Trajectory Inference, Emergent Structure, and the Return of Dynamical Thought: Contemporary Scientific Convergences Across Neuroscience, Cosmology, Machine Learning, and Biological Computation

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Abstract

A growing number of contemporary scientific disciplines are converging upon a shared mathematical and conceptual orientation centered on trajectories, emergent structure, latent geometry, and dynamical inference. Across neuroscience, genomics, cosmology, atmospheric science, acoustics, and machine learning, static categorical models are increasingly giving way to frameworks that reconstruct evolving fields, compositional manifolds, and predictive transport processes. This essay examines several recent research directions that exemplify this transition and argues that they collectively indicate a broader epistemic shift away from object-centered metaphysics toward process-based dynamical systems. The essay further argues that this convergence reveals deep structural affinities between modern scientific practice and emerging field-theoretic frameworks such as RSVP, TARTAN, and CLIO, which treat cognition, biology, and cosmological organization as manifestations of recursive trajectory stabilization within constrained informational manifolds. It concludes by showing that these structural convergences are not merely interpretive but operationally instantiable within unified simulation architectures that treat admissibility, coarse-graining, semantic attraction, and multiscale persistence as formally tractable quantities.

1. Introduction

For much of the twentieth century, scientific explanation was dominated by static taxonomies, equilibrium assumptions, and object-centered ontologies. Systems were frequently modeled as collections of entities possessing intrinsic properties, while dynamics were treated as secondary modifications imposed upon otherwise stable structures. In recent decades, however, a gradual but profound inversion has emerged across multiple scientific domains. Increasingly, the primary explanatory focus is no longer the static description of a thing, but the trajectory through which structure persists, transforms, and stabilizes.

This transition is visible across contemporary neuroscience, where cognition is increasingly understood as the coordination of distributed dynamical states rather than the retrieval of discrete symbolic memories. It appears in genomics, where cellular identity is modeled as motion through transcriptional phase spaces rather than as a static genetic program. It appears in machine learning, where latent embeddings and autoregressive flows replace explicit symbolic rules. It appears in cosmology and astrophysics, where structure formation is increasingly interpreted as emergent relaxation dynamics across coupled fields and density gradients.

The result is the gradual emergence of a new scientific style centered on trajectory inference, field reconstruction, compositional geometry, and multiscale constraint propagation.

1.1. Levels of Interpretation and Scope of Claim

The argument developed in this essay operates across several distinct levels of interpretation that must be carefully distinguished in order to avoid mischaracterization. At the empirical level, individual scientific domains provide domain-specific results grounded in their own experimental and methodological frameworks. At the structural level, these results exhibit a convergent mathematical form centered on trajectories, latent geometries, and constraint-governed evolution. At the ontological level, one may attempt to interpret these convergences as evidence for a more general process-based account of reality.

The present work advances primarily a structural claim. It argues that multiple disciplines are independently converging upon trajectory-centered explanatory frameworks that share formal similarities in their treatment of dynamics, admissibility, and multiscale stabilization. Ontological interpretations are treated as secondary and provisional, and no claim is made that all domains are governed by identical underlying physical mechanisms. Rather, the emphasis is on the emergence of a shared mathematical and methodological orientation whose significance lies in its cross-domain recurrence.

2. Trajectory Inference as a Scientific Primitive

One of the clearest examples of this transition can be found in contemporary RNA velocity methods within systems biology. Traditional genomics often treated cells as static types occupying discrete biological categories. RNA velocity instead models cellular development as motion through a latent dynamical manifold.

Formally, one may interpret cellular state evolution as a vector field over a transcriptional state space:

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}(\mathbf{x}, t)$$

where **x** denotes the local transcriptional configuration and **v** represents inferred directional developmental flow. In this formulation, biological identity becomes inseparable from local trajectory geometry. Applied to clinical contexts, this framework has demonstrated that illness trajectories in whole blood are dynamically legible from transcriptional state alone, suggesting that pathological processes may be understood as deviations from admissible developmental flow rather than as discrete categorical disease states [1].

This conceptual shift is significant. The cell is no longer merely an object possessing traits; it may be reinterpreted as a transient stabilization within a higher-dimensional dynamical process. The same structural logic extends into evolutionary genomics. Recent work reconstructing the complete genomes of early angiosperms from water lily lineages reveals that the major innovations distinguishing flowering plants from their ancestors are legible as constrained structural transitions within genomic morphospace — discrete jumps that, viewed across deep time, trace an evolutionary trajectory through a space of viable developmental architectures [6]. Biological novelty, in this reading, may be understood not as random variation but as admissible geometric displacement within a constrained morphological space.

Such approaches resonate with generalized field-theoretic models in which local scalar densities, directional transport fields, and entropy gradients jointly constrain admissible system evolution. In RSVP-like formulations, one may schematically represent these interactions through coupled fields:

$$X(t) = (\Phi, \mathbf{v}, S)$$

where Φ denotes scalar potential or structural capacity, $\mathbf{v}$ denotes directional transport and trajectory flow, and S denotes entropy density or uncertainty. The increasing prevalence of trajectory inference across biology therefore reflects not merely a technical innovation, but a deeper methodological migration toward dynamical explanation.

2.1. Domain-Specific Instantiation of Field Variables

The tuple $X(t) = (\Phi, \mathbf{v}, S)$ introduced above should be interpreted as a structural schema rather than a fixed physical identity. Each scientific domain instantiates this schema through its own domain-specific quantities and measurement frameworks. Formally, one may consider a family of structure-preserving mappings $\mathcal{F}_D$ such that

$$\mathcal{F}_D : (\Phi, \mathbf{v}, S) \mapsto (\Phi_D, \mathbf{v}_D, S_D),$$

where D indexes the domain under consideration. In genomics, Φ_D may correspond to transcriptional capacity, while $\mathbf{v}_D$ encodes developmental flow inferred from RNA velocity and S_D encodes transcriptional uncertainty or regulatory entropy. In machine learning, Φ_D may correspond to embedding density or representational salience, $\mathbf{v}_D$ to autoregressive update dynamics, and S_D to distributional uncertainty over latent states. In physical systems, Φ_D may correspond to energy density or structural potential, $\mathbf{v}_D$ to transport or flow fields, and S_D to thermodynamic entropy.

The purpose of this mapping notation is not to collapse these domains into a single mechanism, but to make explicit the structural pattern that recurs across them. Shared schema does not entail shared mechanism; it indicates shared mathematical form, which is the structural claim this essay advances.

2.2. On the Status of Objects and Trajectories

The emphasis on trajectories in this essay should not be interpreted as a categorical elimination of objects. Rather, it reflects a shift in explanatory priority. Objects may be understood as regions of state space in which trajectories exhibit sustained coherence under constraint. In this sense, objects are not replaced but reinterpreted as stable configurations within a dynamical process. Trajectories remain defined relative to the underlying state space, and the geometry of that space continues to play a constitutive role in system behavior. The claim is therefore not that structure disappears, but that persistence is better explained through the maintenance of admissible trajectories than through the assumption of intrinsically static entities.

3. Neuroscience and Compositional Dynamics

A similar transformation is occurring within cognitive neuroscience. Contemporary studies of hippocampal ripple coordination increasingly describe cognition in terms of distributed planning sequences, compositional representations, and predictive manifold traversal [2].

This perspective departs sharply from earlier storage-and-retrieval metaphors of memory. Rather than treating cognition as the activation of fixed symbolic contents, modern dynamical neuroscience increasingly models thought as coordinated motion across latent representational geometries.

In simplified form, cognitive evolution may be represented as movement through a constrained semantic manifold:

$$\gamma : [0, T] \to \mathcal{M}$$

where $\mathcal{M}$ denotes a cognitive state manifold and $\gamma(t)$ represents a temporally evolving cognitive trajectory admissible under the continuity constraints governing the manifold's local structure.

The significance of this shift lies in the fact that meaning becomes relational and geometric rather than purely symbolic. Cognitive stability emerges not from fixed representations, but from admissible continuity conditions across evolving state trajectories. A thought is not a retrieval but a path; coherence is not correspondence but sustained geometric compatibility across scales.

This dynamical interpretation aligns naturally with compositional field models in which cognition emerges through recursive coordination among partially overlapping informational projections. Within TARTAN-like approaches, coarse-grained representations are not treated as lossy reductions alone, but as structured projections preserving trajectory continuity across scales. Recent computational phenotyping work on effort-based decision-making further illustrates how dynamical models are now being deployed clinically: pharmacological intervention with semaglutide produces measurable shifts in decision trajectory geometry, interpretable as alterations in the effort-cost manifold through which reward-seeking behavior is navigated [7]. Trajectory inference, here, operates not merely descriptively but diagnostically.

4. Machine Learning and Latent Geometry

Machine learning has undergone a parallel transformation. Earlier symbolic AI systems emphasized explicit rule structures and categorical reasoning. Contemporary large-scale neural architectures instead rely upon latent embeddings, autoregressive sequence evolution, and attractor-like geometry within high-dimensional parameter spaces.

Transformers, diffusion systems, and representation-learning models increasingly function by reconstructing probabilistic trajectories through semantic manifolds rather than by manipulating discrete logical objects [9]. The distinction between symbolic and geometric compositionality is consequential here. Symbolic compositionality assembles meaning through the rule-governed concatenation of discrete units whose interpretations are fixed independently of context. Geometric compositionality, by contrast, assembles meaning through the continuous deformation of trajectories within structured embedding spaces, where admissible combinations are determined by local curvature and constraint rather than by explicit grammar. This distinction is not merely terminological; it identifies a genuine difference in the explanatory resources these frameworks deploy and the kinds of generalization behavior they predict.

Given a latent embedding space $\mathcal{Z}$, inference increasingly takes the form:

$$z_{t+1} = F(z_t, \theta)$$

where z_t denotes the latent semantic state, θ denotes learned system parameters, and F defines a recursive projection operator evolving the system through regions of the embedding space consistent with observed distributional structure. It is important to note that the geometry of this space is not self-arising; it is shaped by training data, loss functions, and optimization dynamics. The trajectory-centered description offered here captures the operational structure of inference without claiming that such systems are physically identical to biological or cosmological processes.

Such systems often display emergent compositionality despite lacking explicit symbolic semantics. This is perhaps most clearly illustrated by meta-learning approaches to immunological recognition, in which models trained to identify antigen-specific T cell receptor binders generalize across sparse and structurally heterogeneous biological data by learning the latent geometric regularities of binding compatibility rather than explicit sequence rules [8]. Coherent structure arises through repeated stabilization of admissible trajectories rather than through predefined ontological categories. Meaning emerges from geometric continuity and recursive closure rather than from symbolic representation alone.

5. Atmospheric Systems and Predictive Transport

Environmental modeling offers another example of this transition. Transformer-based forecasting systems for atmospheric pollutants increasingly approximate transport processes operating across complex coupled dynamical systems [3].

Atmospheric particulate evolution may be schematically represented through an advection-diffusion equation in which pollutant density ρ evolves under the combined influence of diffusion at rate D, transport through velocity field $\mathbf{v}$, and local source terms Q:

$$\frac{\partial \rho}{\partial t} = -D\nabla^2\rho - \nabla \cdot (\rho\mathbf{v}) + Q$$

Modern transformer architectures effectively learn approximations to such evolving transport geometries directly from observational sequences, without explicit access to the underlying physical equations. The significance here is epistemological. Prediction increasingly depends upon reconstructing latent flow geometry rather than identifying static causal objects. The system learns the shape of admissible transport rather than a catalogue of causes.

6. Astrophysics and Emergent Timescales

Recent astrophysical work on young star clusters similarly reflects a growing emphasis on emergent timescales and distributed relaxation dynamics [4]. Structure formation is increasingly modeled not as the execution of static initial conditions, but as multiscale stabilization within interacting density fields.

This orientation is especially notable because it softens the older mechanistic distinction between local and global structure formation. Temporal emergence becomes dependent upon coupled field interactions, local density variation, and recursive feedback between scales.

The broader implication is that cosmological organization may be better understood through dynamical admissibility and field relaxation than through purely equilibrium-based frameworks. Such trends are conceptually compatible with generalized entropic smoothing models in which large-scale structure emerges through recursive redistribution and stabilization processes rather than purely explosive expansion dynamics. It is important to emphasize that the correspondences drawn here are structural rather than reductive. No claim is made that astrophysical systems and informational or computational systems are governed by identical physical laws. The comparison highlights similarities in the mathematical description of multiscale stabilization and emergent structure; these parallels should be understood as heuristic and structural, not as direct ontological equivalences.

7. Acoustics, Geometry, and Projection

Modern acoustics research on head-related transfer functions and pinna modeling likewise demonstrates the growing centrality of geometry as an active informational operator [5].

The ear is not merely a passive receptor. Its geometry filters, reshapes, and constrains incoming wave structure before neural processing occurs. Acoustic propagation within bounded anatomical geometries may be approximated through a wave equation governing pressure variation p at propagation speed c:

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla^2 p$$

where boundary conditions imposed by anatomical structure fundamentally alter the resulting informational geometry before any higher-order interpretation occurs.

In this sense, the auditory system functions not merely as a receiver of external signals, but as an active geometric projector that reshapes incoming wave structure prior to symbolic interpretation. This mirrors the broader TARTAN principle that observation itself is a form of trajectory-aware projection, in which local topology determines which informational continuities survive coarse-graining and which are discarded. Perception is not neutral sampling. It is structured selection, shaped by the constraint surfaces through which signals must pass before they become available to cognition at all.

8. Admissibility, Closure, and Multiscale Consistency

The preceding sections have repeatedly invoked the notions of admissibility, trajectory continuity, and closure. In order to unify these usages across domains, it is useful to introduce a minimal formal characterization that captures their shared structural role without committing to domain-specific mechanisms.

Let $\mathcal{M}$ denote a state space appropriate to the system under consideration, and let $\gamma : [0, T] \to \mathcal{M}$ denote a trajectory through that space.

8.1. Admissibility

A trajectory γ is said to be *admissible* if it satisfies local compatibility constraints imposed by the governing structure of the system. In general form, this may be expressed as a constraint functional:

$$\mathcal{A}(\gamma)(t) = 0 \quad \forall t \in [0, T],$$

where $\mathcal{A}$ encodes the domain-specific conditions required for coherent evolution. These conditions may correspond to conservation laws, developmental viability, semantic continuity, or learned statistical regularities depending on the system under study. Admissibility therefore defines the set of trajectories that remain viable within the constraint geometry of the system. Non-admissible trajectories represent configurations that cannot be sustained under the system's governing dynamics.

8.2. Closure

Admissibility alone is local in character. To account for persistence across scales, one requires a notion of closure. A trajectory γ is said to satisfy closure if it admits consistent reconstruction across coarse-grained representations. Let $F : \mathcal{M} \to \mathcal{M}_c$ denote a coarse-graining map, and let $\tilde{\gamma} = F \circ \gamma$ denote the induced trajectory in the coarse-grained space. Closure requires that there exist a reconstruction operator G such that

$$G(\tilde{\gamma}) \approx \gamma$$

within a tolerance determined by system constraints. Equivalently, one may define an identity gap:

$$\mathcal{E}(\gamma) = \|\gamma - G(F(\gamma))\|^2,$$

and require that $\mathcal{E}(\gamma)$ remain bounded for persistent structures. Closure therefore captures the requirement that a trajectory remain self-consistent across levels of description. Systems that fail closure exhibit fragmentation between scales and loss of coherent identity.

8.3. Multiscale Consistency and Gluing

In spatially extended systems, local admissibility does not guarantee global coherence. Let $\{\gamma_i\}$ denote a collection of local trajectory segments defined over overlapping regions. A gluing condition requires that these local segments agree on overlaps in a manner consistent with the system's constraint structure. One may define a gluing obstruction metric $\Omega(t)$ measuring the degree to which local trajectories fail to compose into a globally consistent structure:

$$\Omega(t) = \sum_{i,j} \|\gamma_i|_{U_i \cap U_j} - \gamma_j|_{U_i \cap U_j}\|^2.$$

Low obstruction corresponds to coherent global structure; high obstruction indicates fragmentation, instability, or transition. In biological systems, admissibility corresponds to developmental viability and biochemical consistency; closure to organismal integrity across scales; and gluing to intercellular coordination. In cognitive systems, admissibility corresponds to semantic continuity; closure to the reconstructability of mental states across coarse representations; and gluing to the coordination of distributed neural processes. In machine learning, admissibility corresponds to likelihood under the learned model; closure to stability under representation compression; and gluing to consistency across attention-mediated representations.

The significance of this formulation is that it provides a common structural language in which persistence, identity, and transformation can be described across domains without collapsing domain-specific mechanisms into a single ontology. The generalized closure condition introduced later in this essay, $\mathcal{C}(\gamma) = 0$, may be understood as shorthand for the simultaneous satisfaction of admissibility, bounded closure error, and low gluing obstruction. Systems persist not because they possess intrinsic substance, but because their trajectories remain admissible, closed, and globally consistent under the constraints imposed by their governing structure.

9. Scope, Limits, and Non-Claims

The convergence described throughout this essay should not be interpreted as a claim that all scientific domains reduce to a single underlying mechanism. The framework developed here does not assert that biological, cognitive, computational, and cosmological systems are identical in their material constitution or governed by a unified physical law in the strict sense.

Instead, the claim is that these domains increasingly employ mathematically similar structures when modeling complex systems, particularly with respect to trajectory inference, constraint satisfaction, and multiscale dynamics. The appearance of shared formal patterns does not entail full ontological equivalence.

Similarly, the framework does not deny the continued relevance of discrete entities, symbolic representations, or domain-specific causal models. Rather, it repositions these constructs within a broader dynamical context in which their stability and explanatory power derive from underlying trajectory-level regularities. The argument advanced here is methodological and structural before it is metaphysical.

10. Simulation, Coarse-Graining, and Operational Dynamics

The preceding sections have argued that multiple scientific disciplines are converging upon structurally similar dynamical intuitions. Trajectory inference, latent geometry, admissibility, and recursive stabilization appear independently across biology, neuroscience, machine learning, atmospheric modeling, acoustics, and cosmology. The remaining question is whether these similarities are merely analogical or whether they admit a common operational representation. The answer has epistemological consequences: if the convergence is merely metaphorical, the essay's argument is interpretive; if it is operationally realizable, the argument becomes methodological.

The convergence toward trajectory-centered reasoning across contemporary science is not merely philosophical, but increasingly computational. Experimental frameworks based on recursive field evolution now permit the direct simulation of admissibility, coarse-graining, semantic attraction, and multiscale reconstruction within unified dynamical environments. In such systems, cognition, biological development, economic concentration, and cosmological organization appear not as fundamentally separate ontological domains, but as distinct observational projections imposed upon shared underlying field processes.

Within the RSVP laboratory framework, field evolution proceeds through coupled scalar, vector, entropy, and residue fields:

$$X(t) = (\Phi, \mathbf{v}, S, R)$$

where Φ denotes scalar potential, **v** directional transport, S entropy density, and R a residue field encoding unresolved constraint tension accumulated across previous evolution steps. The residue field evolves dynamically as a function of constraint violation and structural incompatibility. In schematic form:

$$\frac{dR}{dt} = f(\Omega(t)),$$

where $\Omega(t)$ denotes the gluing obstruction metric introduced in the preceding section. Residue accumulates under persistent constraint incompatibility and is reduced through structural reconfiguration that restores admissible continuity. This situates R as a dynamical bookkeeping quantity encoding the history of unresolved constraint tension within the evolving system rather than as a merely intuitive placeholder.

The operational significance of this architecture lies in the explicit computability of quantities that remain implicit in most scientific modeling. The admissibility operator admissibility$(\Phi, \mathbf{v}, S)$ returns a spatial mask identifying cells whose local field configuration satisfies trajectory continuity constraints — directly instantiating the notion, developed across preceding sections, that stable identity corresponds to constraint satisfaction rather than substance. The gluing obstruction metric $\Omega(t)$ measures global sheaf cocycle error across field patches, providing a quantitative index of the degree to which local field evolution fails to compose into globally consistent structure. The identity gap $\|\Phi - F(\Phi)\|^2$, where F denotes a coarse-graining map, operationalizes the claim that persistence depends upon self-consistency across scales: a field region persists stably to the extent that its fine-grained structure is faithfully reconstructable from its coarse-grained projection.

The observer projection operator observer_projection$(\cdot)$ directly formalizes the acoustics argument developed in the preceding section: different observational geometries impose different informational projections upon the same underlying field, yielding structurally distinct but mutually compatible representations of shared dynamical reality. The anisotropy index, computed across observer ensembles, measures the degree to which distinct projections diverge — which is precisely the epistemological question the essay has been tracking across disciplines: how much of apparent ontological diversity reduces to projection geometry rather than underlying difference.

Unlike traditional simulation architectures that presuppose fixed object categories and externally imposed symbolic semantics, the RSVP framework treats stable structure itself as emergent from recursively constrained trajectory evolution. Objects become temporary coherence structures within evolving admissibility fields rather than primitive ontological units. The semantic attractor basins of the framework's semantic module model meaning geometrically as stable regions of the potential landscape rather than as symbolic references, and inter-basin flux tracks the dynamical transitions through which conceptual reorganization occurs.

The significance of such frameworks lies not merely in their ability to simulate isolated phenomena, but in their demonstration that cognition, biology, economics, and cosmology are computationally instantiable within a common language of recursive field stabilization, multiscale projection, and admissibility-preserving transformation. The philosophical convergence the preceding sections have traced across modern science is, in this sense, not merely an interpretive observation but a computationally instantiable structural claim.

11. From Objects to Constraint Surfaces

Taken collectively, these developments indicate a major conceptual reorientation across modern scientific thought. Increasingly, systems are modeled not as isolated objects possessing intrinsic essence, but as evolving trajectory bundles constrained by multiscale admissibility conditions.

This perspective replaces static ontology with recursive stabilization. Identity itself becomes dynamical. Persistence is no longer explained through immutable substance, but through the maintenance of coherent trajectories within constrained manifolds [10, 11, 12].

Such systems may be understood through a generalized closure condition:

$$\mathcal{C}(\gamma) = 0$$

where $\mathcal{C}$ aggregates admissibility, closure error, and gluing obstruction as developed in Section 7. Stable systems persist because their trajectories simultaneously satisfy local compatibility constraints, remain reconstructable across coarse-grained representations, and compose coherently into globally consistent structure. Instability, transformation, and dissolution all correspond to the failure or relaxation of one or more of these conditions under perturbation.

12. Empirical Consequences and Testable Directions

If trajectory-centered frameworks capture genuine structural features of complex systems, several empirical consequences follow. In biological systems, trajectory deviation from admissible developmental flow should provide earlier and more sensitive indicators of pathology than static categorical markers; the clinical application of RNA velocity to illness prediction represents an initial step in this direction [1]. In cognitive systems, variability in reconstructed memory should reflect the geometry of underlying trajectory reconstruction rather than the fidelity of stored representations, producing characteristic error patterns that differ from those predicted by storage-and-retrieval models. In machine learning, generalization behavior should correlate with the continuity and stability of latent trajectory evolution within embedding spaces, with breakdown occurring precisely where trajectory admissibility fails under distributional shift.

These directions do not constitute definitive tests of the framework in its full generality, but they indicate conditions under which its structural claims may be evaluated against domain-specific data. The framework is therefore not purely interpretive; it suggests concrete avenues for empirical investigation, and it would be disconfirmed by systematic evidence that static categorical models consistently outperform trajectory-based approaches in domains where the present analysis predicts the opposite.

13. Conclusion

Contemporary science is undergoing a gradual but significant migration away from static categorical thinking toward dynamical field-based reasoning. Across biology, neuroscience, machine learning, atmospheric science, acoustics, and cosmology, explanation increasingly depends upon trajectory inference, latent geometry, compositional dynamics, and recursive stabilization.

This transition represents more than methodological evolution. It signals the emergence of a broader epistemic framework in which process supersedes object, geometry supersedes taxonomy, and admissible continuity supersedes static essence [13]. The argument advanced here has been structural before it has been ontological: the claim is that these domains share mathematical form, that this sharing is not accidental, and that the formal language of admissibility, closure, and multiscale consistency provides a common substrate in which that shared form can be precisely expressed.

The convergence of these disciplines suggests that intelligence, life, perception, and cosmological structure are not separate explanatory domains requiring separate foundational metaphysics, but are instead distinct manifestations of a shared underlying dynamic: recursively stabilized trajectories unfolding within constrained informational fields. That this convergence is now computationally instantiable — not merely philosophically arguable — marks a further transition: from the observation that science is moving toward dynamical reasoning, to the demonstration that a unified experimental architecture exists capable of expressing that convergence with formal precision. The consequence is not merely a revision of scientific method, but the gradual dissolution of the static metaphysical categories inherited from industrial-era thought itself.

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