Title :

Information-Driven Order Formation in Natural and Artificial Systems

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Abstract

The spontaneous formation of order in complex systems remains a central problem across physics, biology, and artificial intelligence. While thermodynamics constrains irreversibility through entropy, it does not fully explain why organized structures emerge, persist, and adapt far from equilibrium. In this article, I develop an information-centered framework in which **order formation is driven by informational constraints** that channel system dynamics and counteract entropic dispersion. I analyze the mechanisms through which information shapes organization in natural and artificial systems, introduce a unifying interpretation based on organizational efficiency, and demonstrate how this perspective applies across physical, biological, and computational domains. This work provides a coherent theoretical foundation for understanding order as an information-driven phenomenon.

Keywords

Information-driven organization; order formation; complex systems; entropy; self-organization; biological systems; artificial intelligence; non-equilibrium thermodynamics.

1. Introduction

Order formation is a striking feature of natural and artificial systems. Physical patterns emerge in driven fluids, biological organisms maintain complex internal organization, and artificial learning systems develop structured representations from raw data. Despite their diversity, these systems share a common challenge: they must sustain order under constant entropic pressure.

Classical and non-equilibrium thermodynamics explain how energy flows allow systems to remain far from equilibrium, but they do not fully account for the **structural specificity** and **robustness** of organized states. In particular, thermodynamic descriptions often lack a variable that explicitly captures **informational structure**.

In this article, I argue that order formation is fundamentally **information-driven**. Information acts as a physical constraint that shapes the space of accessible states and channels system dynamics. This perspective allows order formation to be understood without violating thermodynamic principles, while extending their explanatory scope.

2. Entropy and the Limits of Thermodynamic Explanations

2.1 Entropy as a constraint on irreversibility

Entropy quantifies disorder, uncertainty, and irreversibility. In non-equilibrium systems, entropy production characterizes dissipation and energy degradation. These concepts successfully explain why perpetual motion is impossible and why systems relax toward equilibrium.

However, entropy alone does not distinguish:

- functional order from trivial low-entropy states,
- stable organization from transient patterns,
- adaptive systems from fragile ones.

2.2 The explanatory gap

Two systems with similar entropy production rates may exhibit radically different organizational behaviors. This suggests that entropy constrains **what is possible**, but does not determine **what is organized**. A complementary variable is required.

3. Information as a Driver of Order

Information, in this framework, is not treated as abstract symbolism. I define information as **the set of constraints, correlations, and regularities that reduce the effective degrees of freedom of a system**.

Examples include:

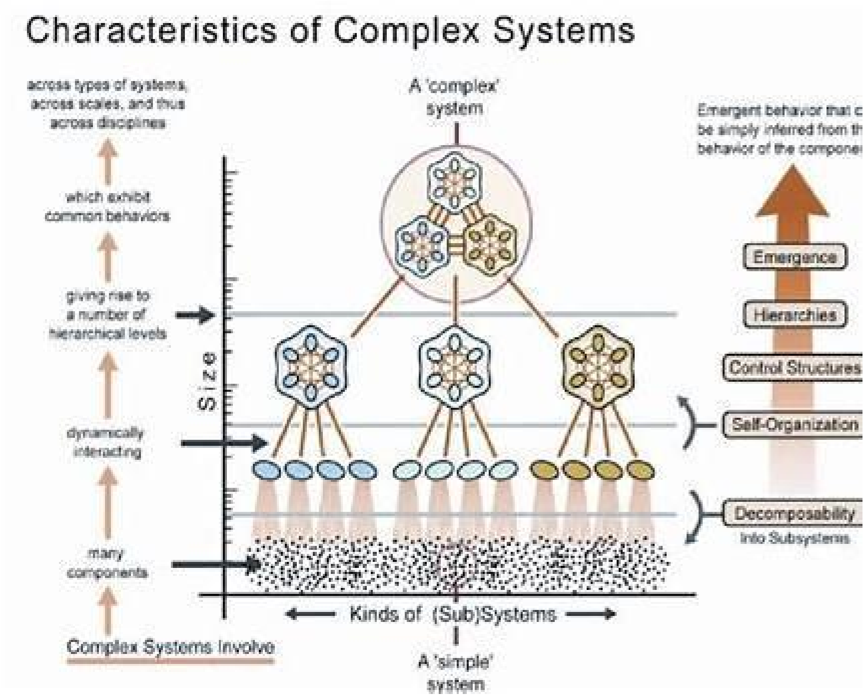
- symmetry constraints and boundary conditions in physics,
- genetic and regulatory networks in biology,
- learned representations and architectures in artificial systems.

Information does not eliminate entropy; it **channels entropy production into structured pathways**, allowing order to persist.

4. Mechanism of Information-Driven Order Formation

Order forms when informational constraints restrict system dynamics more strongly than entropic forces disperse them. This leads to:

- reduced state-space exploration,
- increased predictability,
- stabilization of macroscopic patterns.



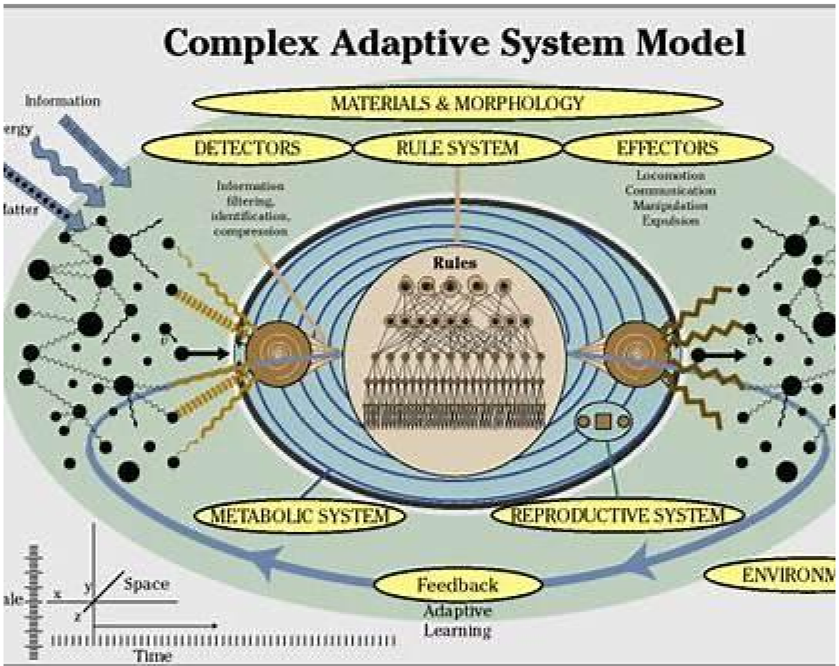


Figure 1 — Conceptual Mechanism of Information-Driven Order Formatio

Conceptual illustration of information-driven order formation. Informational constraints restrict system dynamics and counteract entropic dispersion, enabling stable organized states.

5. Organizational Regimes

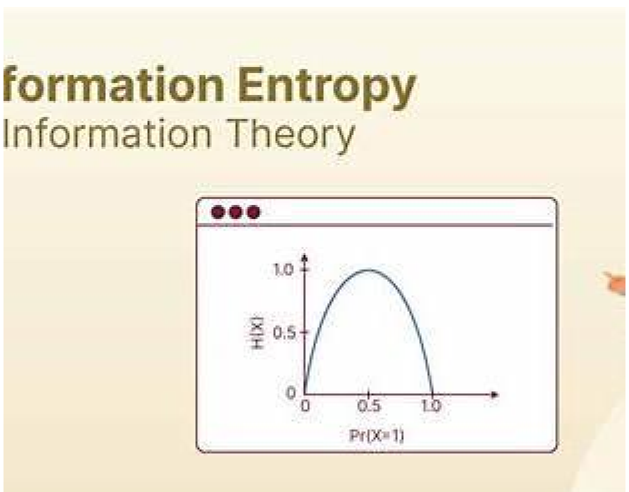
The balance between information and entropy defines three organizational regimes:

1. **Information-dominated regime**
Order increases and stabilizes.

2. **Balanced regime**
Order is maintained in dynamic equilibrium.

3. **Entropy-dominated regime**
Order degrades and structures collapse.

These regimes apply universally across natural and artificial systems.



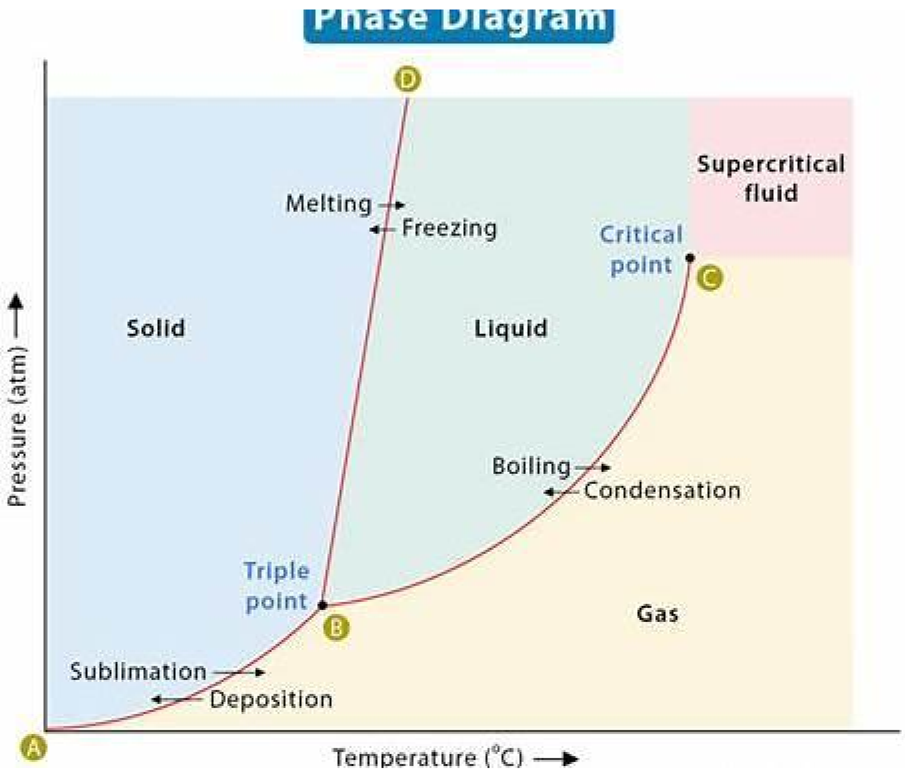


Figure 2 — Organizational Regimes and Transitions
Organizational regimes emerging from the balance between informational constraints and entropic forces, with transitions near critical thresholds.

6. Natural Systems

6.1 Physical systems

In physical systems, order emerges through symmetry breaking, pattern formation, and attractor dynamics. Informational constraints arise from conservation laws, boundary conditions, and interaction rules.

This perspective explains:

- pattern selection,
- robustness to perturbations,
- persistence of dissipative structures.

6.2 Biological systems

Biological organization relies on encoded information (genetic, epigenetic, regulatory). Metabolism supplies energy, but information determines structure.

Loss of informational control leads to aging, disease, and collapse of function.

7. Artificial Systems

In artificial intelligence and learning systems, order emerges through structured representations, hierarchical features, and internal constraints.

Information-driven order formation explains:

- learning stability,
- generalization,
- resistance to noise.

Training corresponds to increasing usable information relative to disorder.

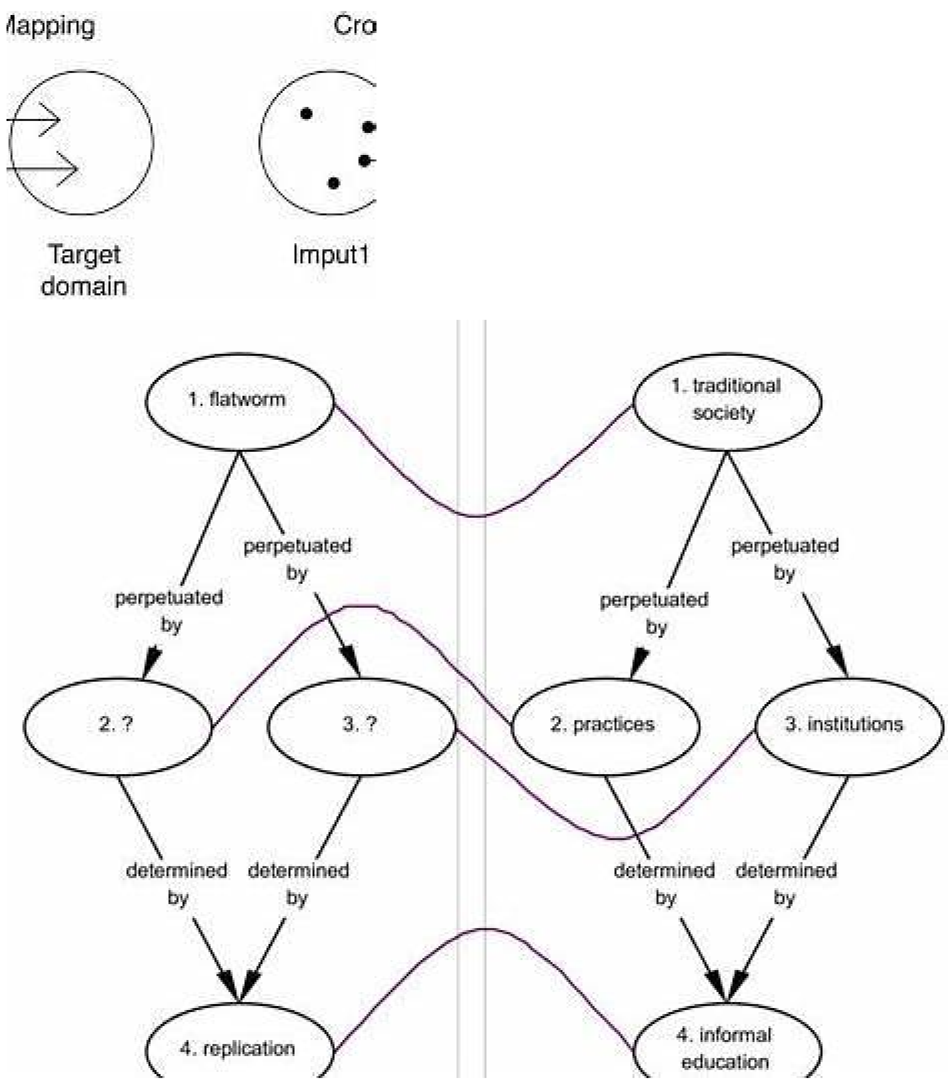


Figure 3 — Cross-Domain Information-Driven Order

Information-driven order formation across physical, biological, and artificial systems, illustrating shared organizational principles.

8. Testable Predictions

This framework yields falsifiable predictions:

1. Loss of order is preceded by degradation of informational constraints.
2. Increasing information stabilizes systems more efficiently than increasing energy input.
3. Systems with similar entropy production may differ in order due to informational structure.

9. Discussion

Viewing order formation as an information-driven process clarifies the limits of thermodynamic explanations. Entropy governs irreversibility, but **information governs structure**.

This framework unifies insights from thermodynamics, information theory, and complexity science, offering a coherent explanation for order across domains.

10. Conclusion

I have shown that order formation in natural and artificial systems is fundamentally information-driven. Informational constraints shape dynamics, counteract entropic dispersion, and enable stable organization. This perspective extends thermodynamic reasoning and provides a unified foundation for studying self-organization and complex systems.

Supplementary Information

Information-Driven Order Formation in Natural and Artificial Systems

Supplementary Note S1 — Conceptual Definition of Information-Driven Order

In the main article, order formation is described as an information-driven process. This does not imply that information replaces energy or entropy, but that it acts as a **structuring constraint** on system dynamics.

Order is defined here as:

- persistent macroscopic structure,
- reduced effective degrees of freedom,
- constrained and predictable dynamics.

Information-driven order formation occurs when informational constraints limit the set of accessible system trajectories more strongly than entropic dispersion expands them.

Supplementary Note S2 — Information as a Physical Constraint

Information is treated as a physical quantity insofar as it constrains system evolution. These constraints may take different forms depending on the system:

- **Physical systems**: symmetries, conservation laws, boundary conditions.
- **Biological systems**: genetic codes, regulatory networks, signaling pathways.
- **Artificial systems**: architectures, learned representations, algorithmic rules.

Information does not act dynamically like a force; instead, it **shapes the geometry** of **state space**, reducing uncertainty in system evolution.

Supplementary Note S3 — Distinction Between Order and Low Entropy

Low entropy alone does not imply meaningful order. For example:

- a crystal has low entropy but limited functional organization,
- random noise can have high entropy without structure,
- biological systems maintain intermediate entropy with high organization.

Information-driven order emphasizes **functional and structural constraints**, not entropy minimization alone.

Supplementary Note S4 — Dynamical Interpretation

From a dynamical systems perspective, information-driven order formation corresponds to:

- the emergence of low-dimensional attractors,
- increased basin stability,
- reduced sensitivity to perturbations.

Informational constraints effectively reshape attractor landscapes, stabilizing certain configurations while suppressing others.

Supplementary Note S5 — Relation to Non-Equilibrium Thermodynamics

Non-equilibrium thermodynamics explains how energy flux sustains systems far from equilibrium. However, it does not specify:

- which structures are selected,
- why some patterns persist longer than others.

Information-driven order formation complements thermodynamics by explaining **pattern selection and persistence**, not just dissipation.

This framework remains fully consistent with the second law of thermodynamics.

Supplementary Note S6 — Natural Systems: Additional Examples

Physical systems

- Rayleigh–Bénard convection patterns arise from boundary and symmetry constraints.
- Reaction–diffusion systems exhibit pattern selection based on interaction rules.

Biological systems

- Developmental processes rely on informational gradients and regulatory logic.
- Ecosystems maintain structure through informational feedback between species.

In both cases, order collapses when informational constraints degrade.

Supplementary Note S7 — Artificial Systems and Learning Dynamics

In artificial systems:

- training increases structured representations,
- regularization reduces effective entropy,
- learning stabilizes dynamics.

Information-driven order formation explains why:

- well-trained models generalize,
- poorly constrained models become unstable or noisy.

The framework applies independently of specific algorithms.

Supplementary Note S8 — Quantitative Extensions

Although this article focuses on conceptual foundations, quantitative extensions are possible. Potential proxies include:

- mutual information measures,
- correlation structure,
- dimensionality reduction metrics,
- stability indices.

These proxies can be used to empirically track information-driven order formation.

Supplementary Note S9 — Limitations and Scope

This framework does not claim:

- a single universal measurement of information,
- a replacement of existing thermodynamic laws.

Instead, it provides:

- a unifying interpretive layer,
- a conceptual bridge across disciplines,
- a foundation for future formalization.

Care must be taken to define information consistently within each domain.

Supplementary Note S10 — Experimental and Theoretical Outlook

Future research directions include:

- experimental detection of informational degradation prior to system collapse,
- cross-scale comparisons of order formation,
- integration with control theory and adaptive systems,
- application to artificial intelligence robustness and safety.

Information-driven order formation offers a promising avenue for a unified science of organization.

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