Information as a Relational Property of Physical Dynamics

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Contents

Abstract

The concept of information is widely used across physics, computer science, biology, and philosophy, yet it lacks a shared minimal definition that is independent of semantics, intentionality, or symbolic representation. As a result, information is often reified and treated as an additional ontological ingredient, leading to persistent conceptual confusions—most notably in discussions of abiogenesis, biological organization, and the relation between information and the second law of thermodynamics.

This paper proposes a minimal operational definition of information grounded in physical dynamics. Information is defined as the existence of distinguishable states of a physical system whose differences lead to different causal consequences. On this basis, information is shown to be a relational property of non-trivial physical dynamics rather than an abstract entity or external addition to matter. The definition is developed formally and illustrated through simple physical and chemical examples, including selection processes and replication.

The resulting framework dissolves the apparent tension between information, physical law, and thermodynamics. Information does not violate physical constraints, nor does it require appeal to intention, meaning, or design. Instead, it arises naturally wherever physical dynamics is not indifferent to differences. Later notions of information—quantitative, biological, or semantic—are shown to be higher-level extensions built upon this foundational condition.

1 Introduction: Why "Information" Requires a Minimal Definition

The term *information* occupies a peculiar position in contemporary science and philosophy. It is indispensable and yet remarkably unstable. In physics, information appears in discussions of entropy, black holes, and statistical mechanics.[1] In computer science, it is measured, transmitted, and compressed.[2] In biology, it is said to be stored in DNA and expressed through genetic codes.[3] In philosophy, it is invoked to explain meaning, representation, and cognition.[4]

Despite this ubiquity, there is no consensus on what information is at its most basic level. Existing accounts tend to begin either with quantitative measures (such as Shannon information), with semantic notions (meaning, reference, interpretation), or with biological metaphors (codes, instructions, programs). Each of these approaches is useful within its own domain, but none of them clarifies the minimal conditions under which information exists at all.[5]

This lack of a foundational definition has significant consequences. Information is frequently treated as if it were an ontologically independent ingredient—something that must be "added" to matter in order to explain life, organization, or complexity. In debates over the origin of life, this assumption leads to the claim that physical and chemical processes are insufficient because they allegedly cannot generate information.[6] In other contexts, information is implicitly treated as a conserved or quasi-mystical quantity, placed in tension with physical laws such as the second law of thermodynamics.[7]

The present work argues that these difficulties arise from starting at the wrong level. Before asking how much information a system contains, or what that information means, it is necessary to ask a simpler and more fundamental question: under what conditions does it make sense to say that information exists at all?

The guiding idea of this paper is that information should be defined prior to semantics, intentionality, and symbolic representation. It should apply equally to simple physical systems and to complex biological ones. To achieve this, the paper develops a minimal op-

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[1] See, for example, C. E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, 1948; and J. Preskill, "Information and Black Holes," *Scientific American*, 1997.

[2] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley, 2006.

[3] F. Crick, "Central Dogma of Molecular Biology," *Nature*, 1970.

[4] L. Floridi, *The Philosophy of Information*, Oxford University Press, 2011.

[5] For a survey of these divergent approaches, see L. Floridi, "Information," *The Stanford Encyclopedia of Philosophy*, 2022.

[6] For representative examples of this line of argument, see discussions in the context of intelligent design and anti-abiogenesis literature.

[7] For a clear physical treatment of entropy and information, see E. T. Jaynes, "Information Theory and Statistical Mechanics," *Physical Review*, 1957.

erational definition of information grounded directly in physical dynamics. This definition captures the intuitive notion that information exists whenever differences matter—whenever distinct states of a system lead to distinct outcomes.

By adopting this perspective, information is no longer an abstract entity or external addition to matter. It becomes a relational property of physical systems whose dynamics is non-trivial. From this standpoint, the emergence of information in physical and biological systems is neither mysterious nor exceptional; it is an inevitable consequence of the fact that the laws of nature are sensitive to differences.

2   Methodological Scope and Commitments

Before introducing a formal definition, it is necessary to clarify the scope and methodological commitments of this paper. Many disputes surrounding information arise not from disagreement over facts, but from the use of the same term at different conceptual levels.[8]

The notion of information developed here is *pre-semantic*. It does not presuppose meaning, reference, interpretation, or an observer. It is also *pre-biological* in the sense that it applies equally to simple physical systems and to complex living ones. Finally, it is *pre-intentional*: no notion of choice, purpose, or goal is assumed. These exclusions are not deficiencies of the definition, but conditions of its generality.[9]

This paper does not attempt to replace existing theories of information. Shannon's information theory, semantic accounts of information, and biological notions such as genetic codes all remain valid within their respective domains.[10] However, they presuppose that information already exists in some form. The present goal is more basic: to specify the minimal condition under which it is meaningful to say that a physical system contains information at all.

Accordingly, the definition proposed here should be understood as *necessary but not sufficient*. It specifies what must be the case for information to exist, not what is required for information to be meaningful, useful, or interpretable. Quantitative measures of information, symbolic encoding, and semantic content are treated as higher-level constructions built upon this foundational condition.[11]

Methodologically, the approach is conservative. No new physical principles are intro-

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[8]For general discussions of level-confusion in theories of information, see L. Floridi, *The Philosophy of Information*, Oxford University Press, 2011.

[9]A similar motivation for pre-semantic accounts can be found in discussions of physical information in statistical mechanics; see E. T. Jaynes, "Information Theory and Statistical Mechanics," *Physical Review*, 1957.

[10]C. E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, 1948.

[11]For a clear distinction between foundational and quantitative notions of information, see T. M. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley, 2006.

duced, and no appeal is made to non-physical entities. The analysis proceeds entirely within standard assumptions of physical dynamics, including deterministic and probabilistic evolution, and respects established constraints such as the second law of thermodynamics.[12] The aim is conceptual clarification rather than theoretical revision.

By fixing the scope in this way, the paper avoids two common errors. The first is *reification*, in which information is treated as an ontologically independent ingredient added to matter. The second is *category confusion*, in which properties of high-level descriptions (such as meaning or code) are projected onto the most basic physical processes. The definition developed in the following sections is intended to block both moves by making explicit the level at which information first appears.

3   Formal Framework

To define information at the most basic operational level, we begin by specifying a minimal formal framework. The purpose of this framework is not to introduce mathematical sophistication, but to make explicit the structure that is already implicit in ordinary physical reasoning. In particular, it allows us to state precisely what it means for differences to matter.

Consider a physical system $\mathcal{U}$ evolving in time according to its physical laws. At any given moment, the system can occupy one of several possible states, and its future evolution depends on which state it is in. This dependence is the sole feature required for the existence of information in the present account.

Let S denote the set of possible states of the system $\mathcal{U}$ at time t. These states may be microscopic or macroscopic, discrete or continuous, depending on the level of description. Let D denote the set of possible future states, trajectories, or outcomes of the system at a later time $t + \Delta t$. Finally, let F denote the physical dynamics of the system, understood as a mapping from present states to future outcomes.

In the simplest, deterministic case, this mapping can be written as

$$F : S \to D,$$

where each initial state determines a unique future state. In more realistic cases—especially in chemistry, thermodynamics, and biology—the dynamics may be probabilistic. In that case, the mapping assigns to each initial state a probability distribution over possible out-

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[12]For classical formulations of the second law in physical systems, see H. B. Callen, *Thermodynamics and an Introduction to Thermostatistics*, Wiley, 1985.

comes. This can be expressed as

$$F : S \to \mathcal{P}(D),$$

where $\mathcal{P}(D)$ denotes the set of probability distributions over D.[13]

Nothing substantial hinges on this distinction. The framework applies equally to deterministic and probabilistic dynamics. What matters is only whether the dynamics is sensitive to differences in the initial state.

This framework deliberately avoids any reference to observers, measurements, representations, or interpretations. The states in S are not "descriptions" of the system but physical configurations it can actually occupy. Likewise, the mapping F does not represent a rule of inference or computation; it represents the causal evolution of the system itself.[14]

The question of information can now be stated in its most basic form: does the physical evolution of the system distinguish between different possible states? If all states in S lead to the same outcome in D, then the system is dynamically indifferent to its initial conditions. If, on the other hand, at least some differences in S lead to different outcomes under F, then the system is not indifferent, and those differences have physical consequences.

The framework introduced here is intentionally minimal. It does not presuppose coding, storage, communication, or meaning. It merely formalizes the idea that physical laws may or may not respond differently to different initial conditions. In the following section, this structure will be used to give a precise operational definition of information.

4   Definition: Causal / Operational Information

With the formal framework in place, we can now state a minimal operational definition of information. The definition is intentionally simple. It does not aim to capture all uses of the word "information" in science or philosophy. Its purpose is to identify the most basic condition under which it is meaningful to say that information exists at all.

Definition (Causal / Operational Information). A physical system $\mathcal{U}$ contains information if and only if there exist at least two distinct states $s_1, s_2 \in S$ such that the physical dynamics of the system distinguishes between them, that is,

$$\exists s_1, s_2 \in S \ (s_1 \neq s_2 \wedge F(s_1) \not\equiv F(s_2)).$$

In words: information exists whenever a difference in the state of a system leads to a differ-

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[13]For standard treatments of deterministic and probabilistic dynamics in physical systems, see H. B. Callen, *Thermodynamics and an Introduction to Thermostatistics*, Wiley, 1985.

[14]This distinction between physical dynamics and representational or computational interpretations is emphasized in E. T. Jaynes, "Information Theory and Statistical Mechanics," *Physical Review*, 1957.

ence in its subsequent physical consequences.

This condition is both necessary and sufficient for information in the present sense. If no such pair of states exists—if the system's dynamics treats all possible states as equivalent—then there is no information. Conversely, if at least one such pair exists, then the system is informationally non-trivial.

The definition applies equally to deterministic and probabilistic dynamics. In the deterministic case, $F(s_1) \neq F(s_2)$ means that the system evolves into different future states. In the probabilistic case, it means that the probability distributions over outcomes are not identical. In both cases, the essential point is the same: the future of the system depends on its present state in a way that makes a physical difference.[15]

It is important to emphasize what this definition does *not* assume. It does not require an observer who detects the difference, an agent who interprets it, or a code that represents it. It does not presuppose meaning, purpose, or intention. It does not rely on symbolic representation, language, or computation. The definition is therefore prior to any epistemic or semantic notion of information.[16]

The definition also does not presuppose any quantitative measure. Information, in this minimal sense, is not something that must be counted in bits or expressed numerically. The definition concerns the *existence* of information, not its amount. Quantitative notions of information can be introduced later as refinements, but they are not required for information to exist.[17]

Finally, this definition makes clear that information is not an independent entity or substance. It is a relational property of physical dynamics. Information exists wherever the laws governing a system are not indifferent to differences in its possible states. In the next section, we will examine the immediate consequences of this definition and clarify what follows from it—and what does not.

5   Immediate Properties of the Definition

The definition introduced in the previous section has several immediate and important consequences. These consequences follow directly from the formal condition itself and do not depend on any additional assumptions. Clarifying them explicitly helps prevent common misunderstandings that arise when higher-level notions are projected onto the most basic

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[15]For standard discussions of deterministic and probabilistic dynamics in physical systems, see H. B. Callen, *Thermodynamics and an Introduction to Thermostatistics*, Wiley, 1985.

[16]For contrasting semantic and representational accounts, see L. Floridi, *The Philosophy of Information*, Oxford University Press, 2011.

[17]See C. E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, 1948, for the classical quantitative framework.

level of information.

First, information in the present sense does *not* presuppose the existence of an observer or interpreter. The definition makes no reference to measurement, perception, or representation. Information exists solely in virtue of the system's physical dynamics distinguishing between different possible states. Whether or not any agent detects or uses that distinction is irrelevant at this level.[18]

Second, the definition does *not* involve meaning, semantics, or reference. No state is said to "stand for" or "represent" anything else. Information is not defined in terms of symbols or messages, but in terms of causal consequences. Semantic notions of information therefore belong to a later stage of analysis and cannot serve as foundational criteria.[19]

Third, the definition does *not* require choice, intention, or goal-directed behavior. The dynamics F need not involve any decision-making process. Physical selection resulting from stability, energy constraints, or boundary conditions is sufficient. The system may be entirely non-living and non-cognitive, yet still informationally non-trivial.

Fourth, the definition does *not* presuppose symbolic encoding or computation. No alphabet, code, or syntactic structure is required. The mapping from states to outcomes is given directly by physical law, not by a system of symbols or rules of interpretation.[20]

Fifth, the definition distinguishes clearly between the *existence* of information and its *quantity*. Information exists whenever the dynamics is not indifferent to differences. Formally, information is absent if and only if the dynamics is constant over the state space:

$$\forall s_1, s_2 \in S \ : \ F(s_1) = F(s_2).$$

In this case, all initial states lead to identical outcomes, and no physical difference makes a difference. Conversely, information exists whenever there is at least one pair of states for which this condition fails:

$$\exists s_1, s_2 \in S \ : \ F(s_1) \neq F(s_2).$$

This existential condition is sufficient for information in the present sense. No numerical measure is required. Quantitative notions—such as entropy, mutual information, or bit counts—can be introduced later as refinements, but they presuppose the existence of information rather than define it.[21]

Taken together, these properties show that information, at its most basic level, is neither

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[18]This point is emphasized in physical and non-semantic approaches to information; see E. T. Jaynes, "Information Theory and Statistical Mechanics," *Physical Review*, 1957.

[19]For a clear distinction between semantic and non-semantic notions of information, see L. Floridi, *The Philosophy of Information*, Oxford University Press, 2011.

[20]For a critique of overly computational readings of physical dynamics, see J. R. Searle, "Is the Brain a Digital Computer?," *Proceedings and Addresses of the American Philosophical Association*, 1990.

[21]See C. E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, 1948.

mysterious nor metaphysically demanding. It is simply the fact that physical dynamics may respond differently to different possible states. Information is therefore not an object or substance, but a relational feature of how systems evolve.

In the next section, this abstract characterization will be connected to concrete physical processes. In particular, we will show how ordinary physical selection—arising from stability, kinetics, and energy constraints—naturally generates information in the operational sense defined here, without invoking choice, intention, or design.

6   Physical Selection Without Choice

The operational definition of information introduced above is intentionally minimal. It makes no reference to choice, intention, or agency. Nevertheless, a common intuition persists that information must somehow involve selection in the sense of choosing between alternatives. This section shows why that intuition is misleading, and how purely physical selection is sufficient for information in the operational sense.

The crucial distinction is between *intentional choice* and *physical selection*. Intentional choice presupposes an agent, goals, and evaluation. Physical selection, by contrast, arises whenever the laws governing a system favor some states or trajectories over others. No decision-making process is involved. The selection is imposed by the structure of physical dynamics itself.[22]

In formal terms, physical selection occurs whenever the mapping

$$F : S \to D$$

is sensitive to differences in the state space S. If two distinct states lead to different outcomes, then the dynamics distinguishes between them. This distinction is sufficient for information, regardless of whether any agent is present.

Consider a simple chemical system. Let S be the set of possible configurations of reactants, and let D be the set of possible reaction products or kinetic pathways. The physical dynamics F is determined by thermodynamic stability and reaction kinetics. Some configurations lead to stable products, while others rapidly decay or fail to react. Formally, there exist states s_1 and s_2 such that

$$F(s_1) \neq F(s_2).$$

This difference does not result from a choice, but from energy constraints and reaction rates.

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[22]For classic discussions of selection without agency in physical systems, see I. Prigogine, *From Being to Becoming*, W. H. Freeman, 1980.

Nevertheless, it satisfies the operational condition for information.[23]

The same structure appears in crystallization. Let S be the set of possible atomic arrangements, and let D be the set of resulting macroscopic structures and their lifetimes. Only a subset of configurations minimizes free energy and persists over time. Others are unstable and disappear. The dynamics selects stable configurations without any reference to goals or decisions. The fact that some structures persist while others do not is already an informational distinction in the present sense.[24]

More generally, physical selection is ubiquitous. In any system governed by differential stability, boundary conditions, or kinetic constraints, not all possible states are treated equally. Some states are amplified, others suppressed. This asymmetry is sufficient to generate information, because it ensures that differences in initial conditions lead to differences in outcomes.

It is therefore a mistake to conclude that information requires choice. What information requires is *non-indifference*. If the dynamics of a system responds differently to different states, then information exists. If the dynamics is completely indifferent—if

$$\forall s_1, s_2 \in S \ : \ F(s_1) = F(s_2),$$

then no information is present, because no difference ever makes a difference.

Physical selection is thus the most basic mechanism by which information arises. It operates wherever physical laws constrain and shape the evolution of a system. No appeal to agency, intention, or design is required. In the next section, this idea will be extended to the case of abiogenesis, where information accumulates gradually through long-term physical selection rather than appearing in a single discrete event.

7 Abiogenesis as a Dynamical Process

The framework developed in the previous sections allows the problem of abiogenesis to be reformulated in a precise and non-mystifying way. In particular, it removes the widespread assumption that information must appear suddenly or be introduced from outside physical and chemical processes.

Abiogenesis is not a discrete event but a dynamical process unfolding over extended periods of time. Chemical systems continuously explore a space of possible configurations, while physical dynamics selectively stabilizes some configurations and suppresses others.

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[23]See P. W. Atkins, *Physical Chemistry*, Oxford University Press, for standard treatments of stability and reaction kinetics.

[24]For a general discussion of crystallization and free energy minimization, see D. Chandler, *Introduction to Modern Statistical Mechanics*, Oxford University Press, 1987.

From the operational perspective developed here, information is present whenever differences between configurations lead to systematically different outcomes. No special threshold or qualitative jump is required.

Formally, consider a prebiotic chemical system with a state space S and a dynamical mapping

$$F : S \to \mathcal{P}(D),$$

where D represents possible future trajectories, reaction pathways, or long-term outcomes. Information exists whenever there are distinct states $s_1, s_2 \in S$ such that

$$F(s_1) \not\equiv F(s_2).$$

This condition is satisfied whenever chemical dynamics favors some configurations over others, for example by differences in stability, reactivity, or catalytic potential.

On this view, abiogenesis does not involve a transition from a state with no information to a state with information. Rather, information accumulates gradually as physical selection reshapes the space of possible states. Certain molecular structures persist longer, participate in autocatalytic cycles, or modify their environment in ways that enhance their own continuation, while others decay or remain inert. Each such asymmetry introduces informational structure by making some differences causally relevant and others irrelevant.

This process is continuous with other well-understood phenomena of physical self-organization. Crystallization, pattern formation in reaction–diffusion systems, and the emergence of dissipative structures all exhibit the same basic logic: physical laws amplify some configurations and suppress others without invoking choice, intention, or design.[25]

From this perspective, the appeal to information as an external explanatory ingredient in discussions of the origin of life is misplaced. Information is not something that must be added to matter in order to produce life-like behavior. It is an intrinsic consequence of non-trivial physical dynamics operating over time. Abiogenesis therefore becomes a question of dynamical pathways, stability landscapes, and environmental constraints, rather than a problem of how information could be generated ex nihilo.

Understanding abiogenesis in this way aligns it with standard physical reasoning and removes the need for exceptional explanatory principles. Life emerges not because physical laws are circumvented, but because they operate persistently in systems that are far from equilibrium.[26]

In the next section, this dynamical account will be extended to replication. We will show

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[25] For classic discussions of self-organization and dissipative structures, see I. Prigogine and I. Stengers, *Order Out of Chaos*, Bantam, 1984.

[26] For modern treatments of far-from-equilibrium systems in prebiotic contexts, see J. L. England, "Statistical Physics of Self-Replication," *The Journal of Chemical Physics*, 2013.

that self-replicating structures fit naturally within the same framework and remain fully consistent with the second law of thermodynamics.

8   Replication as a Physical Process

The notion of replication is often treated as a qualitative leap that separates living systems from non-living matter. In many discussions, replication is implicitly assumed to require a prior informational code, intentional design, or a special organizing principle. Within the framework developed in this paper, none of these assumptions is necessary.

Replication can be understood as a purely physical process in which certain structures, under suitable conditions, give rise to structures sufficiently similar to themselves. What distinguishes replicating systems is not the presence of a symbolic code, but the existence of dynamical pathways that preferentially produce copies of a given structure rather than alternatives.

Formally, consider a system with state space S and dynamics

$$F : S \to \mathcal{P}(D),$$

where D represents future outcomes over some time interval. A structure $s \in S$ is replicative if the evolution governed by F increases the number of states in D that are structurally similar to s. Replication, in this sense, is a property of the dynamics, not of any representational scheme.

Importantly, replication does not require foresight, intention, or goal-directed behavior. The process may be driven entirely by local interactions, energy gradients, and environmental constraints. Autocatalytic chemical networks provide a clear illustration: certain molecular configurations catalyze reactions that produce additional instances of the same or closely related configurations. No code is consulted, and no symbolic instruction is executed.[27]

Within the operational definition of information introduced earlier, replication is a special case of physical selection. Replicating structures are those for which differences in configuration lead to differences in long-term abundance. Structures that replicate persist and multiply; those that do not replicate decay or disappear. This asymmetry is informational in exactly the same sense as other selection processes discussed above.

Replication therefore does not introduce information as a new ontological ingredient. Rather, it amplifies existing informational distinctions by reinforcing certain dynamical pathways over others. In this way, replication increases the persistence and visibility of

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[27]For early work on autocatalytic networks, see S. A. Kauffman, *The Origins of Order*, Oxford University Press, 1993.

informational structure without altering its fundamental nature.

It is also crucial to note that replication alone does not imply biological complexity. Replicating crystals, autocatalytic reactions, and simple molecular templates all exhibit replication without metabolism, heredity in the biological sense, or semantic information. These systems nonetheless satisfy the operational criteria for information, demonstrating that replication is continuous with non-living physical processes rather than categorically distinct from them.

In the following section, we will examine the relationship between replication and the second law of thermodynamics. In particular, we will show that replication does not violate thermodynamic constraints, but instead represents a highly efficient mode of energy dissipation in open systems.

9   Information Is Not Conserved

A common source of confusion in discussions of information is the implicit assumption that information behaves like a conserved physical quantity. This assumption often arises by analogy with energy, momentum, or mass, and it underlies arguments that treat the growth of informational structure as something that must violate fundamental physical laws.

Within the framework developed in this paper, this assumption is misplaced. Information, in the operational sense defined here, is not a conserved quantity. It is a relational property of physical dynamics, and as such it can increase, decrease, or disappear depending on how the dynamics of a system treats differences between states.

Energy is conserved because it is defined through invariances of physical laws under time translation. Information, by contrast, is defined through sensitivity to differences in state space. There is no physical principle requiring such sensitivity to remain constant over time. When the dynamics of a system becomes more discriminating—when differences between states lead to increasingly divergent outcomes—informational structure increases. When the dynamics becomes indifferent to differences, information is lost.

This distinction is especially important in open systems. Living and prebiotic systems are not isolated; they exchange energy and matter with their environment. In such systems, informational structure can grow locally while remaining fully consistent with physical law. The growth of information is therefore not analogous to the creation of energy from nothing, but to the emergence of ordered patterns under sustained energy flow.

From this perspective, arguments that compare the emergence of information to a hypothetical perpetual motion machine are based on a category error. Perpetual motion machines would violate conservation laws. The emergence of information does not, because information is not governed by a conservation principle in the first place.[28]

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[28]For a clear discussion of entropy, information, and physical law, see E. T. Jaynes, "Information Theory

It is true that the growth of informational structure is constrained by thermodynamics. In particular, local increases in informational differentiation must be accompanied by increases in entropy elsewhere. This constraint, however, does not forbid the accumulation of information; it merely specifies the conditions under which it can occur. Information can increase in open systems precisely because entropy is exported to the environment.

The non-conservation of information also explains why informational structures are fragile. Information can be degraded, erased, or rendered causally irrelevant when differences between states no longer lead to different outcomes. This occurs routinely in physical systems through thermal noise, mixing, and equilibration. The loss of information is therefore as natural as its emergence.

Recognizing that information is not conserved clarifies its proper place in physical explanation. Information is neither a substance nor a fundamental currency of nature. It is a feature of how physical dynamics differentiates between possibilities over time. In the next section, we will consider how this understanding applies to biological information and why genetic information does not constitute a special ontological category.

10   The Ontological Status of Biological Information

Biological information is often treated as a special category of information, distinct from physical information and endowed with unique ontological status. Genetic sequences are described as codes, instructions, or messages, and this language easily suggests that biological information is something over and above the physical processes in which it is embedded.

Within the framework developed in this paper, this interpretation is unnecessary. Biological information does not constitute a distinct ontological kind. It is a particular manifestation of the same operational notion of information already described, realized in systems whose dynamics has become highly structured through replication, selection, and long-term stabilization.

DNA and related biomolecules are not informational because they encode symbolic meaning. They are informational because differences in their physical structure lead to systematic differences in their causal consequences. Variations in molecular configuration result in different patterns of interaction, synthesis, and regulation. These differences matter because the underlying dynamics is sensitive to them. That sensitivity, not semantic interpretation, is the source of biological information.

From this perspective, the so-called genetic code is not a code in the abstract or linguistic sense. It is a stabilized mapping between molecular structures and biochemical outcomes.

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and Statistical Mechanics," *Physical Review*, 1957.

This mapping emerged historically through physical selection and persists because it is dynamically robust. No additional interpretive layer is required to account for its function.[29]

The apparent distinctiveness of biological information arises from its functional integration within complex systems. Replication, heredity, and metabolism jointly amplify certain informational distinctions and suppress others. Over time, this leads to highly constrained and reproducible pathways of development. However, this increase in functional specificity does not imply a change in the ontological status of information itself. The underlying criterion remains the same: differences that lead to differences.

Treating biological information as a separate ontological entity often reintroduces the very confusions this paper seeks to avoid. It invites questions about how information is inserted into matter, how it is preserved independently of physical substrates, or how it exerts causal influence without being physical. All such questions dissolve once biological information is recognized as a relational feature of physical dynamics rather than an independent substance.

This view places biological information in continuity with non-living physical processes. The transition from chemistry to biology does not require the emergence of a new kind of information, but only the progressive stabilization and amplification of informational distinctions already present in physical dynamics. Biological organization is thus not an exception to physical explanation, but one of its most elaborate expressions.

In the concluding section, we will summarize the main results of this analysis and clarify the broader implications of treating information as a relational property of physical systems.

11 Conclusion

This paper has argued that information should be understood at its most basic level as a relational property of physical dynamics. Information exists whenever differences between possible states of a system lead to differences in their causal consequences. This minimal operational condition is prior to semantics, intentionality, symbolic representation, and biological organization.

By adopting this perspective, several persistent conceptual confusions are resolved. Information does not need to be introduced as an additional ontological ingredient, nor does it require appeal to design, meaning, or agency. It is not a conserved quantity analogous to energy, and its emergence does not conflict with thermodynamic principles. In open systems, informational structure can grow naturally as physical dynamics becomes increasingly sensitive to differences.

Within this framework, abiogenesis and replication are continuous with ordinary phys-

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[29]For classical discussions of the genetic code and its physical basis, see F. Crick, "Central Dogma of Molecular Biology," *Nature*, 1970.

ical processes. They do not mark the appearance of a new kind of information, but the progressive stabilization and amplification of informational distinctions already present in non-trivial dynamics. Biological information, including genetic information, does not constitute a separate ontological category; it is a highly structured instance of the same relational phenomenon.

The analysis presented here does not aim to replace existing quantitative, semantic, or biological theories of information. Rather, it provides a foundational clarification of the level at which information first appears and the conditions under which it exists. Higher-level notions of information can be understood as refinements built upon this minimal condition, not as its alternatives.

Understanding information in this way restores continuity between physics, chemistry, and biology, and removes the need for exceptional explanatory principles. Information does not explain life by standing apart from physical processes. Instead, it names the fact that physical dynamics is not indifferent to differences.

A   Appendix A: Quantitative Refinement (Optional)

The operational definition of information developed in this paper is qualitative by design. It specifies the minimal condition under which information exists, without introducing any quantitative measure. For readers interested in a numerical refinement of this notion, the definition admits a natural extension in terms of mutual information.

Let S denote the space of system states and D the space of possible outcomes under the dynamics F. In probabilistic settings, the degree to which knowledge of S reduces uncertainty about D can be quantified by the mutual information $I(S; D)$, as defined in standard information theory.[30]

If the dynamics is informationally indifferent—so that the outcome is statistically independent of the initial state—then $I(S; D) = 0$. This corresponds exactly to the absence of information in the operational sense defined in the main text. Conversely, whenever differences in S systematically influence outcomes in D, mutual information is positive, reflecting the presence of informational structure.

From this perspective, abiogenesis can be understood not as a random search followed by a miraculous outcome, but as a gradual increase in correlation between molecular structure and long-term persistence within a given environment. As physical selection stabilizes certain configurations and suppresses others, the mutual information between structure and outcome increases over time. This quantitative picture is fully consistent with the qualitative framework developed in the paper and does not introduce any additional ontological

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[30]See T. M. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley, 2006.

commitments.

This appendix is intended only as a refinement for readers familiar with quantitative information theory. The core argument of the paper does not depend on this extension.

B   Appendix B: Responses to Common Objections

This appendix briefly addresses several recurring objections to the operational account of information developed in the paper. The responses are clarificatory rather than polemical and are intended to prevent misunderstandings about the scope and intent of the framework.

Objection 1: "This definition ignores semantic information."

The definition presented in the paper is intentionally pre-semantic. It does not deny the existence or importance of semantic information; it specifies the minimal condition under which information exists at all. Semantic notions require additional structures—such as interpretation, modeling, or use by an agent—and therefore belong to a higher level of analysis. Treating semantics as foundational would presuppose information rather than explain it.

Objection 2: "This reduces information to Shannon information."

No such reduction is proposed. Shannon information provides a quantitative measure of correlations under specific probabilistic assumptions. The operational definition in this paper specifies an existential condition for information, not a measure. As noted in Appendix A, quantitative notions can refine the framework, but they are not required for information to exist.

Objection 3: "Purely random processes can generate information."

Randomness alone does not generate information in the operational sense defined here. If outcomes are statistically independent of initial states, then the dynamics is informationally indifferent. Information arises when differences in state systematically influence outcomes, typically through physical constraints and selection. Random variation may contribute to exploration, but information emerges only through non-indifferent dynamics.

Objection 4: "The account presupposes determinism."

The framework is compatible with both deterministic and probabilistic dynamics. The criterion for information is sensitivity to differences, not determinism. Probabilistic systems

can be informationally non-trivial whenever state differences alter outcome distributions.

Objection 5: "Replication introduces a new kind of information."

Replication amplifies informational distinctions but does not introduce a new ontological category of information. Replicating systems are those in which differences in structure lead to differences in persistence or abundance. This is a special case of the same operational criterion applied to long-term dynamics.

Objection 6: "Information must be conserved to be physical."

Information, as defined here, is not a conserved quantity. Conservation applies to quantities defined by symmetries of physical laws. Information is a relational feature of dynamics and can increase or decrease in open systems without violating physical constraints.

Objection 7: "The definition is too general to be informative."

Generality is a feature, not a defect. The purpose of the definition is to identify a necessary condition for information that applies across physical, chemical, and biological systems. More specific notions of information can be built upon this foundation without altering it.

These clarifications are sufficient to situate the operational definition within existing debates while preserving its minimal and transdisciplinary character.