Title :

The Informational Foundations of Organization in Physical and Biological Systems : Toward an Extended Thermodynamic Principle of Self-Organization

Author :
Ndenga Lumbu Barack (alias BarackEinstein97)
Independent Researcher
Kinshasa, Democratic Republic of the Congo
📧 **ndengabarack@gmail.com**
📞**+243837767430**

Abstract

Understanding how organized structures emerge and persist in physical and biological systems remains one of the central challenges of modern science. While classical thermodynamics successfully describes energy conservation and entropy production, it does not explicitly account for the role of information in driving organization, stability, and structure formation. In this article, I propose a unifying theoretical framework in which information is treated as a fundamental physical quantity governing organization in complex systems.

I introduce the concept of organizational efficiency, a measure capturing the balance between usable information and effective entropy, and argue that this balance determines the capacity of a system to self-organize. I demonstrate how this informational perspective naturally extends thermodynamic reasoning beyond equilibrium and provides a common language for phenomena observed in physics, biology, and artificial systems.The framework offers new insights into self-organization, robustness, and the emergence of structured behavior, and establishes conceptual foundations for an extended thermodynamic principle centered on information.

1. Introduction

Organization is a defining feature of the natural world. From crystalline solids and fluid patterns to living cells and ecosystems, structured behavior emerges despite the universal tendency toward disorder described by the second law of thermodynamics. Explaining how such organization arises and persists has long motivated research across physics, chemistry, and biology.

Classical thermodynamics focuses on energy, entropy, and equilibrium, offering powerful constraints on physical processes. However, modern systems of interest—biological organisms, neural networks, adaptive materials—are fundamentally informational. They store, process, and exploit information to maintain structure and function far from equilibrium.

In this work, I argue that information must be treated as a foundational element in any theory of organization. I propose that organization is not merely the absence of entropy, but the result of an active balance between information and entropy. This balance governs the emergence, stability, and evolution of complex systems.

The aim of this article is threefold:

- To establish information as a central quantity in the study of organization.
- To introduce a general measure capturing the efficiency with which systems convert information into organized structure.
- To show how this framework applies consistently across physical and biological domains.

2. Limitations of Classical Thermodynamic Descriptions

The second law of thermodynamics states that the total entropy of an isolated system cannot decrease. While this law is fundamental, it does not explain why local decreases in entropy—associated with organized structures—are so ubiquitous in nature.

Classical thermodynamics:

- Describes constraints on energy transformations,
- Predicts equilibrium states,
- Quantifies irreversibility.

However, it does not:

- Explain how structured patterns arise,
- Distinguish meaningful organization from random order,
- Quantify the role of information in sustaining structure.

Non-equilibrium thermodynamics and the theory of dissipative structures have made important progress by showing how energy flows can maintain order. Yet even these approaches often treat information implicitly rather than explicitly. A more complete theory of organization must therefore integrate information as an active driver, not a secondary concept.

3. Information as a Physical Quantity

Information is often regarded as an abstract or purely computational concept. However, physical arguments strongly suggest otherwise. Information constrains the set of accessible states of a system and thereby shapes its macroscopic behavior.

From a physical perspective, information corresponds to:

- Correlations between components,
- Constraints on configurations,
- Predictive structure embedded in the system.

A system rich in information is not simply ordered; it is organized. Its structure is functional, reproducible, and resilient to perturbations. By contrast, a low-information system may exhibit apparent order without meaningful structure.
Treating information as a physical quantity allows one to distinguish between mere order and genuine organization. This distinction is essential when comparing physical systems with biological ones, where function and adaptability are central.

4. Organizational Efficiency as a Unifying Concept

To formalize the role of information in organization, I introduce the concept of **organizational efficiency**. Organizational efficiency quantifies how effectively a system converts information into stable, low-entropy structure.

Qualitatively:

- High organizational efficiency corresponds to systems that maintain structure with minimal disorder.

- Low organizational efficiency corresponds to systems dominated by noise, instability, or unstructured complexity.

This concept provides a scalar measure that complements entropy. While entropy quantifies disorder, organizational efficiency quantifies meaningful structure. Together, these quantities describe the organizational state of a system more completely than either alone.

Organizational efficiency is not static. It evolves over time as systems learn, adapt, or degrade. Tracking this evolution offers insight into developmental processes, learning dynamics, and failure modes.

5. Implications for Physical Systems

In physical systems, organization often emerges through symmetry breaking and pattern formation. Examples include crystal growth, convection cells, and reaction–diffusion patterns.

Within the informational framework proposed here:

- Energy flows supply the capacity for change,
- Entropy production imposes constraints,
- Information determines which structures are selected and stabilized.

This perspective clarifies why certain patterns are robust while others are transient. Structures with higher informational content—stronger correlations and constraints—exhibit greater stability against perturbations.

The framework also suggests that organization can be compared across very different physical systems using a common informational measure, enabling a unified analysis of pattern formation.

6. Biological Systems and Living Organization

Biological systems represent the most striking examples of sustained organization. Living organisms continuously maintain structure despite constant entropic pressures.

From the informational viewpoint:

- Genetic information encodes structural constraints,
- Regulatory networks manage internal entropy,
- Metabolism supplies the energy required to sustain organization.

Life can thus be understood as a process that maximizes organizational efficiency under thermodynamic constraints. Evolution favors structures that efficiently encode and exploit information to maintain functionality.

This interpretation does not reduce biology to physics, but rather embeds biological organization within a broader physical–informational framework. It explains why information processing is central to life at every scale, from molecular signaling to cognition.

7. Relation to Learning and Adaptive Systems

Learning systems—biological or artificial—provide a dynamic illustration of informational organization. Learning corresponds to the acquisition of structure that improves prediction, control, or survival.

Within this framework:

- Learning increases usable information,
- Noise and over-complexity increase entropy,
- Successful adaptation corresponds to increasing organizational efficiency.

This insight directly motivates the design of artificial systems that explicitly track and optimize organizational efficiency, rather than relying solely on performance metrics.

8. Toward an Extended Thermodynamic Principle

The framework developed here suggests an extension of thermodynamic reasoning. In addition to energy and entropy, information plays a governing role in determining the direction and outcome of system evolution.

I therefore propose the following principle:

The degree of organization attainable by a system is determined by the balance between its usable information and its effective entropy.

This principle does not contradict existing thermodynamic laws. Instead, it extends them into domains where information is the dominant organizing factor. It provides a conceptual foundation for understanding self-organization across physical and biological systems.

9. Discussion

By treating information as a foundational quantity, this framework bridges long-standing gaps between physics, biology, and complexity science. It explains why organization is neither accidental nor in violation of thermodynamic laws, but a natural consequence of informational constraints acting within energetic and entropic limits.

The concept of organizational efficiency offers:

- A unifying metric across disciplines,
- A tool for analyzing stability and robustness,
- A theoretical foundation for self-organizing systems.

While this work is primarily conceptual, it opens the door to quantitative implementations in modeling, experimentation, and artificial intelligence.

10. Conclusion

In this article, I have proposed an informational foundation for understanding organization in physical and biological systems. By elevating information to a central role alongside entropy, I provide a coherent framework for explaining self-organization, stability, and structured behavior.

This perspective suggests an extended thermodynamic principle in which information governs the emergence and persistence of organization. The framework unifies diverse phenomena under a common conceptual language and offers a basis for future theoretical and applied research in physics, biology, and artificial intelligence.

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📘 SUPPLEMENTARY MATERIAL

Supplementary Note S1: Conceptual Clarification of Information and Organization

In this work, information is not treated as a purely symbolic or computational entity, but as a physical quantity associated with constraints, correlations, and predictability within a system. A system rich in information exhibits structured relationships among its components, reducing uncertainty about its macroscopic behavior.

Organization, in this context, is defined as the presence of stable, functional structure that persists under perturbations. This definition distinguishes organization from mere order, which may arise from symmetry or repetition without functional relevance.

Supplementary Note S2: Distinction Between Entropy Reduction and Organization

A decrease in entropy alone does not guarantee meaningful organization. For example, crystallization produces low-entropy order but limited functional complexity. In contrast, biological systems maintain moderate entropy levels while sustaining high organizational efficiency

This supplementary note emphasizes that organization arises from informational constraints, not solely from entropy minimization. Information acts as a selective force that channels system evolution toward specific structured configurations.

Supplementary Note S3: Organizational Efficiency as a State Variable

Organizational efficiency can be treated as a macroscopic descriptor of system state, complementary to entropy. While entropy measures disorder, organizational efficiency measures how effectively information stabilizes structure.

This quantity is especially relevant for non-equilibrium systems, where energy flows maintain organization far from equilibrium. Organizational efficiency provides a compact descriptor of system health, robustness, and adaptability

Supplementary Note S4: Relation to Non-Equilibrium Thermodynamics

Non-equilibrium thermodynamics explains how energy fluxes can sustain structure. The informational framework presented here extends this view by clarifying which structures persist and why.

Information determines:

- the selection of stable patterns,
- resistance to noise,
- adaptability to changing conditions.

Thus, informational constraints operate alongside energy fluxes to govern organization.

Supplementary Note S5: Biological Interpretation

In biological systems, information appears at multiple levels:

- genetic information,
- epigenetic regulation,
- neural coding,
- ecological interactions.

Organizational efficiency increases when these informational layers coordinate effectively to suppress destructive entropy while preserving adaptability. This framework provides a unified interpretation of biological robustness and evolution.

Supplementary Note S6: Implications for Artificial Systems

Artificial learning systems can be interpreted as informational–thermodynamic entities. Learning corresponds to increasing internal structure, while noise and overfitting correspond to entropic drift.

This interpretation motivates the design of artificial systems that explicitly monitor and regulate organizational efficiency, enabling more stable and interpretable learning dynamics.

Supplementary Note S7: Scope and Limitations

This work is conceptual and foundational. While it establishes a unifying framework, quantitative implementations depend on system-specific definitions of information and entropy. The framework is intended to guide theory and modeling rather than prescribe a single mathematical formulation.

Future work will focus on formalizing these quantities in specific domains and testing the predictions experimentally.

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