The Emergence of Causal Cores: From Thermodynamic Foundations to Biological Functionality

Introduction

The newly introduced concept of the "causal core" represents an innovative theoretical framework that describes a central organizational form within dynamic systems, where lines of influence converge, decisions are prepared, and systemic transitions are initiated (Stegemann 2025). This conceptualization brings together previously fragmented phenomena of biological organization under a unified theoretical framework for the first time.

While the existence of local control centers in biological systems has been extensively documented—from molecular clusters to neural networks—a comprehensive theoretical description explaining the common emergence principles and functional properties of these structures has been lacking. The concept of the causal core fills this gap by adding a specific causal dimension to established theories of self-organization and emergent complexity (Prigogine & Stengers, 1984; Haken, 1983).

The theory of causal cores developed here offers a novel approach to understanding biological organization that goes beyond previous descriptions of self-organization. It postulates that the emergence of such cores is not a contingent invention of nature, but results from fundamental physical and biological principles—a thesis that is systematically developed in this article and supported through concrete biological examples.

This article argues that the emergence of causal cores results from fundamental physical and biological principles. The argumentation proceeds in several interconnected steps: First, the thermodynamic framework is outlined, then the biological concretization is analyzed, followed by consideration of information-theoretic aspects, and finally discussion of evolutionary implications.

1. Thermodynamic Foundations: Dissipative Structures and Order Formation

1.1 Non-equilibrium Systems and Spontaneous Structure Formation

Living systems are par excellence open, non-equilibrium systems that exist in constant energy and matter exchange with their environment (Kondepudi &

Prigogine, 1998). This fundamental property inevitably leads to the emergence of state constellations characterized by local accumulation of certain parameters—whether concentrations of specific molecules, energy densities, or electrochemical potentials (Haken, 2006).

The theory of dissipative structures, developed by Ilya Prigogine and his collaborators, shows that such systems can spontaneously form spatial and temporal order structures under certain conditions (Prigogine, 1980). This order formation is not random but follows the laws of nonlinear dynamics and is amplified by positive feedback mechanisms (Cross & Hohenberg, 1993).

1.2 Local Density and Energy Flow Maxima as Structural Seeds

Local density and energy flow maxima that occur in non-equilibrium systems exhibit several characteristic properties that make them potential seeds of causal cores:

Increased Reaction Probability: In areas with high concentrations of relevant molecules or energy, the probability of chemical reactions, protein interactions, or signal transduction events increases exponentially (Atkins & de Paula, 2014). This increase follows the basic principles of collision theory and can be described by the Arrhenius equation, where local concentration directly enters the reaction rate (Laidler, 1987).

Stability Under Dissipation: These centers do not represent random turbulences but stabilize themselves through continuous energy flow. Stability results from the principle of minimal entropy production in stationary states far from thermodynamic equilibrium (Glansdorff & Prigogine, 1971). Such stationary structures can persist over long periods as long as energy flow is maintained.

Nonlinear Amplification: Small disturbances or fluctuations can be strongly amplified in these centers through nonlinear processes, leading to bifurcation and the emergence of new organizational forms (Strogatz, 2014). This is a central mechanism for the emergence of higher organizational levels.

1.3 Mathematical Description of Seed Formation

The emergence of structural seeds can be mathematically described by reaction-diffusion equations (Murray, 2002). For a system with concentration c(x,t) and diffusion coefficient D:

$$\partial c/\partial t = D\nabla^2 c + f(c,x,t)$$

where f(c,x,t) describes the local reaction terms. Under certain conditions, these equations lead to Turing instability, where homogeneous distributions become unstable and spatial patterns emerge (Turing, 1952; Gierer & Meinhardt, 1972).

2. Biological Concretization: From Physical Seeds to Functional Centers

2.1 The Transition from Structure to Function

For a thermodynamic structural seed to become a biologically effective causal core, functional filling of this zone must occur. This transition is enabled by the principle of "canalization"—the tendency of biological systems to utilize and amplify physicochemical constraints (Waddington, 1957; Salazar-Ciudad, 2006).

Functional filling occurs through several complementary mechanisms:

Molecular Recruitment: Proteins and other biomolecules are guided to centers of high activity by physicochemical gradients (Karsenti, 2008). This recruitment follows principles of self-assembly and is mediated by weak but specific intermolecular interactions.

Positive Feedback: Once established, centers reinforce themselves by recruiting additional functional components, leading to positive feedback (Ferrell, 2002). This amplification can occur through direct protein-protein interactions as well as modification of the local physicochemical environment.

Functional Specialization: Recruited molecules take on specific functions that contribute to information processing, signal transmission, or behavior control (Hartwell et al., 1999).

2.2 Prokaryotic Examples of Causal Core Formation

2.2.1 Chemotaxis Clusters in E. coli

The chemotaxis system of E. coli represents a paradigmatic example of causal core emergence and function (Sourjik & Wingreen, 2012). The spatial organization of the system shows all characteristic features of thermodynamically favored structure formation:

Molecular Composition: Chemoreceptors (Methyl-accepting chemotaxis proteins, MCPs) spontaneously assemble into hexagonal clusters in the cytoplasmic membrane (Briegel et al., 2009). This cluster formation is favored by lateral protein-protein interactions and membrane curvature (Endres, 2009).

Functional Properties: The clusters function as biochemical nanomachines that amplify and integrate external signals (Tu et al., 2008). Cooperative ligand binding leads to a sigmoidal dose-response relationship that enables high sensitivity while maintaining robustness against noise (Keymer et al., 2006).

Signal Amplification: A single ligand molecule can influence the activity of up to 35 receptor complexes through cooperative interactions within the cluster (Frank & Vaknin, 2013). This amplification is essential for detecting concentration changes in the nanomolar range.

Adaptive Properties: The clusters show perfect adaptation—they return to their original activity level after a disturbance, regardless of disturbance strength (Barkai & Leibler, 1997). This property is achieved through a robust biochemical network with integrated negative feedback.

2.2.2 Transcription Hotspots at the Nucleoid

The organization of gene expression in prokaryotic cells also shows causal core formation (Dorman, 2013). These emerge at sites of maximal transcriptional activity:

Spatial Concentration: RNA polymerases, sigma factors, and transcriptional regulators concentrate in discrete zones of the nucleoid (Cabrera & Jin, 2003). This concentration is stabilized by three-dimensional DNA folding and protein-DNA interactions.

Co-transcription of Related Genes: Genes with similar expression patterns are often transcribed in spatial proximity, even when they are far apart on the linear DNA sequence (Jeong et al., 2004). This suggests the existence of "transcription factories"—stable centers of co-regulated gene expression.

Dynamic Reorganization: The position and composition of these centers change depending on environmental conditions and the physiological state of the cell (Sobetzko et al., 2012). This plasticity enables rapid adaptation of gene expression to changing conditions.

2.2.3 ATP Synthase Complexes as Energetic Control Centers

The spatial organization of ATP synthase in bacterial membranes shows characteristic features of core formation (Vonck & Schäfer, 2009):

Gradient Optimization: ATPase complexes position themselves at sites of optimal proton gradient utilization (Cook & Dimroth, 2006). This positioning is determined by local membrane architecture and the distribution of other membrane proteins.

Energetic Coupling: Spatial proximity to other energetic systems (such as the electron transport system) enables efficient energetic coupling (Mitchell, 1961; Nicholls & Ferguson, 2013).

Systemic Control: These energetic centers have causal relevance for the overall system, as they control cellular energy supply and thus influence all energy-dependent processes (Rich, 2003).

2.3 Emergent Properties of Causal Cores

The described examples show that causal cores develop several emergent properties that go beyond the sum of their individual components:

Information Integration: Causal cores function as centers of information processing where multiple signals are integrated and processed into coordinated responses (Laughlin & Sejnowski, 2003).

Temporal Coordination: They enable temporal coordination of various cellular processes and function as "pacemakers" for complex behavioral patterns (Goldbeter, 1996).

Adaptive Plasticity: Causal cores show adaptive plasticity—they can modify their function and organization in response to changing environmental conditions (West-Eberhard, 2003).

3. Information-Theoretic Perspective: Causal Cores as Information Processing Centers

3.1 Information and Causality in Biological Systems

Information-theoretic analysis of causal cores extends thermodynamic understanding to include the dimension of information processing (Adami, 2016). Biological systems can be viewed as information-processing entities that extract, transform, and utilize information from their environment (Davies & Walker, 2016).

Information Flow and Causality: Causal cores are characterized by high information flows and strong causal connections to other system components (Lizier et al., 2012). These can be quantified through measures like Transfer Entropy and Integrated Information (Schreiber, 2000; Tononi, 2008).

Signal Amplification and Noise Suppression: A central feature of causal cores is their ability for signal amplification while simultaneously suppressing noise (van Kampen, 2007). This is achieved through cooperative effects and threshold behavior.

3.2 Quantification of Causal Relevance

The causal relevance of a center can be quantified through various information-theoretic measures:

Effective Information: This measure describes how strongly a system determines the state of downstream components (Hoel et al., 2013). Causal cores typically show high values for Effective Information.

Integrated Information (Φ): This measure quantifies the degree of information integration within a system (Tononi, 2008). Causal cores often exhibit local maxima of integrated information.

Causal Flow: This measure describes the strength and direction of causal influences between system components (Ay & Polani, 2008).

3.3 Information Architecture of Biological Systems

Information-theoretic analysis shows that biological systems develop characteristic information architectures:

Hierarchical Organization: Information is processed at various hierarchical levels, with causal cores often functioning as bridges between levels (Simon, 1962; Salthe, 1985).

Modularity: Biological systems show modular information architectures with specialized processing modules (Wagner et al., 2007). Causal cores can occur both within modules and at interfaces between modules.

Robustness and Evolvability: The information architecture of biological systems balances robustness (resistance to disturbances) and evolvability (capacity for adaptive change) (Wagner, 2005; Kitano, 2004).

4. Evolutionary Emergence and Selection of Causal Cores

4.1 Evolutionary Advantages of Centralized Control

The evolution of causal cores can be explained by several selective advantages:

Efficiency Enhancement: Centralized information processing and control reduces energy expenditure for communication and coordination (Laughlin, 2001). This is particularly important in systems with limited energetic resources.

Improved Response Speed: Central cores enable faster coordinated responses to environmental changes through shortened communication pathways (Alon, 2007).

Robustness Through Redundancy: Although centralization creates potential vulnerabilities, multiple specialized cores can provide redundancy and thus robustness (Carlson & Doyle, 2002).

4.2 Evolutionary Pathways to Core Formation

The evolution of causal cores can take various pathways:

Gene Duplication and Subfunctionalization: Gene duplication followed by functional divergence can lead to the emergence of specialized control centers (Lynch & Conery, 2000).

Horizontal Gene Transfer: In prokaryotic systems, horizontal gene transfer can lead to rapid acquisition of new control functions (Keeling & Palmer, 2008).

Modularity and Recombination: The modular organization of biological systems enables recombination of functional modules into new control architectures (Wagner et al., 2007).

4.3 Constraints and Trade-offs

The evolution of causal cores is subject to various constraints and trade-offs:

Cost-Benefit Ratio: The complexity and energy costs of a causal core must be justified by its functional advantages (Lenski et al., 2003).

Robustness vs. Efficiency: There is a trade-off between system robustness and its energetic efficiency (Kitano, 2004).

Evolvability vs. Stability: Systems must balance between the ability for adaptive change and the stability of their core functions (Wagner, 2005).

5. Causal Cores in More Complex Biological Systems

5.1 Eukaryotic Cells: Organelles as Specialized Cores

In eukaryotic cells, specialized organelles have evolved as functional cores:

Cell Nucleus: The cell nucleus functions as a central information processing and control core for gene expression and cell cycle regulation (Misteli, 2001).

Mitochondria: These organelles represent energetic control centers that regulate cellular energy supply and metabolic signaling (McBride et al., 2006).

Endoplasmic Reticulum: As a center of protein biogenesis and quality control, the ER forms an important regulatory core (Schröder & Kaufman, 2005).

5.2 Multicellular Systems: Tissues and Organs

In multicellular organisms, causal cores emerge at higher organizational levels:

Nervous System: The central nervous system represents the paradigmatic case of a causal core in multicellular systems (Sporns, 2011). Specialized neural networks function as information processing and control centers.

Endocrine System: Hormone-producing glands and their target tissues form distributed control networks for physiological regulation (Hadley & Levine, 2006).

Immune System: The adaptive immune system shows characteristic features of core formation through clonal selection and memory formation (Abbas et al., 2014).

5.3 Developmental Biology Aspects

The emergence of causal cores during embryonic development shows characteristic patterns:

Organizing Centers: Embryonic organizing centers (such as Spemann's organizer) function as temporary causal cores that control pattern formation (De Robertis, 2006).

Morphogenetic Fields: These concepts describe spatial domains of coordinated developmental processes (Gilbert, 2010).

Epigenetic Landscapes: Waddington's concept of epigenetic landscapes describes the dynamic organization of developmental pathways (Waddington, 1957; Huang, 2012).

6. Theoretical Implications and Further Questions

6.1 General Principles of Self-Organization

The analysis of causal cores contributes to understanding general principles of self-organization:

Emergence and Downward Causation: Causal cores show how emergent properties at higher organizational levels can influence the dynamics of lower levels (Campbell, 1974; Kim, 1999).

Criticality and Phase Transitions: Many biological systems operate near critical points where small changes can have large systemic effects (Bak, 1996; Mora & Bialek, 2011).

Scaling Laws and Universality: The organization of biological systems often shows universal scaling laws that point to fundamental physical principles (West et al., 1997; Brown et al., 2004).

6.2 Philosophical Implications

The existence of causal cores raises fundamental philosophical questions:

Reductionism vs. Holism: The properties of causal cores cannot be completely reduced to the properties of their components, which argues for emergentist approaches (Bedau, 1997; Kim, 2006).

Teleology and Function: The functional organization of causal cores seems to show teleological properties, even though they arise through non-teleological processes (Rosen, 1991; Christensen & Hooker, 2000).

Consciousness and Mental Causation: In neural systems, causal cores might be connected to conscious experiences and mental causation (Tononi, 2008; Seth, 2016).

6.3 Open Questions and Research Directions

Several important questions remain open:

Predictability: Under what conditions do causal cores emerge, and can we predict their properties a priori?

Optimization: Are naturally evolved causal cores optimal for their functions, or do they show historical constraints?

Artificial Systems: Can the principles of biological core formation be used for designing artificial systems?

Evolutionary Dynamics: How do causal cores influence the evolutionary dynamics of the systems in which they occur?

7. Conclusions

7.1 Synthesis of Main Arguments

The analysis shows that the emergence of causal cores is the result of a multi-stage process that leads from fundamental physical principles to complex biological functions:

1. **Thermodynamic Foundation:** Non-equilibrium systems spontaneously develop local density and energy centers through principles of dissipative structure formation.
2. **Biological Concretization:** These physical centers are "occupied" by biological mechanisms and functionally elaborated.
3. **Information Processing:** The emerging structures develop emergent properties of information processing and causal control.
4. **Evolutionary Optimization:** Selective processes shape these cores into efficient and robust control systems.

7.2 The Causal Core as a New Fundamental Organizational Principle

The concept of the causal core developed here proves to be a new fundamental organizational principle of biological systems that occurs at various scales—from molecular complexes to organ systems. Its universality suggests that it represents a previously overlooked but necessary consequence

of the physical and information-theoretic constraints under which biological systems operate.

The theoretical innovation lies in recognizing that seemingly disparate biological phenomena—from protein clusters to neural centers—follow a common organizational logic. This unity was previously hidden because different examples were studied in different disciplines and at various organizational levels. The concept of the causal core offers the first integrative theoretical framework.

7.3 Implications for Our Understanding of Life

The existence and properties of causal cores have far-reaching implications for our understanding of life:

Life as Information-Processing System: Living systems can be understood as complex information-processing networks organized and coordinated by causal cores.

Emergence and Hierarchy: The hierarchical organization of causal cores shows how complex properties can emerge at higher organizational levels and influence lower levels.

Evolution and Self-Organization: Evolution utilizes and shapes the spontaneous self-organization processes that lead to causal core emergence.

7.4 Outlook: Implications of a New Theory

The theory of causal cores presented here opens entirely new research directions. Since this is a novel theoretical concept, its comprehensive empirical validation and mathematical formalization are still in their infancy. Future work should focus on quantitative characterization of causal cores, development of specific experimental methods for their identification, and application of gained insights to artificial system design.

Particularly promising is the integration of this new concept with established approaches from systems biology, complexity theory, and information theory. The theory of causal cores could serve as a bridge between different disciplines and lead to a deeper, more unified understanding of biological organization.

The emergence of causal cores is thus—as systematically shown here for the first time—neither chance nor evolution's goal, but the probable and predictable consequence of the fundamental properties of dissipative, information-processing systems. This new understanding opens revolutionary perspectives on the deeper organizational principles of life and could lead to groundbreaking developments in biotechnology and artificial intelligence.

8. Epilogue: Between Physical Necessity and Biological Emergence

The emergence of life is characterized by a sequence of thermodynamically structured phase transitions—each new organizational level builds on preceding ordered states without implying a goal. Initially, open reaction cycles existed in hydrothermal environments without fixed boundaries. Under suitable environmental conditions, however, spontaneous boundary structures—membranes—formed as a consequence of amphiphilic molecular distributions and energetic gradients. These formed the basis of the first cells, i.e., prokaryotes, which still lacked a structural cell nucleus.

Only within these membrane-bound systems could functional centers of maximal reaction probability establish themselves under conditions of sustained dissipation: proto-causal cores, as visible in chemotaxis or transcription clusters. These cores were initially not structurally delineated but functionally dominant. The later formation of a cell nucleus in the eukaryotic sense represents only a morphological concretization of an already operating principle: thermodynamically driven functional centralization.

Evolution follows no plan, but the configurations that are systemically stable under dissipative conditions occur with such high probability that they appear necessary in retrospect—not in the sense of a goal, but as an expression of the formal laws of open systems.

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