From quantum indeterminacy to biological mutation: probabilistic stability across physical and living systems

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Abstract

The classical deterministic worldview that dominated science from the seventeenth to the nineteenth century has been profoundly challenged by developments in modern physics and biology. Quantum mechanics has revealed that indeterminacy and probability are not merely epistemic limitations, but intrinsic features of physical reality. At the same time, evolutionary biology has shown that random genetic variation, filtered by natural selection, is the fundamental driver of biological diversity and adaptation. This article explores the conceptual parallel between quantum indeterminacy and evolutionary randomness, not as a reduction of biology to physics, but as an epistemological reflection on how stability and order emerge from probabilistic processes across different levels of organization. Its original contribution is to formulate a cross-domain account of probabilistic stability, according to which stable macroscopic regularities emerge from indeterminate micro-processes through constraints, selective filtering, and scale-dependent organization. By examining emergence, contingency, historical irreversibility, and the limits of prediction, the paper argues that determinism is best understood as a scale-dependent approximation rather than a foundational ontological principle. The absence of finality in nature does not imply chaos or nihilism, but invites a renewed philosophical understanding of explanation, responsibility, and scientific humility in a probabilistic universe.

Keywords: quantum indeterminacy; evolutionary biology; emergence; contingency; philosophy of science; epistemology.†

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1. Introduction: The end of classical determinism

From Galileo to Newton, classical science was structured around the ideal of determinism. The universe was conceived as a vast, intelligible mechanism governed by precise laws, such that complete knowledge of initial conditions would, in principle, allow the prediction of all future states. Uncertainty, within this framework, was interpreted as a limitation of knowledge or measurement, not as a property of reality itself. Laplace's well-known image of a hypothetical intelligence capable of calculating the entire future of the universe from present conditions epitomized this epistemological ideal [1].

This deterministic conception profoundly influenced early biological thought. Even after Darwin introduced variation and natural selection as central mechanisms of evolution [2], biological processes were often interpreted as if they followed necessary or optimal trajectories, an outlook exemplified by Claude Bernard's insistence on strict experimental determinism in physiology [3].

During the twentieth century, however, this worldview underwent a radical transformation. Quantum mechanics revealed that indeterminacy and probability are not merely epistemic artifacts but intrinsic features of physical reality [4, 5]. In parallel, modern genetics and evolutionary theory demonstrated that biological novelty arises from random mutations whose evolutionary fate depends on contextual selection rather than necessity. Together, these developments challenge the classical assumption that scientific explanation requires determinism, replacing it with a framework in which probability and context play constitutive roles.

While these themes have been separately discussed in philosophy of physics and philosophy of biology, they are rarely integrated into a unified framework. The present article proposes such integration by comparing how probabilistic micro-processes generate higher-level stability in both domains.

The central thesis of this article is that determinism is best interpreted not as a fundamental ontological principle, but as an effective higher-level regime emerging from probabilistic processes under constraints of historical filtering, relational dynamics, path dependence, and statistical aggregation. This position also contributes to current debates on reductionism, levels of explanation, and probabilistic causation in contemporary philosophy of science across different domains of nature.

The paper proceeds as follows. Section 2 examines quantum indeterminacy and its philosophical interpretations. Section 3 analyzes randomness and selection in evolutionary biology. Section 4 develops emergence as a key conceptual bridge between levels of organization. Section 5 explores contingency, history, and irreversibility. Sections 6 and 7 address the epistemological consequences of probabilistic explanation, while Section 8 considers broader philosophical and ethical implications. The conclusion synthesizes these insights into a coherent view of science in a probabilistic world.

2. Quantum indeterminacy: probability as a feature of reality

2.1. Ontological and instrumental interpretations

Quantum mechanics introduced a profound rupture with classical physics by challenging the assumption that physical systems possess well-defined properties independent of observation. According to the standard formalism, the quantum state does not describe an actual configuration of properties but encodes a set of probabilities for possible measurement outcomes. This feature has generated extensive philosophical debate concerning the ontological status of quantum states.

The Copenhagen interpretation, historically dominant, adopts a form of epistemic modesty: quantum theory does not describe reality "as it is," but provides probabilistic rules for predicting measurement outcomes. In contrast, realist interpretations, such as many-worlds, attempt to preserve an ontological description of quantum reality, though at the cost of revising classical intuitions about individuality, locality, or actuality.

For the purposes of this article, it is not necessary to resolve this debate. What matters philosophically is that most major interpretations of quantum mechanics depart from classical Laplacian determinism in at least one essential respect. Whether indeterminacy is understood as ontological or as a limit of representability, the theory itself assigns probabilities, not certainties, even under conditions of maximal knowledge.

2.2 Indeterminacy is not chaos

It is crucial to emphasize that quantum indeterminacy does not imply disorder or arbitrariness. Quantum systems obey precise mathematical laws, conservation principles, and statistical regularities. The probabilistic nature of quantum mechanics is tightly constrained: not all outcomes are possible, and those that are possible occur with well-defined probabilities.

This distinction between indeterminacy and chaos is philosophically significant. A probabilistic world can be highly structured and intelligible. Statistical laws play a central explanatory role. At larger scales, these regularities give rise to remarkably stable macroscopic phenomena.

This insight prepares a conceptual transition to biology. Just as probabilistic quantum events do not entail physical disorder, random mutations in biology do not entail evolutionary arbitrariness. In both cases, probability operates within a framework of constraints.

2.3 Decoherence and levels of explanation

The emergence of classical stability from quantum indeterminacy is largely explained by the theory of decoherence. Through constant interaction with their environment, quantum systems rapidly lose phase coherence, leading to the suppression of interference effects and the appearance of classical behavior [6]. Importantly, decoherence does not eliminate indeterminacy; it explains why probabilistic superpositions are not observed at the macroscopic level.

Decoherence thus illustrates a key philosophical point: stability can emerge without determinism. Deterministic behavior appears as a higher-level approximation resulting from scale, interaction, and averaging effects. This lesson will prove central when we turn to biological systems.

3. Random mutation and natural selection in evolutionary theory

Evolutionary biology is structured around a similar interplay between randomness and constraint. Genetic mutations arise from specific causal molecular processes explaining why they occurred, such as replication errors or DNA damage. Therefore, they are causally grounded but undirected in evolutionary terms. This structure mirrors the quantum case: events may be causally embedded while remaining non-deterministically distributed with respect to relevant outcomes.

Randomness in this sense does not imply biological disorder. Natural selection acts as a systematic filtering process, preserving variants that enhance reproductive success in given environments. As Mayr emphasized, variation provides possibilities, while selection confers directionality without foresight [7].

This distinction clarifies a persistent conceptual confusion: evolutionary processes generate adaptive traits with functional organization (teleonomic), yet without intentional design or intrinsic purpose (teleological). Monod's formulation of "chance and necessity" captures this dual structure: chance generates variation, while necessity reflects the constraints imposed by physical laws and environmental conditions [8].

Crucially, selective necessity should not be confused with global determinism. Evolutionary outcomes are contingent, path-dependent, and historically irreversible. The necessity involved is local and conditional, not global or absolute. A comparable situation arises in quantum physics, where probabilistic laws constrain outcomes without fixing them uniquely.

4. Emergence and levels of organization

4.1. Weak and strong emergence

The concept of emergence plays a central role in understanding how probabilistic processes yield stable patterns. Philosophically, a distinction is often drawn between strong emergence where higher-level phenomena break lower-level laws, and weak emergence where higher-level patterns arise from lower-level interactions but require distinct explanatory frameworks.

The position defended here aligns with a conception of weak emergence. Biological phenomena are grounded in micro-molecular processes, including genetic variation and biochemical interactions, yet they cannot be fully understood through micro-level descriptions alone. Concepts such as function, adaptation, and natural selection are indispensable for biological explanation, even though they presuppose molecular substrates. Rejecting brute reductionism at the explanatory level does not imply a denial of physical causation, nor does it entail any appeal to vitalistic principles. Rather, it reflects the necessity of distinct explanatory frameworks capable of capturing the organized, historical, and probabilistic character of living systems.

As Lewontin argued, organisms are not passive outcomes of genes or environments, but dynamic systems constituted by reciprocal interactions across levels [9]. Comparable anti-reductionist arguments have also been developed in recent philosophy of biology and systems science [10, 11]. Stability, in this framework, is not imposed from below but emerges from coordinated processes across scales.

4.2. Epigenetics as a paradigmatic case

Epigenetics provides a particularly illuminating illustration of emergent organization. Mechanisms such as DNA methylation, histone modification, and regulatory RNA activity modulate gene expression without altering nucleotide sequences. These processes demonstrate that genetic information does not function as a fixed causal script, but as a context-sensitive resource shaped by developmental and environmental history.

Recent work emphasizes that epigenetic states can stabilize phenotypes across generations while remaining probabilistic and reversible [12, 13]. This introduces a form of downward or contextual causation, where higher-level organizational states constrain molecular processes without violating physical laws.

Epigenetics thus reinforces a non-reductionist yet rigorously naturalistic understanding of biological stability as an emergent, historically contingent phenomenon.

5. Contingency, history and irreversibility

One of the most profound implications of evolutionary theory is the centrality of historical contingency. Evolutionary trajectories depend on sequences of events that could have unfolded differently. Gould's thought experiment of "replaying the tape of life" vividly illustrates the non-repeatability of biological history [14]. This does not imply absence of pattern, but sensitivity of outcomes to historically contingent branching points.

This historical dimension finds a parallel in the physics of complex systems. As Prigogine argued, systems far from equilibrium exhibit genuine irreversibility, introducing an objective arrow of time into physical processes [15]. While physical and biological histories differ in important respects, both resist reduction to timeless laws.

In both domains, prediction becomes limited. Science can identify constraints, tendencies, and probability distributions, but not precise long-term outcomes. Path dependence implies that small, contingent events can have enduring consequences, reinforcing the role of historical explanation alongside law-based reasoning.

6. Ontological and epistemic randomness

A common objection to probabilistic interpretations is that randomness merely reflects incomplete knowledge. According to this view, a sufficiently complete model would restore determinism. While this argument has intuitive appeal, it faces serious difficulties.

In quantum mechanics, indeterminacy persists even when systems are fully described by their wave functions. In evolutionary biology, even exhaustive knowledge of genetic and environmental conditions does not allow precise prediction of long-term evolutionary outcomes. The complexity and historical openness of biological systems exceed what deterministic modeling can capture.

Distinguishing ontological from epistemic randomness is therefore essential. Ontological randomness refers to genuine indeterminacy in processes themselves; epistemic randomness reflects limitations of knowledge or representation. Modern physics and biology suggest that both forms coexist, and that ontological randomness cannot be eliminated without distorting empirical reality.

Accepting this does not weaken scientific explanation. On the contrary, it clarifies its scope: explanation becomes the identification of structured spaces of possibility rather than the derivation of unique outcomes. The relevant philosophical task is therefore not to eliminate randomness, but to understand the diverse forms and explanatory roles through which randomness operates across the sciences.

7. Epistemological consequences for scientific explanation

The convergence between quantum physics and evolutionary biology invites a reassessment of classical epistemological ideals. Prediction, long considered the hallmark of scientific success, must be supplemented by explanation and understanding.

In probabilistic sciences, explanation often consists in mapping possible trajectories, identifying constraints, and characterizing distributions rather than predicting singular outcomes. Recent philosophy of science increasingly treats explanation as probabilistic, model-based, and context-sensitive rather than purely predictive, particularly in the study of complex systems [16].

Models, scenarios, and simulations play a central epistemic role. They explore spaces of possibility rather than exact futures. This approach preserves the unity of science while respecting disciplinary specificity. Physics and biology share a probabilistic structure, yet operate with distinct concepts and explanatory aims. This supports a pluralist conception of scientific unity grounded in shared explanatory values rather than identical methods.

8. Philosophical and ethical implications

A world without predetermined finality may initially appear unsettling. However, contingency is not equivalent to meaninglessness. On the contrary, contingency makes agency possible. In a fully deterministic universe, action would merely unfold necessity. In a probabilistically structured world, actions can function as genuine difference-makers within open trajectories.

This insight supports an ethics of prudence and responsibility, particularly relevant in domains such as environmental intervention, biotechnology, and public policy. Decision-making under uncertainty requires humility, reflexivity, and awareness of long-term consequences.

Scientific humility follows naturally from this worldview. Recognizing the limits of prediction and control does not diminish science; it situates it within a broader understanding of complexity and responsibility.

9. Conclusion

The comparison developed in this paper suggests that quantum physics and evolutionary biology share a deeper explanatory architecture: indeterminate micro-processes can generate robust macro-regularities under suitable constraints. Determinism is therefore better conceived as an emergent regime than as the primitive grammar of nature.

Life, like matter, unfolds within a structured space of possibilities shaped by chance, law, and history. Embracing this perspective deepens our philosophical understanding of explanation, freedom, and responsibility. To think the living world probabilistically is not to abandon rigor or meaning, but to recognize contingency as a condition of creativity, humility, and ethical responsibility in an evolving universe.

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