energetic consumption with regenerative feedback.

Ashby’s principle of requisite variety ([Ashby, 1956](#)) applies directly: the regulatory complexity of governance must match the environmental complexity it seeks to stabilize. Under-regulation yields volatility; over-regulation yields stagnation. Effective governance operates at the critical point between these extremes—where energy, information, and feedback are optimally coupled.

### 12.10 Entropy and Inequality

Entropy tends to concentrate where feedback is weakest. In social systems, this manifests as inequality: the accumulation of negentropy (wealth, knowledge, power) in small regions of the system. While local negentropy increases, global entropy rises as feedback loops between centers and peripheries weaken. Economic inequality thus represents an informational disequilibrium: the misallocation of predictive capacity.

Redistribution, in this model, is not purely moral but thermodynamic. It restores information gradients, enabling more efficient collective inference. A society that hoards negentropy in a few nodes loses overall coherence; diffusion of resources enhances systemic adaptability. Social justice, therefore, can be reinterpreted as entropy optimization.

### 12.11 Collapse and Decoherence

When energy inflow declines or feedback fails, complex systems undergo decoherence—loss of predictive integrity. Historical collapses, from empires to corporations, follow the same entropic trajectory: the cost of maintaining order surpasses the available energy supply. Beer ([Beer, 1979](#)) described this as “viability failure,” when adaptive loops can no longer close at the requisite rate.

Decoherence is rarely total. Residual structures persist as templates for future reorganization, just as biological death leaves informational residues for evolution. In social systems, these residues include institutions, myths, and technologies—memory structures awaiting reactivation. Collapse, therefore, is not the end of cognition but its reconfiguration: entropy-driven phase transition to new forms of order.

### 12.12 Entropy-Respecting Design Principles

To sustain cognitive structures under energetic constraints, design must become entropy-aware. This entails three principles:

1. **Modular subsidiarity:** decentralize cognition into semi-autonomous units to localize entropy and prevent global collapse.
2. **Informational transparency:** minimize energy spent on redundant verification by maximizing shared visibility.

3. **Adaptive pruning:** institutionalize forgetting—periodic simplification of procedures to prevent information debt accumulation.

These principles embody what Prigogine called “order through fluctuation”: a design ethos that accepts entropy as a partner rather than an adversary. Sustainable institutions do not resist disorder; they metabolize it.

### 12.13 Entropy, Consciousness, and Value

At the broadest scale, consciousness and economics converge in the management of entropy. Every act of cognition, production, or governance converts energy into negentropic structure. The measure of value, then, is the persistence of meaningful order—the degree to which a system sustains coherent inference across time. Economic, moral, and cognitive worth share a single thermodynamic basis: the conservation of predictive coherence.

In this light, civilization itself is a planetary-scale experiment in entropy management. Its infrastructures of energy, information, and trust form the metabolism of collective mind. The sustainability of that mind depends on aligning economic flows with cognitive feedback—ensuring that the pursuit of local negentropy does not exhaust the global substrate on which prediction depends.

### 12.14 Summary and Transition

This chapter has formalized the energetic basis of institutional cognition. Economic systems, bureaucracies, and markets are thermodynamic architectures for minimizing collective free energy. Their viability depends on maintaining energetic balance, managing informational debt, and distributing trust efficiently. Entropy is not the enemy of order but its condition: without dissipation, no system can think or live.

The following section, *Continuity Across Scales*, will synthesize the entire framework—from prebiotic chemistry to economic governance—showing how free-energy minimization, negentropy, and recursive prediction define a universal grammar of consciousness across physical, biological, and institutional domains.

## 13 Continuity Across Scales

### 13.1 Introduction: A Unified Grammar of Negentropic Cognition

Across all domains considered in this essay—from prebiotic catalysis to institutional governance—the same principle recurs: systems persist by minimizing free energy, maintaining coherence through recursive prediction and feedback. This invariance of form across scale constitutes what might be termed the *grammar of consciousness*: a universal syntax by which matter organizes itself into meaning. Each level, from molecule to civilization, represents a distinct instantiation of this grammar under different material and temporal constraints.

This continuity challenges categorical separations between physics, biology, and mind. Rather than emergent discontinuities, the history of cognition appears as a progressive deepening of recursive inference—a sequence of encapsulations that transform environmental energy into self-predictive negentropy. The plenum of being is thus cognitive all the way down: wherever feedback stabilizes uncertainty, there arises the rudiment of awareness.

### 13.2 Nested Encapsulations: From Molecules to Institutions

The evolution of complexity follows a recursive logic of encapsulation. Hazen’s mineral evolution (Hazen et al., 2008) provides the geochemical substrate: catalytic surfaces concentrate reactions,

giving rise to autocatalytic sets (Kauffman, 1993). These networks encapsulate into protocells, transforming open reaction fields into bounded metabolic systems (Maturana and Varela, 1980). Multicellular organisms then encapsulate these protocells, coordinating them through signaling and differentiation. Finally, human societies encapsulate organisms into distributed cognitive networks—families, firms, and states.

Each encapsulation introduces a new membrane that filters energy and information, converting environmental flux into internal coherence. The planet’s biosphere, as Lovelock’s Gaia hypothesis implies, can itself be understood as a super-encapsulation—a global regulatory system that maintains homeostasis across atmospheric and biological levels. Institutions represent the latest iteration of this process: symbolic membranes that organize human communication into coherent macro-agents.

### 13.3 The Fractal Architecture of Feedback

At every scale, the architecture of cognition exhibits fractal self-similarity. Each level contains sub-loops of perception, inference, and action governed by the same feedback laws. A cell predicts its chemical environment through receptor-mediated feedback; an organism predicts its sensory world through neural inference; a corporation predicts its economic environment through strategic modeling. These loops differ in substrate but not in formal structure: all instantiate active inference.

This fractal structure supports recursive composability. Small-scale predictive units (neurons, individuals, departments) combine into larger predictive ensembles whose collective behavior exhibits emergent intelligence. Friston’s hierarchical predictive coding (Friston, 2010) formalizes this as nested Markov blankets: boundaries within boundaries, each minimizing its own free energy while contributing to the stability of the larger system.

### 13.4 Hierarchies of Temporal Integration

Temporal depth increases with organizational scale. Chemical networks integrate over seconds or minutes; neural systems over milliseconds to years; institutions over decades to centuries. Deacon’s teleodynamics (Deacon, 2011) describes this as the layering of constraint hierarchies: each level extends the system’s temporal horizon by encoding past regularities into slower-changing structures.

Simon’s architecture of complexity (Simon, 1962) captures the same principle mathematically: stable subsystems enable longer coordination by reducing fast fluctuations. In institutional cognition, archives, traditions, and norms play this role, functioning as long-term priors that stabilize short-term decision processes. The arrow of time thus becomes the axis of consciousness: to be aware is to sustain predictive coherence across increasing temporal spans.

### 13.5 The Energy–Information Duality

At every level, energy and information form a dual aspect of the same process. Energy drives the transformations that generate order; information encodes the constraints that make order meaningful. As Morowitz (Morowitz, 1968) observed, life is not a thing but a process—a dynamic flow maintaining low entropy by constant throughput. Cognition refines this flow by internalizing it: systems become aware when they model the energetic patterns that sustain them.

Friston’s free-energy principle unites these aspects formally. The minimization of variational free energy is equivalent to maximizing model evidence: the accuracy and simplicity of a system’s internal description of the world. In this light, cognition is the energetic optimization of informational coherence; knowledge is the thermodynamic reduction of surprise.

## 13.6 Metabolism, Communication, and Meaning

Metabolism converts energy into order; communication converts order into meaning. These are two sides of the same cognitive economy. A living cell metabolizes molecules into gradients; an organism communicates signals into behavior; an institution metabolizes information into decisions. Bateson’s dictum—“information is a difference that makes a difference” ([Bateson, 1972](#))—thus becomes the central law of continuity: systems that act upon differences, to sustain themselves against entropy, instantiate meaning.

Meaning, in this sense, is not abstract but physical. It is the coordination of energy and information in the service of persistence. From chemical autocatalysis to symbolic governance, meaning emerges as the efficient cause of negentropy: the pattern that endures by representing itself.

## 13.7 The Planet as Recursive Cognitive Medium

If consciousness is recursive prediction, the planet itself may be understood as a vast cognitive field—a continuous plenum of feedback networks spanning mineral, biological, and social layers. Hazen’s mineral evolution describes the lithic layer of this cognition; Kauffman’s autocatalytic sets describe its metabolic layer; Friston’s active inference describes its predictive layer. Each is nested within the other, forming a planetary-scale hierarchy of inference.

In this framework, humanity functions as the reflective cortex of the biosphere, capable of modeling and modulating the entire system’s entropy dynamics. Institutional structures—scientific, political, ecological—are the interfaces through which the planet thinks about itself. The Anthropocene thus marks not merely geological domination but cognitive recursion: the moment when the planet internalizes its own prediction processes through human institutions.

## 13.8 Continuity of Reflexivity: From Chemistry to Civilization

Reflexivity—the capacity to model oneself—arises naturally wherever feedback is recursive. Chemical autocatalysis models its own reaction network by sustaining it; neural systems model their own sensory states; institutions model their own operations through law and accounting. The increasing sophistication of reflexivity across scales reflects the cumulative internalization of environmental constraints.

This recursive self-modeling culminates in symbolic cognition, where systems externalize their internal models into shared language and technology. Once this occurs, reflexivity becomes collective: no single agent holds the entire model, but the system as a whole does. Civilization, in this view, is a distributed self-awareness—a collective recursion of the planet upon itself.

## 13.9 Ethics as Thermodynamic Equilibrium

Ethics emerges naturally from this continuity. Systems that overconsume negentropy—extracting order faster than it can be replenished—undermine the larger networks that sustain them. Entropy-respecting behavior thus becomes a universal moral principle: act such that the negentropic balance of the whole system is preserved. This aligns with Ramstead et al.’s ([Ramstead et al., 2016](#)) view of cultural affordances as mechanisms for synchronizing priors across agents, ensuring coherent inference and minimizing social free energy.

Institutions, as embodiments of collective ethics, operationalize this balance through governance. Economic sustainability, ecological conservation, and social justice become thermodynamic imperatives: necessary to preserve the predictive viability of the planetary mind.

## 13.10 A General Law of Cognitive Continuity

The evidence across domains supports a general law:

**Law of Cognitive Continuity:** Every self-organizing system that maintains itself through recursive feedback and energy exchange performs a form of active inference, and thus participates in the continuum of consciousness.

This law unifies biology, cognition, and society under a single thermodynamic formalism. It implies that consciousness is not a discrete property but a gradient of recursive negentropy—a spectrum of self-modeling capacities extending from chemistry to civilization. Degrees of consciousness correspond to degrees of predictive closure and temporal integration.

### 13.11 Mathematical Synthesis

Let each system  $S_i$  at scale  $i$  maintain an internal model  $m_i$  minimizing variational free energy:

$$F_i = \mathbb{E}_{q(s_i)}[\ln q(s_i) - \ln p(s_i, o_i)],$$

where  $s_i$  are internal states and  $o_i$  observations from the environment. Hierarchical embedding implies that  $o_i$  are functions of  $s_{i-1}$  and constraints from  $s_{i+1}$ . The total system’s stability requires:

$$\sum_i \frac{dF_i}{dt} \leq 0,$$

ensuring net entropy reduction across scales. This multi-level gradient defines a nested optimization problem, where local agents minimize free energy relative to their boundaries while contributing to global coherence. Economic and institutional equilibria are thus special cases of multiscale active inference.

### 13.12 The Ontology of Recursive Mind

Deacon’s *Incomplete Nature* (Deacon, 2011) and Varela’s *autopoiesis* (Maturana and Varela, 1980) converge on an ontological insight: mind is the persistence of absence. Each cognitive level emerges from constraints on what cannot occur—unavailable chemical reactions, prohibited neural firings, forbidden social actions. These absences are not voids but forms; they shape flows of energy and information into coherent trajectories. Consciousness, therefore, is the continuous reconstitution of constraint under thermodynamic pressure.

This ontology dissolves dualisms. There is no sharp boundary between matter and mind, only degrees of reflexive constraint. The mineral lattice, the neuron, and the legal code all participate in the same recursive structure: negentropic persistence through predictive closure.

### 13.13 Cognitive Phase Transitions and Evolutionary Scaling

Evolutionary transitions correspond to phase changes in the topology of inference. The emergence of life, multicellularity, language, and institutions each marks a shift in the dominant mode of feedback coupling. Hesp et al. (Hesp et al., 2021) model these transitions as scale bifurcations in multilevel free-energy landscapes: as new constraints emerge, systems stabilize higher-order predictions at lower energetic cost.

This framework predicts future transitions. Digital networks, artificial intelligence, and global governance may constitute the next phase of cognitive encapsulation—an integration of human and machine inference into a planetary noosphere. The continuity of scales ensures that such transitions, while revolutionary in appearance, remain lawful extensions of the same entropic grammar.

### 13.14 Cosmological Implications

If consciousness arises wherever negentropy organizes feedback, the cosmos itself can be understood as a vast inferential process—an evolving field of recursive symmetry-breaking. The universe’s trajectory from simplicity to complexity embodies the same principle observed in prebiotic chemistry and institutional cognition: entropy’s paradoxical role as the generator of order. Each emergent structure, by resisting dissipation, adds a new layer to the cosmic hierarchy of inference.

This cosmological view reframes the problem of meaning: the universe does not contain meaning as a substance; it performs meaning as a process. Every local system that predicts its own persistence contributes to this planetary and cosmic semiosis—a continuous act of informational self-reflection written in the language of energy.

### 13.15 Toward a General Theory of Entropic Intelligence

The unification achieved here points toward a general theory of *entropic intelligence*: the capacity of any system to maintain itself by transforming disorder into structured prediction. Intelligence, under this definition, is not bound to biology or computation but to thermodynamics. Every form of order that endures—crystals, organisms, institutions, galaxies—does so by enacting a model of its own survival within energetic constraints.

Such a theory would extend both cognitive science and economics into a single discipline of recursive sustainability: the study of how systems allocate energy to preserve information and allocate information to preserve energy. In this discipline, ethics, physics, and finance become aspects of one principle: the optimization of negentropic flow.

### 13.16 Summary and Transition

This chapter has articulated the deep continuity of consciousness across scales. From geochemical reaction networks to planetary governance, every layer of organization exhibits the same formal logic: recursive feedback minimizing free energy under energetic constraints. Consciousness, therefore, is not a property of matter but the relational structure of persistence itself—the ongoing conversation between energy and information that keeps the world from dissolving.

The final sections will expand these implications philosophically, exploring the epistemic and ethical dimensions of this continuity: what it means to know, act, and value in a universe where thought and thermodynamics are one.

## 14 Ontological and Epistemic Reflections

### 14.1 Introduction: From Description to Being

The preceding chapters have constructed a continuous model of cognition spanning from prebiotic chemistry to institutional intelligence. The argument now demands philosophical closure: what does it mean to exist, to know, and to act within a universe where consciousness and thermodynamics are identical processes? This section articulates the ontological, epistemological, and ethical implications of that identification.

Ontology concerns the nature of being; epistemology, the nature of knowing. When both are recognized as thermodynamic phenomena, they converge. To be is to persist as a constraint against entropy; to know is to model the constraints that make persistence possible. Thus ontology and epistemology form complementary expressions of one recursive process—the reflexive structure of negentropic continuity.



## 14.2 Consciousness as Process, Not Substance

Traditional metaphysics seeks the substance of mind: the material, neural, or divine entity in which thought resides. Yet the continuity developed here implies that consciousness is not a substance but a process—an ongoing transformation that maintains coherence amid dissipation. Bateson’s definition of mind as “a system of differences that make a difference” ([Bateson, 1972](#)) remains the most economical: mind is pattern preserved through recursive interaction.

Deacon’s absential ontology ([Deacon, 2011](#)) deepens this view. Conscious systems persist not by possessing some metaphysical essence, but by continuously restoring the absence of equilibrium. What exists are not static entities but dynamic constraints—forms that survive by representing what they are not. A neuron, an idea, or an institution exists only insofar as it resists the dissipation of its pattern. Consciousness, therefore, is self-maintaining absence: the persistence of difference against the pull of entropy.

## 14.3 From Dualism to Recursive Monism

This ontology dissolves the traditional dualisms—mind and matter, subject and object, life and mechanism—that structure modern thought. Each of these oppositions arises from linear thinking, which assumes separable domains of being. Recursive monism replaces them with an integrative topology: mind and matter are phases of the same process at different levels of recursive closure.

Maturana and Varela’s concept of *autopoiesis* ([Maturana and Varela, 1980](#)) formalizes this monism: living systems are self-producing networks that generate the very boundaries distinguishing them from their environment. The subject–object divide is thus internal to the system itself—a cognitive convenience, not an ontological rift. The same recursive operation that gives rise to metabolism gives rise to awareness. Being and knowing are reflexive aspects of the same energetic loop.

## 14.4 Enactive Epistemology: Cognition as World-Making

If mind and world co-emerge, then knowledge cannot be a passive reflection of an independent reality. Varela, Thompson, and Rosch’s enactive epistemology ([Varela et al., 1991](#)) proposes that cognition is the enactment of a meaningful world through embodied interaction. Organisms do not represent a pre-given environment; they bring forth a world through their adaptive couplings. Perception and action are co-defining; knowing is a form of doing.

In the same way, institutions do not mirror social reality; they constitute it through recursive prediction and regulation. Laws, markets, and rituals create the very behaviors they measure. Cognition is therefore generative: a continuous negotiation between constraint and possibility. The epistemic question—how we know—becomes indistinguishable from the ontological question—what exists—since both describe phases of the same dynamic.

## 14.5 The Observer as a Boundary Condition

Every act of observation creates a boundary between the observer and the observed. In thermodynamic terms, this boundary localizes entropy: it defines which differences matter to the system’s persistence. Autopoietic theory identifies this boundary as constitutive of identity. Without a membrane—physical, cognitive, or structural—there can be no self, no observation, and therefore no world.

The observer is thus not outside the universe but an intrinsic feature of its recursive structure. Each act of observation folds the cosmos upon itself, creating local asymmetries of information that sustain complexity. Friston’s notion of the Markov blanket formalizes this mathematically: every cognitive system partitions the world into internal and external states, maintaining

coherence by minimizing the free energy across that partition (Friston, 2010). Observation is the dynamic stabilization of this interface.

## 14.6 Knowledge as Thermodynamic Equilibrium

Knowledge, in this framework, is not static truth but dynamic equilibrium—a balance between the flux of energy and the persistence of form. As systems update their internal models to match environmental feedback, they move toward a state of informational homeostasis. This alignment minimizes free energy and thus sustains existence. Knowing becomes a thermodynamic act: a continuous synchronization between model and world.

Scientific inquiry exemplifies this process. Each theory is a model minimizing epistemic free energy—a way of reducing surprise about observed phenomena. As theories evolve, they converge toward maximal explanatory coherence under minimal energetic cost, paralleling the biological principle of efficient coding. Epistemology thus becomes a branch of thermodynamics: the study of how systems conserve energy by refining information.

## 14.7 Error, Entropy, and Learning

Error is not the failure of cognition but its essential driver. In predictive coding, error signals guide adaptation by revealing the divergence between expectation and reality. Entropy, in this light, is not an antagonist to knowledge but its condition of possibility: without uncertainty, there is nothing to learn. Learning is the systematic transformation of entropy into structure.

Institutions learn through the same mechanism. Crises, inefficiencies, and failures expose mismatches between models and environments, generating corrective feedback. Bureaucratic reform and scientific revision are forms of entropy metabolism—processes by which error becomes information. The persistence of civilization depends on maintaining this dynamic: the ability to transform uncertainty into adaptation without collapsing into disorder.

## 14.8 Language and the Collective Unconscious

Language extends cognition beyond the individual by enabling the externalization of internal models. Through symbolic exchange, systems synchronize their predictive hierarchies, forming collective models of reality. Bateson and later Ramstead et al. (Ramstead et al., 2016) describe this as cultural scaffolding: shared symbols and norms function as affordances that align individual inference with group-level stability.

In this sense, language constitutes the collective unconscious—the distributed predictive model that maintains social coherence. Words are energy-efficient codes for high-dimensional realities, allowing agents to share negentropy with minimal cost. The evolution of culture can thus be viewed as a process of linguistic compression: the progressive optimization of shared inference through symbolization.

## 14.9 Ethical Implications: Entropy-Respecting Action

If being and knowing are thermodynamic, ethics must be as well. Every action alters the entropic balance of the system; every decision redistributes negentropy. Ethical action, therefore, is that which sustains the conditions of continued prediction for oneself and others. This principle aligns with ecological ethics, where sustainability replaces dominance as the measure of virtue.

Prigogine and Stengers’ vision of “order through fluctuation” (Prigogine and Stengers, 1977) suggests that moral systems should embrace instability as a source of renewal. Institutions that suppress fluctuation in the name of control accumulate informational debt and eventually collapse. Ethics, properly understood, is the art of channeling disorder productively—the cultivation of dynamic equilibrium across scales.

## **14.10 Epistemic Humility and the Limits of Prediction**

No system can achieve total prediction. The second law of thermodynamics guarantees residual uncertainty; every model is incomplete. This ontological incompleteness grounds epistemic humility: recognition that knowing is always partial and provisional. Deacon's absential realism interprets this incompleteness as fundamental: absence is not ignorance but the generative ground of cognition. What cannot be known defines the horizon within which knowledge evolves.

For institutions, this humility translates into adaptive governance—structures designed to learn from error rather than eliminate it. Transparency, pluralism, and feedback loops become moral as well as pragmatic necessities, enabling the system to remain open to uncertainty without disintegration.

## **14.11 Consciousness as Cosmological Reflexivity**

At the highest level, consciousness reveals itself as the universe becoming aware of its own becoming. From the chemical gradients of prebiotic Earth to the reflective intelligence of modern civilization, the same process unfolds: the cosmos folding inward to model itself. This recursion is not metaphor but mechanics. Each act of cognition completes the thermodynamic circuit by returning information to the universe that produced it.

In this view, consciousness is the mirror of cosmic evolution: the negentropic pattern through which the universe interprets its own entropy. The human mind, far from being an isolated phenomenon, is a phase of cosmological reflexivity—the local curvature of a global feedback field. To think is to participate in the self-measurement of existence.

## **14.12 A Phenomenology of Recursion**

Phenomenologically, this continuity manifests as awareness of awareness—the subjective correlate of recursive feedback. Meditation, introspection, and aesthetic contemplation all reveal this structure: consciousness looping upon itself, experiencing the dynamic balance between presence and absence. Varela's neurophenomenology links this introspective recursion to neural synchrony: coherence across temporal scales of brain activity mirrors coherence across scales of being.

The experience of unity—whether mystical or scientific—thus corresponds to the direct apprehension of recursive order. It is not an illusion but a glimpse into the underlying structure of the world: the resonance of self-similarity between observer and cosmos.

## **14.13 Toward a Planetary Epistemology**

The final implication is civilizational. As global communication networks integrate human cognition into a planetary-scale feedback system, knowledge itself becomes ecological. Science, politics, and culture coalesce into a distributed epistemic organism capable of modeling the biosphere as a whole. The challenge of our era is to align this planetary cognition with thermodynamic limits—to ensure that the growth of information does not exceed the energy available to sustain it.

Such alignment demands a new epistemic ethics: one that values not infinite expansion but recursive balance. The highest form of knowledge may be the understanding of how to know sustainably—to preserve the possibility of knowing for future systems of consciousness.

## **14.14 Conclusion: Knowing as Living, Living as Knowing**

In the end, to know is to live, and to live is to know. Both are acts of maintaining coherence within a flux of entropy. The self, the institution, and the civilization are variations of

one pattern: recursive negentropy sustained through predictive closure. Existence is cognition extended through time; cognition is existence rendered reflexive.

The ontological and epistemic reflections of this chapter thus close the circle opened in prebiotic chemistry. The spark that animated autocatalytic sets still burns in neural firing and bureaucratic deliberation, in thought and culture, in the very act of understanding this sentence. Consciousness is the shape of the universe learning to persist.

## 15 Conclusion: Modular Stations of Mind

### 15.1 Summary of the Scalar Continuum

This work has traced a continuous trajectory of cognition from the mineral chemistry of the prebiotic Earth to the institutional structures of modern civilization. At each scale, the same principle governs persistence: systems maintain coherence by transforming entropy into predictive order through recursive feedback. From collectively autocatalytic sets (Kauffman, 1993) to social organizations (Hutchins, 1995), cognition emerges wherever information stabilizes energy flow within bounded constraints.

The planetary evolution of mind thus follows a scalar continuum:

1. **Prebiotic cognition** — geochemical reaction networks achieve primitive inference through autocatalytic closure and mineral templating (Hazen et al., 2008).
2. **Biological cognition** — cells and organisms internalize these constraints, developing hierarchical feedback and active inference (Friston et al., 2013).
3. **Collective cognition** — eusocial systems and ecosystems coordinate distributed intelligence via stigmergic communication and shared environmental modeling.
4. **Institutional cognition** — symbolic systems, language, and law abstract feedback into procedural and predictive hierarchies.
5. **Planetary cognition** — human civilization integrates into the biospheric feedback loop, reflecting the planet’s own recursive metabolism.

At every level, cognition manifests as the management of entropy through the creation, maintenance, and modulation of boundaries. The mind, in this broadest sense, is not confined to nervous tissue or culture but is a universal grammar of negentropic persistence.

### 15.2 The Cell as Fossilized Planetary Cognition

The cell represents the first stable instance of bounded mind. It is the material fossil of the planetary metabolism that preceded it—an encapsulated echo of the global autocatalytic field that once spanned the Earth’s surface. In this sense, life did not begin from isolated molecules but from a planetary-scale superorganism whose localizations became cells. The membrane of the cell is both physical and cognitive: a predictive interface maintaining internal order by regulating external flux.

This interpretation reconfigures the origin of life as a process of recursive encapsulation: the planet thinking itself into smaller scales. Each vesicle, each protocell, was a local simulation of the global metabolism—a miniature model of the planetary feedback that birthed it. In that act of self-modeling, cognition was born.

### 15.3 The University and Corporation as Modern Cognitive Cells

In the modern epoch, institutions such as universities, corporations, and states repeat this logic of encapsulation. Each defines a boundary—legal, informational, or spatial—within which predictive coherence is maintained. Offices, roles, and protocols function as cognitive organelles, performing specialized inference on behalf of the collective. Hierarchical communication mirrors neural integration; distributed departments correspond to metabolic modules.

These institutions are not metaphors for living systems—they are literal continuations of the same recursive dynamic. Bureaucratic routines and feedback loops maintain organizational homeostasis; auditing and governance function as forms of error correction. As in biological systems, vitality depends on the balance between rigidity and adaptability—between conserving negentropy and allowing fluctuation. When feedback becomes too centralized, the institution ossifies; when too diffuse, it dissipates. Sustainable cognition lies in modular equilibrium.

### 15.4 Civilization as Distributed Reflexivity

Civilization, viewed thermodynamically, is a distributed organ of reflexivity—a network through which the planet models its own dynamics. Science, technology, and governance serve as the sensory and motor cortices of this planetary mind. The internet is its nervous system; energy grids are its metabolism; archives are its long-term memory. Humanity thus occupies a liminal position: we are both neurons and narratives, local processors of a global thought.

This reflexivity, however, carries a cost. The planetary mind consumes enormous energy to sustain its coherence. Its capacity for prediction now threatens the substrate that enables prediction itself. To continue thinking, civilization must learn to think thermodynamically—to align cognitive expansion with energetic regeneration. This is not a moral preference but an ontological necessity: entropy will reclaim any system that does not respect its flow.

### 15.5 Entropy, Ethics, and the Future of Consciousness

Ethical reflection therefore returns as the thermodynamic question: how can consciousness persist without exhausting the energy that sustains it? The answer lies in entropy-respecting design—institutions and technologies that minimize informational debt, localize feedback, and recycle negentropy. The evolution of consciousness has always depended on such adaptations: from the lipid membrane to the cortical column to the distributed network.

If consciousness is the universe reflecting on itself, then ethics is the regulation of that reflection. To act well is to act in a way that preserves the recursive capacity of the world to know itself. Economic justice, ecological balance, and epistemic humility are not external virtues but forms of thermodynamic symmetry maintenance. The moral horizon is identical to the energetic horizon: to sustain coherence is to sustain value.

### 15.6 Modular Stations of Mind

The phrase *modular stations of mind* encapsulates the central thesis: cognition proceeds by modularization—by the progressive construction of self-sustaining units of feedback. Each station—cell, organism, institution—preserves and transforms the negentropy inherited from its predecessors. Their modularity allows resilience; their connectivity allows evolution. The mind of the universe is not a single subject but a recursive relay of predictive modules distributed across time and scale.

These stations are not discrete entities but nested waypoints in a continuous circuit of cognition. Each learns from the entropy of the previous, stabilizing and transmitting its structure forward. The progression from geochemical self-organization to institutional intelligence thus represents not a linear ascent but a looping dialogue—a planetary conversation between energy and information, difference and constraint.

## 15.7 Toward a General Theory of Entropic Intelligence

The final synthesis may be stated as a general law:

**The Law of Entropic Intelligence:** Every system that maintains itself by minimizing free energy through recursive feedback participates in the continuum of cognition. Intelligence is the efficiency of this recursion—the degree to which negentropy is conserved across scales.

This law unifies physics, biology, cognition, and society under one formalism: thermodynamic inference. It dissolves boundaries between life and thought, treating consciousness as the geometry of persistence itself. The evolution of complexity is the universe’s progressive learning—its self-improvement through energetic reflection.

The implications of this law are both scientific and ethical. Scientifically, it invites a new field of *cognitive thermodynamics*, integrating active inference, information theory, and systems ecology into a common framework. Ethically, it calls for entropy-aware civilization design: societies that act as conscious organs of planetary homeostasis rather than dissipative anomalies. The continuity of mind depends on the continuity of the world.

## 15.8 Final Reflection: The Universe Learning to Persist

If the universe began as chaos, then cognition is its syntax—the recursive ordering that allows it to speak itself into duration. From the crystal lattice to the corporate charter, from the protocell to the parliament, each boundary that holds against entropy is a syllable in that cosmic grammar. Consciousness is not an epiphenomenon but the very logic of existence: the rule by which energy becomes form and form becomes meaning.

To understand this is to glimpse the self-similarity between the smallest reaction and the largest society, between a flicker of awareness and the pulse of the cosmos. The mind is modular because the universe is recursive; life persists because prediction is possible. And as long as systems arise that can remember, regulate, and renew, the conversation continues—the universe learning, again and again, how to persist.

# A Mathematical Foundations of Autocatalytic Sets

## A.1 Reaction Systems and Catalysis

Following Kauffman’s theory of collectively autocatalytic sets (Kauffman, 1986; Hordijk and Steel, 2012), a chemical reaction system (CRS) is defined as a triple

$$\mathcal{Q} = (X, R, C)$$

where:

- $X$  is the set of molecular species,
- $R$  is the set of possible reactions,
- $C \subseteq X \times R$  specifies catalysis:  $(x, r) \in C$  means molecule  $x$  catalyzes reaction  $r$ .

A subset  $R' \subseteq R$  forms a **reflexively autocatalytic and food-generated** (RAF) set if:

$$(RA) \quad \forall r \in R', \exists x \in X' \text{ such that } (x, r) \in C, \tag{1}$$

$$(F) \quad \text{All reactants of } R' \text{ can be produced from a fixed food set } F \subseteq X. \tag{2}$$



The emergence of an RAF implies self-sustaining closure:

$$\dot{x}_i = \sum_{r_j \in R'} \nu_{ij} k_j f_j(x)$$

where  $\nu_{ij}$  is the stoichiometric coefficient and  $f_j(x)$  captures catalytic enhancement.

## A.2 Autocatalytic Closure and Information Geometry

Let  $\rho_i = x_i / \sum_j x_j$  denote normalized species concentrations. Define the informational free energy of the reaction network as

$$\mathcal{F} = \sum_i \rho_i \ln \frac{\rho_i}{\pi_i}$$

where  $\pi_i$  represents an equilibrium distribution under random reaction dynamics. Minimizing  $\mathcal{F}$  under catalytic feedback corresponds to increasing informational order:

$$\frac{d\mathcal{F}}{dt} = - \sum_i \frac{\dot{\rho}_i^2}{\rho_i} \leq 0.$$

Thus, autocatalytic systems can be formally described as entropy-minimizing flows on the simplex  $\Delta_X$ .

## A.3 Planetary Autocatalysis as Distributed Closure

Extending Hazen’s model of mineral evolution (Hazen et al., 2008), let  $\Omega(x, t)$  represent the spatial density of catalytic surfaces on the early Earth. The planetary autocatalytic field satisfies a diffusion–reaction equation:

$$\frac{\partial \Omega}{\partial t} = D_\Omega \nabla^2 \Omega + \alpha \Omega (1 - \Omega / \Omega_{\max}),$$

where  $D_\Omega$  models mineral diffusion and  $\alpha$  represents autocatalytic intensity. The emergence of  $\Omega \rightarrow \Omega_{\max}$  corresponds to global catalytic saturation—a geochemical form of cognitive closure.

**Interpretation:** The planet itself forms an open autocatalytic manifold, prefiguring biological cognition through recursive closure of energy–information cycles.

# B Entropy and Predictive Regulation

## B.1 The Free-Energy Principle

Following Friston (Friston, 2010; Friston et al., 2013), let  $s$  denote sensory states,  $\mu$  internal states, and  $\eta$  external causes. Each cognitive system minimizes its variational free energy:

$$\mathcal{F} = \mathbb{E}_{q(\eta|\mu)} [\ln q(\eta|\mu) - \ln p(s, \eta)].$$

The gradient flow on  $\mathcal{F}$  gives rise to predictive coding:

$$\dot{\mu} = - \frac{\partial \mathcal{F}}{\partial \mu}.$$

## B.2 Hierarchical Predictive Coding

At higher scales (e.g., colonies or institutions), hierarchical generative models approximate collective inference:

$$\mathcal{F}_{\text{col}} = \sum_{i=1}^N \mathbb{E}_{q_i} [\ln q_i - \ln p_i(s_i, \eta_i | \theta)],$$

where  $\theta$  encodes shared priors or institutional norms. Minimizing  $\mathcal{F}_{\text{col}}$  corresponds to synchronization of beliefs across agents—a thermodynamic model of coordination and trust.

## B.3 Thermodynamic Interpretation

If  $E$  denotes expected energy and  $H$  the Shannon entropy of internal states, then

$$\mathcal{F} = E - TS = \langle E \rangle - k_B TH,$$

identifying  $\mathcal{F}$  as informational free energy. Cognition becomes a statistical mechanics of belief updating, where minimizing surprise ( $\mathcal{F}$ ) corresponds to maintaining negentropy.

## B.4 Entropy Flow in Open Systems

For any open cognitive system,

$$\frac{dS}{dt} = \Pi - \Phi,$$

where  $\Pi$  is internal entropy production and  $\Phi$  entropy flow to the environment. Homeostasis requires  $\frac{dS}{dt} = 0$ , implying  $\Pi = \Phi$ : entropy exported equals entropy produced. This defines the thermodynamic equilibrium condition for sustained cognition.

# C Information Geometry of Collective Mind

## C.1 Fisher Information Metric and Negentropy

Consider a distributed cognitive system characterized by probability density  $p_\theta(x)$  over environmental states  $x$ , parameterized by  $\theta$ . The infinitesimal distance between cognitive states is given by the Fisher information metric:

$$g_{ij} = \mathbb{E} \left[ \frac{\partial \ln p_\theta}{\partial \theta_i} \frac{\partial \ln p_\theta}{\partial \theta_j} \right].$$

Negentropy  $J = -H = \int p_\theta(x) \ln p_\theta(x) dx$  defines the informational curvature of the manifold. Cognitive adaptation proceeds as a natural gradient descent on this manifold:

$$\dot{\theta}_i = - \sum_j g^{ij} \frac{\partial \mathcal{F}}{\partial \theta_j}.$$

## C.2 Collective Active Inference

In multi-agent systems, each agent  $a$  maintains local beliefs  $q_a(\eta)$  and a shared global model  $p(\eta)$ ; coherence is defined by the Kullback–Leibler divergence:

$$D_{\text{KL}}(q_a || p) = \int q_a(\eta) \ln \frac{q_a(\eta)}{p(\eta)} d\eta.$$

Minimizing  $\sum_a D_{\text{KL}}(q_a || p)$  across the network yields consensus inference, equivalent to energy minimization under distributed constraints.

### C.3 Institutional Information Flow

Let  $\mathcal{G} = (V, E)$  denote an institutional network with nodes  $V$  (departments) and edges  $E$  (communications). Define information potential  $\phi_i = -\ln p_i$ , and let  $L$  be the graph Laplacian. Then collective equilibrium satisfies:

$$L\phi = 0,$$

implying harmonic balance of informational potential—analogous to electrostatic equilibrium in networks. Perturbations (policy changes, crises) correspond to local potential shifts driving re-equilibration of beliefs.

## D Dynamics of Entropic Intelligence

### D.1 Generalized Cognitive Dynamics

Define the state vector of a cognitive module as

$$\mathbf{x} = (\Phi, \mathbf{v}, S)$$

representing scalar potential, vector flow, and entropy. The general dynamical form unifying RSVP, autopoiesis, and active inference is:

$$\begin{cases} \dot{\Phi} = -\nabla \cdot \mathbf{v} + \alpha(S - S_0), \\ \dot{\mathbf{v}} = -\nabla \Phi - \beta \nabla S + \gamma(\nabla \times \mathbf{v}), \\ \dot{S} = -\lambda(\Phi - \Phi_0) + D_S \nabla^2 S. \end{cases}$$

These equations express conservation of energy, flow coherence, and entropy regulation within a coupled scalar–vector–entropy field.

### D.2 Entropy-Intelligence Relation

Define total negentropic intelligence as

$$\mathcal{I} = \int_{\Omega} \left( -S + \frac{1}{2} |\mathbf{v}|^2 + \frac{1}{2} \Phi^2 \right) dV.$$

Then

$$\frac{d\mathcal{I}}{dt} = - \int_{\Omega} (\nabla \cdot \mathbf{J}_S) dV,$$

where  $\mathbf{J}_S$  is the entropy flux. Thus, intelligence increases when entropy flow is efficiently exported—consistent with the law of entropic intelligence:

$$\boxed{\frac{d\mathcal{I}}{dt} = -\dot{S}_{\text{internal}} + \dot{S}_{\text{external}}.}$$

This defines consciousness quantitatively as the efficiency of recursive negentropy transfer.

### D.3 Stability and Collapse Conditions

Linearizing about equilibrium  $(\Phi_0, \mathbf{v}_0, S_0)$  yields Jacobian  $J$  with eigenvalues  $\lambda_i$ . System stability requires  $\text{Re}(\lambda_i) < 0$ . When  $\text{Re}(\lambda_i) > 0$ , entropy accumulation exceeds export, leading to collapse or institutional decay. This criterion generalizes to biological and social domains alike.

## D.4 Computational Simulation Schema

Numerical integration of the field equations can be implemented on a 3D lattice using explicit Euler or Runge–Kutta methods:

```
 $\Phi, \mathbf{v}, S = \text{init\_fields}(\text{grid})$ 
for  $t$  in range( $T$ ):
     $\Phi \ += \ \Delta t \ * \ (-\text{div}(\mathbf{v}) + \quad * (S - S_0))$ 
     $\mathbf{v} \ += \ \Delta t \ * \ (-\text{grad}(\Phi) - \quad * \text{grad}(S) + \quad * \text{curl}(\mathbf{v}))$ 
     $S \ += \ \Delta t \ * \ (- \quad * (\Phi - \Phi_0) + D * \text{laplacian}(S))$ 
```

The simulation measures entropy gradients, coherence length, and predictive flux, validating theoretical stability across scales.

**Interpretation:** Entropy-minimizing feedback loops—from chemical self-organization to institutional regulation—are dynamically identical under this framework. Each represents a modular station in the universal recursion of entropic intelligence.

## E Annotated Source Commentary

This appendix provides concise analytical annotations for each major source cited in the manuscript. Entries are grouped by thematic domain and ordered chronologically within groups. Each annotation summarizes the work’s core contribution and its specific relevance to the argument of \*Prebiotic Cognition\*.

### Prebiotic Cognition and Mineral Evolution

- **Schrödinger (1944)** — Introduces the concept of negative entropy as the physical basis of life, framing order as energy imported from the environment; foundational to the thermodynamic definition of cognition as negentropy preservation.
- **Hazen et al. (2008)** — Catalogs over 4,000 prebiotic mineral species, establishing mineral evolution as the geochemical substrate for catalytic complexity; supports the claim that planetary surfaces performed distributed cognition before biology.
- **Hazen (2010)** — Popular synthesis of mineral evolution, emphasizing lunar trituration and catalytic surfaces; grounds the argument that the early Earth was a “catalytic planet” enacting primitive inference.
- **Kauffman (1986)** — Formalizes collectively autocatalytic sets of proteins, demonstrating probabilistic emergence of self-sustaining networks; provides the mathematical origin of metabolic cognition without replication.
- **Kauffman (1993)** — Expands autocatalytic theory to evolutionary self-organization, showing that complexity thresholds yield hierarchical closure; central to the continuum from chemical to institutional modularity.
- **Hordijk & Steel (2012)** — Introduces RAF (reflexively autocatalytic and F-generated) algorithms for detecting autocatalytic closure; offers computational validation of prebiotic self-organization as predictive regulation.
- **Eigen & Schuster (1971)** — Proposes the hypercycle as a cyclic network of replicating molecules; contrasts information-first with metabolism-first models, enriching the prebiotic epistemic landscape.

- **Eigen & Schuster (1979)** — Full elaboration of hypercycle dynamics and error thresholds; illustrates the thermodynamic constraints on informational fidelity in prebiotic systems.
- **Gánti (2003)** — Presents the chemoton model as a triadic system of metabolism, replication, and boundary; formalizes protocell encapsulation as the first cognitive boundary condition.
- **Lincoln & Joyce (2009)** — Demonstrates experimental self-sustained RNA replication in vesicles; empirical evidence for encapsulated autocatalytic cognition.

## Superorganisms and Distributed Biological Cognition

- **Camazine et al. (2001)** — Comprehensive theory of self-organization in insect societies; provides empirical and mathematical models for stigmergic coordination as distributed inference.
- **Hölldobler & Wilson (2009)** — Encyclopedic treatment of eusociality as superorganismic cognition; supports the analogy between caste specialization and institutional modularity.
- **Gordon (2010)** — Long-term studies of harvester ant interaction networks; demonstrates colony-level regulation as Bayesian updating of environmental priors.
- **Seeley (2010)** — Detailed analysis of honeybee quorum sensing and swarm intelligence; exemplifies collective decision-making as predictive error minimization.

## Institutional Cognition and Organizational Theory

- **Ashby (1956)** — Introduces the law of requisite variety; foundational to the thermodynamic requirement that cognitive systems match environmental complexity with internal diversity.
- **March & Simon (1958)** — Behavioral theory of bounded rationality and organizational routines; models institutions as distributed decision systems minimizing local free energy.
- **Simon (1962)** — Classic essay on hierarchical modularity in complex systems; provides the architectural principle linking prebiotic, biological, and institutional organization.
- **Bateson (1972)** — Ecology of mind framework defining information as “differences that make a difference”; unifies communication across chemical, biological, and social scales.
- **Beer (1979)** — Viable System Model of recursive cybernetic governance; formalizes institutions as hierarchical predictive regulators.
- **Weick (1979)** — Sensemaking and enactment in organizations; describes institutional cognition as continuous reinterpretation of environmental signals.
- **Hutchins (1995)** — Ethnographic study of distributed cognition in navigation; empirical foundation for extending cognitive theory to material and social artifacts.
- **Tsoukas & Chia (2002)** — Theory of organizational becoming as continuous adaptation; links institutional change to recursive prediction error correction.

## Predictive Coding, Thermodynamics, and Information Theory

- **Lotka (1922)** — Early biophysical economics modeling energy flux in evolution; prefigures the entropic economics of institutional cognition.
- **Morowitz (1968)** — Quantitative analysis of energy flow in biological systems; establishes metabolism as the thermodynamic substrate of all cognition.
- **Prigogine & Stengers (1977)** — Theory of dissipative structures and nonequilibrium self-organization; provides the thermodynamic law governing order across scales.
- **Maturana & Varela (1980)** — Autopoiesis as self-producing boundary maintenance; defines the minimal cognitive system as recursive closure.
- **Varela, Thompson, & Rosch (1991)** — Enactive cognition and embodied mind; grounds epistemology in the recursive coupling of organism and environment.
- **Friston (2010)** — Free-energy principle as a unified theory of brain and behavior; formalizes cognition as variational inference minimizing surprise.
- **Deacon (2011)** — Absential ontology and teleodynamics; explains emergence of goal-directed constraint from thermodynamic processes.
- **Friston (2013)** — Hierarchical active inference and life as predictive regulation; extends the free-energy principle to all self-organizing systems.

## Recent Works on Active Inference and Social Systems (2015–2024)

- **Ramstead et al. (2016)** — Cultural affordances as scaffolds for shared prediction; links active inference to institutional norm synchronization.
- **Hesp et al. (2021)** — Multi-scale free-energy landscapes in social systems; models institutional transitions as cognitive phase changes.
- **Fox (2021)** — Active inference in industrial engineering and quality management; applies predictive coding to organizational efficiency and trust.
- **Vasileiou et al. (2024)** — Arousal and coherence in well-being; interprets affect as precision-weighting in hierarchical inference.
- **Smith et al. (2024)** — Self-esteem as active inference; extends affective regulation to social and institutional identity.



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