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On the Origin of Life

by means of non-trivial computation, in a pancomputational universe

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Abstract

Life is defined here as a driven thermodynamic organisation whose horizon-relative persistence depends on distinction-conditioned constraint-maintenance. The paper does not treat life as a new substance, a metaphysical exception, a checklist of biological familiarities, or a synonym for complexity, metabolism, reproduction, feedback, adaptation, or persistence. It treats life as a physically grounded regime in which discriminable distinctions become causally operative in maintaining the constraint-structured order of the system that carries them.

The first task is to discipline computation. If every lawful physical process can be described computationally under some encoding, then computation alone cannot explain the transition from chemistry to life. The paper therefore distinguishes Trivial Computation from Non-Trivial Computation. Trivial Computation is lawful state evolution redescribable under a chosen encoding. Non-Trivial Computation is physically enacted discrimination: organisation-dependent, counterfactually testable downstream outcome dependence on discriminable distinctions at a specified reference boundary, reference scale, operational horizon, and discrimination/noise regime.

The Nested Multiscale Framework grounds this distinction without introducing new physics. It moves from the Kinematic Microstate Baseline through boundary conditions, thermodynamic state spaces, thermodynamic information, emergent boundary conditions, constrained and driven thermodynamic regimes, Shannon-style discriminability, and finally Non-Trivial Computation. Each layer adds no new ontology. It adds a stable descriptive regime only where constraints, abstractions, and distinctions remain physically supported at the reference scale.

The framework is made testable through Baseline Dynamics. A Baseline Dynamics comparator is not an inert null. It is an intervention-defined comparator family that preserves relevant boundary context, driving, component inventory, reference scale, operational horizon, and discrimination/noise assumptions while ablating, scrambling, neutralising, resetting, or bypass-controlling the organisation proposed to make distinctions causally operative. The Information Processing Locus localises that organisation: it identifies what must remain intact, or what must be disrupted, for downstream trajectory selection to depend on the relevant distinction.

Life is then defined as a stricter condition than Non-Trivial Computation alone. Life is a Driven Thermodynamic System that contains an Information Processing Locus whose Non-Trivial Computation supports maintenance of constraint-structured order over the relevant operational horizon, yielding a counterfactual order advantage over Baseline Dynamics under comparable driving and boundary conditions. In compressed form: life is driven thermodynamic constraint-maintenance supported by IPL-mediated Non-Trivial Computation.

1. Pancomputation and Trivial Computation

1.1. The problem of pancomputation

Pancomputation is the view that physical reality is, in some sense, computational. At its strongest, it claims that every physical process can be described as computation because lawful state evolution can be mapped onto transitions in an abstract state machine.

The difficulty is not that such mappings are impossible. The difficulty is that they can become unconstrained. If any physical trajectory can be redescribed as computation under a chosen encoding, then computation loses explanatory specificity. It no longer identifies a distinctive physical regime. It becomes a description imposed by an observer rather than a discriminator in the system.

For a theory of life, this permissiveness is fatal. A formal definition of life cannot rest on computation if computation means only that a mapping can be written after the fact. Rivers, crystals, flames, storms, chemical reactions, falling stones, planetary orbits, and equilibrating systems can all be computationally redescribed in some weak sense. That does not show that they process information in the physically significant sense required for life.

The question is therefore not whether lawful physical evolution admits computational description. It does. The question is whether some physical systems organise their own evolution such that discriminable distinctions make counterfactual differences to downstream trajectory classes. Where that condition is absent, computation remains trivial. Where it is present, computation becomes a physical discriminator.[1]

1.2. Trivial Computation

Trivial Computation is present whenever a physical state evolution can be described computationally under a chosen encoding.

TC is computation as redescribability. A system evolves lawfully. An observer supplies an encoding. The resulting state sequence can be mapped onto an abstract computational description. This may be mathematically legitimate and explanatorily useful for some purposes, but it does not by itself show that the system physically processes information in a non-trivial sense.

TC therefore names the broad, weak, pancomputational condition. It preserves the fact that lawful physical evolution can often be represented computationally while denying that such representation is enough to establish physically enacted information processing.

A TC claim does not require that the system itself supports a physically stable alphabet, registers alternatives, preserves discriminable distinctions, or uses distinctions to condition downstream outcomes. It requires only that the trajectory can be described under an encoding.

This is why TC cannot define life. A living system may be TC-describable, but so may many non-living systems. The relevant discriminator must separate external computational description from internal organisation-dependent selection.

1.3. Non-Trivial Computation

Non-Trivial Computation is computation as physically enacted discrimination.

NTC is present when changing a discriminable informational distinction, while holding relevant constraints comparable, yields systematically different downstream trajectories and outcomes at the specified reference scale and operational horizon. In NTC, the system's organisation makes certain admissible outcomes occur and others not occur conditional on informational state.

The distinction between TC and NTC is therefore the distinction between interpretive attribution and physically enforced selection.

In TC, the computational description depends on the observer's mapping. In NTC, the system's own organisation makes outcome classes depend counterfactually on distinctions instantiated within the regime. The test is not whether the system can be described computationally. The test is whether downstream trajectory selection changes when the relevant informational distinction changes, and whether that dependence collapses, degrades, or changes when the mediating organisation is disrupted under adequate comparator conditions.

This makes NTC regime-relative. It is always indexed to a reference boundary, reference scale, operational horizon, discrimination/noise regime, and comparator family. A process may be non-trivial at one scale and trivial at another. A distinction may be causally operative under one noise regime and unavailable under another. A registration may matter over one horizon and vanish over another.

Non-triviality is therefore not a metaphysical property attached to matter in general. It is an operationally testable relation between physical organisation, discriminable distinction, and downstream trajectory selection.

1.4. Introduction of the Nested Multiscale Framework

The TC/NTC distinction cannot float above physics. If NTC is to do explanatory work, it must be grounded in the physical regimes that make distinctions stable, discriminable, costly, persistent, and causally operative.

The Nested Multiscale Framework provides that grounding. It separates descriptive layers without treating them as separate ontologies. Microphysical admissibility, boundary conditions, thermodynamic state spaces, emergent constraints, driven maintenance, channel-relative discriminability, and non-trivial computation are not competing realities. They are nested regimes of description, each valid where the relevant constraints and variables remain stable at the chosen reference scale and operational horizon.

The framework resolves the tension between pancomputational permissiveness and empirical discrimination. It allows two claims to be held together:

Any lawful physical evolution may admit computational description at some level.

Only some physical systems support physically meaningful information processing in which distinctions become organisation-dependent, counterfactually testable determinants of downstream trajectory classes.

The first claim preserves the weak pancomputational insight. The second supplies the discriminator needed for life.

2. Nested Multiscale Framework

2.1. Nested Multiscale Framework

The Nested Multiscale Framework is a structured way to describe physical reality across nested descriptive levels. Each level introduces constraints, abstractions, and operational distinctions appropriate to the regime under study.

The framework runs from microphysical admissibility through thermodynamic and informational regimes to Non-Trivial Computation. Its central claim is that higher-level descriptions are not merely arbitrary conveniences. They become physically grounded regimes when stable, constraint-bearing patterns support coarse-grained regularities and operational distinctions at a reference scale.

Each layer is defined relative to those below it. A higher layer does not replace the lower layers and does not add a new ontology. It adds a regime of constraint. It becomes valid where its variables and distinctions remain stable and predictive under the relevant boundary, scale, horizon, and noise conditions.

This matters because information and computation are not free-floating predicates. What counts as a distinction, what counts as a token, what counts as an outcome, and what counts as downstream dependence all depend on the regime in which they are evaluated. The NMF prevents informational and computational claims from being detached from their physical support.

2.2. Evaluation conditions

Unless otherwise specified, all operational test criteria in this paper are indexed to shared evaluation conditions.

Reference boundary is the system/environment boundary at which driving, throughput, coupling, and component inventory are specified for comparison. Boundary Condition names the physical system-environment delimitation. Reference boundary names the operational scope at which that boundary, associated driving, and relevant inventory are held fixed for comparison.

Reference scale is the descriptive or measurement scale at which coarse-grained variables, symbol classes, token stability, trajectory classes, and outcome classes are assessed. Without reference scale, a claim may drift between microphysical, chemical, thermodynamic, informational, and biological descriptions without preserving the relation under evaluation.

Operational horizon is the time or step window over which persistence, consultability where claimed, and outcome classes are evaluated. In one-shot NTC tests, the operational horizon may be the minimal interval spanning registration of a discriminable distinction and its first causal effect on downstream transition selection. It does not imply multi-step reuse, extended memory, or repeated consultation unless those are explicitly claimed.

Comparability condition means preserving relevant boundary context, driving, component inventory, scale, horizon, and noise assumptions while varying only the distinction, organisation, or pathway under test as far as practicable.

Discrimination/noise regime fixes what counts as a reliably discriminable distinction rather than noise, drift, saturation, carrier microvariation, or below-threshold difference. Claims about information, computation, and life are only well-posed when the discrimination/noise regime is specified strongly enough for the claim being made.

2.2.1. Readout and reference-indexed objectivity

Operational tests in this paper do not assume abstraction-free access to reality. Whenever the paper speaks of observable outcomes, trajectory classes, outcome dependence, collapse toward Baseline Dynamics, or objective transition in physical organisation, those claims are readout claims indexed to boundary, scale, horizon, discrimination/noise regime, and comparator conditions.

A readout is itself a bounded registration. Measurement, instrument trace, simulation output, experimental classification, and model comparison all select and stabilise differences under finite conditions. This does not make them arbitrary. It means their objectivity depends on explicit reference conditions, stable readout pathways, error control, comparator discipline, and reproducibility under admissible variation.

The real constrains which abstractions survive, but no operational claim in this framework is made from nowhere. NTC and life-discriminator claims are claims about real physical organisation made through bounded observational and experimental interfaces.

2.2.2. Temporal framing

Time in this paper is used as the ordering parameter of lawful state evolution. It indexes the sequence-structure according to which later physical states depend on earlier physical states under governing dynamics and boundary conditions.

This is not an account of time as experience, phenomenology, duration, passage, attention, memory, or temporal qualia. Those phenomena belong to later organismic and cognitive levels. The temporal notion required here is captured by operational horizon: the time or step window over which persistence, consultability, maintenance, depletion, correction, or outcome-class divergence is evaluated.

The paper sometimes uses state-update language. An update means the local application of governing dynamical constraints, together with boundary and organisational constraints, carrying a system from one admissible state or coarse-grained macrostate to a successor along a physically allowed trajectory. Where dynamics are continuous, update should be read as a limit description. Where discrete models are adopted, it may be read literally.

TC requires only ordered evolution under an encoding. NTC requires more: varying a discriminable distinction under comparable conditions must yield registered differences in downstream trajectory classes above noise, and that dependence must collapse, degrade, or change under appropriate organisational ablation.

2.3. Background commitments

The framework uses standard commitments from adjacent domains only to the extent required for operational discrimination.

First, it assumes lawful microdynamics. Microstate evolution is treated as governed by fundamental dynamics appropriate to the domain, with higher descriptive layers arising

through coarse-graining, boundary conditions, and constraint stability rather than new microphysics.

Second, it assumes statistical-mechanical and thermodynamic description. Macrostates, coarse-grained trajectories, entropy relations, and nonequilibrium maintenance are meaningful only relative to boundary conditions, reference scale, and operational horizon.

Third, it assumes nonequilibrium driving. Sustained throughput of energy or matter at a reference boundary can maintain persistent nonequilibrium structure over an operational horizon.[2]

Fourth, it assumes channel-relative information in the Shannon sense. Information requires discriminable distinctions over a channel relative to an alphabet, noise model, and receiver discrimination capacity.[3]

Fifth, it assumes that stable distinctions in finite-temperature physical systems have physical costs and constraints. Informational stability, manipulation, erasure, persistence, and reliable discrimination require thermodynamic support, even where the exact accounting is not derived in full.[4]

Sixth, it assumes interventionist testability. Claims about non-trivial computation require comparator families that preserve relevant driving and component inventory while targeting the organisation or distinction proposed to mediate downstream dependence.[5]

2.4. NMF layers

The following layers are regime-relative. Their boundaries need not be sharp under arbitrary zoom. The ladder is a grounding scaffold for identifying which constraints are doing explanatory work at the reference scale.

2.4.1. Layer 0 — Kinematic Microstate Baseline

Definition

Kinematic Microstate Baseline is the universe-level space of all kinematically admissible microstates: the maximally fine-grained descriptive baseline licensed by high-consensus fundamental physics, while remaining agnostic about any final ontology.

KMB is strictly kinematic. It specifies what states are possible in principle. It does not include initial conditions, boundary conditions, environmental couplings, organisational constraints, or contingent structure that would select, restrict, or privilege particular histories.

Fundamental dynamics are assumed as a background legality constraint over KMB. Boundary conditions, initial conditions, and couplings do not add laws. They select subsystem-relative admissible histories within KMB.

Key characteristics

KMB is universe-level admissibility prior to contingent selection.

KMB is trajectory-neutral. It does not specify realised histories.

KMB excludes contingent boundary and organisational constraints.

KMB supports principled zoom-in and zoom-out. Finer distinctions absent at a given reference scale are upstream dependencies, not negations.

2.4.2. Layer 1 — Boundary Condition

Definition

A Boundary Condition is any constraint imposed on a system's microphysical evolution by the delimitation of the system and its interaction with its environment. BC specifies what is treated as system, what is treated as environment, and which exchanges of energy, matter, charge, or other conserved quantities are permitted or constrained.

Key characteristics

BC defines system-environment delimitation.

BC specifies exchange constraints across the boundary.

BC enables stable coarse-grained description by making a system-description possible.

BC is scale-dependent. What functions as a boundary at one scale may be porous, distributed, or irrelevant at another.

2.4.3. Layer 2 — Thermodynamic State Space

Definition

Thermodynamic State Space is a coarse-grained description of a system in terms of macroscopic variables such as temperature, pressure, volume, chemical potential, density, entropy, and related thermodynamic parameters that remain stable and predictive under the imposed boundary conditions.

TSS describes the system's state in thermodynamic rather than microphysical coordinates.

Key characteristics

TSS uses coarse-grained macrostates in which many microstates correspond to one thermodynamic state.

TSS is constraint-stabilised by boundary conditions that support stable averages.

TSS supports thermodynamic entropy and the statistical relation between macro and micro descriptions.

TSS is regime-relative. The appropriate macrovariables depend on the scale, boundary, and physical domain.

2.4.4. Layer 3 — Thermodynamic Information Theory

Definition

Thermodynamic Information Theory is the regime in which informational quantities are defined in relation to thermodynamic constraints and costs, especially in contexts involving work extraction, dissipation, erasure, stability, and the physical embodiment of distinctions.

This layer establishes that distinctions are not immaterial labels. Their maintenance, manipulation, and reliable discrimination occur in physical systems with energetic and entropic constraints.

Key characteristics

Distinctions have physical costs. Maintaining and manipulating distinguishable states is constrained by thermodynamic conditions.

Information can couple to work extraction under appropriate physical regimes.

Irreversibility, dissipation, and entropy production constrain information-processing systems.

Informational claims at this layer remain operationally anchored in physical intervention and resource accounting.

2.4.5. Layer 4 — Emergent Boundary Conditions

Definition

Emergent Boundary Conditions are higher-level constraints that arise from system organization and collective dynamics, and which function effectively as boundary conditions for lower-level components. They are "boundaries" not imposed externally, but generated internally by stable organizational structure.

An EBC is a boundary-like constraint produced by the system's own organisation.

Key characteristics

EBCs are organisation-generated constraints.

EBCs restrict accessible microstate trajectories of subsystems.

EBCs are stable and robust enough at the reference scale to support reproducible macrodynamics.

EBCs are nested. They may be supported by lower-level conditions and may themselves function as components in larger systems.

EBCs are central to the life definition because living systems are not merely driven systems. They are systems whose organisation maintains emergent constraints over time.[6]

2.4.5a. Two senses of information

This framework uses information in two linked but distinct senses.

At Layer 3, informational notions are thermodynamically loaded. Distinctions are physically costly to maintain, manipulate, and erase, and their relevance is tied to work, dissipation, and resource constraints.

At Layer 7, informational notions are Shannon-style. Distinctions are treated as discriminable symbols over a channel relative to an alphabet, noise model, and receiver discrimination capacity.

The bridge between these senses is operational. Shannon-style symbols become physically meaningful only when the system's thermodynamic and organisational conditions support stable, discriminable equivalence classes at the reference scale over the operational horizon.

2.4.6. Layer 5 — Constrained Thermodynamic State Space

Definition

Constrained Thermodynamic State Space is the subset of thermodynamic macrostates and trajectories accessible to a system given emergent boundary conditions and organisational constraints. CTSS describes how system organisation restricts which macroscopic thermodynamic trajectories are actually realisable.

Key characteristics

CTSS restricts macrostate accessibility. Organisation removes large regions of nominal TSS from practical accessibility.

CTSS channels evolution along constraint-structured thermodynamic trajectories.

Order at this layer is persistent restriction of accessible macrostates. It is not a metaphysical property and not merely visual complexity.

CTSS depends on stable EBCs. Without emergent ordered constraints, CTSS restriction is not maintained as a regime.

2.4.6a. Constrained Thermodynamic System

Definition

A Constrained Thermodynamic System is a BC-defined system whose expressed coarse-grained thermodynamic trajectory, at the chosen reference boundary and operational horizon, lies within CTSS because of EBC or organisational constraints.

CTSS names the state-space restriction or regime descriptor. CTS names the system-instance and its realised trajectory occupying that restricted space.

2.4.7. Layer 6 — Driven Thermodynamic State Space

Definition

Driven Thermodynamic State Space is the thermodynamic regime in which a system is maintained away from equilibrium by sustained driving: continuous throughput of energy and/or matter under boundary conditions that support persistent nonequilibrium structure.

DTSS describes systems that are not simply relaxing toward equilibrium but are held in a constrained nonequilibrium regime through ongoing throughput.

Key characteristics

DTSS involves sustained nonequilibrium.

DTSS is throughput-dependent. The regime depends on continuous or sufficiently renewed flow, not isolated initial conditions alone.

DTSS supports constraint maintenance. Driving can sustain EBCs and preserve CTSS restrictions against dissipation.

DTSS is a thermodynamic regime, not a claim about microphysical novelty.

2.4.7a. Driven Thermodynamic System

Definition

A Driven Thermodynamic System is a BC-defined system whose expressed coarse-grained thermodynamic trajectory is embedded in DTSS at the chosen reference boundary and operational horizon. It is maintained away from equilibrium by sustained driving or throughput.

DTSS names the driven-maintenance regime. DTS names the system-instance whose trajectory occupies that regime.

A DTS is a CTS whose CTSS restriction is maintained over the operational horizon by sustained throughput. A CTS need not be a DTS. It may exhibit transient or finite-horizon constraint persistence by drawing down stored free-energy resources while failing to maintain those restrictions over longer horizons.

The distinction between CTSS and DTSS is therefore horizon-relative. Many real systems lie on a continuum from transient constraint persistence to robust constraint maintenance under sustained throughput.

2.4.8. Layer 7 — Shannon Information Theory

Definition

Shannon Information Theory is the regime in which information is defined as discriminable distinctions over a channel, abstracted away from thermodynamic detail. It provides measures of uncertainty, entropy, mutual information, and channel capacity relative to a reference alphabet, noise model, and receiver discrimination capacity.

Key characteristics

SIT operates over coarse-grained symbols.

SIT is channel- and noise-dependent. Discriminability depends on the channel, noise regime, and receiver constraints.

SIT is reference-scale anchored. Symbol alphabets and capacities are defined relative to the chosen observational and operational scale.

SIT is abstract but operational. Its quantities are mathematically defined but empirically grounded through discrimination and communication tests.

2.4.8a. Alphabet, tokenisation, and physical manifestation

A reference alphabet becomes physically meaningful only when the regime supports stable, reproducible symbol classes at the chosen reference scale.

A tokenisation is a physically implementable classification rule that assigns admissible microphysical states, or state histories over an operational window, to labels under the regime's boundary conditions, emergent constraints, driving, and noise envelope.

A reference alphabet is the set of symbol classes induced by tokenisation. Two states belong to the same symbol class when the tokenisation assigns them the same label. Each symbol therefore corresponds to a coarse-grained region of the regime's admissible KMB state space.

A regime physically supports a reference alphabet when its symbol classes are stable and reproducible under admissible perturbations. States prepared within the same symbol class must be classified as the same with high reliability over the operational horizon. States prepared in different symbol classes must be classified as different with high reliability over the same horizon.

This condition distinguishes a physically supported alphabet from an arbitrary external encoding.

A supported symbol is not only discriminable. It is physically manifested by the regime as a maintained macrocondition. Each symbol class corresponds to a region of KMB that remains robust enough, over the operational horizon, for the system to be prepared into it and remain within the class's discrimination boundaries despite admissible noise or drift.

This also requires a read/write interface at the reference scale. The regime must support preparation or intervention operations that can place the system into different supported symbol classes, and discrimination operations that can reliably classify symbol instances. The read side remains a bounded registration event, not abstraction-free access.

2.4.9. Layer 8 — Non-Trivial Computation

Definition

Non-Trivial Computation is the physically realised capacity of an organisationally constrained system, or coupled system-of-systems, to condition downstream states on discriminable distinctions in a stable, reproducible way at the reference scale, establishing counterfactual outcome dependence beyond noise and beyond arbitrary external encoding.

NTC requires that discriminable distinctions are not merely describable from outside. They must be physically instantiated within a regime that supports stable differentiation, and downstream trajectories must depend on which distinction is present.

Operational test criterion

NTC is present when, under comparable boundary conditions, driving, component inventory, reference scale, operational horizon, and discrimination/noise regime:

1. the system supports at least one physically discriminable distinction above noise;
2. the distinction is instantiated in a stable enough form to condition downstream evolution over the operational horizon;
3. varying the distinction yields systematically different downstream trajectory classes or outcomes;
4. the difference is not explained by carrier microvariation, uncontrolled boundary variation, or arbitrary observer encoding;
5. ablating, scrambling, bypass-controlling, resetting, or otherwise disabling the relevant organisation collapses, degrades, or changes the downstream dependence in the expected way.[7]

Minimal NTC may occur in a one-shot episode. It does not require extended memory, multi-step reuse, recursive processing, symbolic reasoning, cognition, agency, awareness, or life. Stronger forms of NTC may include retention, redeployment, chaining, learning, and internal registration-relay architectures, but these are stronger cases, not minimal requirements.

Key characteristics

NTC is regime-relative.

NTC is counterfactual.

NTC is organisation-dependent.

NTC is not mere mapping.

NTC is not any state transition.

NTC is not automatically life.

NTC supplies the discriminator by which computation becomes physically meaningful rather than merely interpretive.

3. Identifying computation

3.1. Why NTC requires comparator discipline

A claim of NTC cannot rest on apparent complexity, successful behaviour, signal flow, responsiveness, or post-hoc description. A system may appear to compute because an observer can identify input-output regularities, impose an encoding, or describe its transitions abstractly. That is not enough.

The NTC claim must show that distinctions are made causally operative by organisation in a way that survives controlled comparison. The decisive question is: what happens when the proposed distinction-conditioned organisation is removed, scrambled, neutralised, reset, or bypass-controlled while the relevant boundary context, driving, component inventory, scale, horizon, and discrimination/noise assumptions remain comparable?

This is the role of Baseline Dynamics.

3.2. Baseline Dynamics

Definition

Baseline Dynamics is an intervention-defined comparator family describing how a system, or comparable system class, evolves under the same relevant boundary context, driving, component inventory, reference scale, operational horizon, and discrimination/noise regime when the specific information-bearing channel, tokenisation regime, mediating organisation, or distinction-conditioned pathway under test is ablated, scrambled, neutralised, reset, bypass-controlled, or otherwise disabled.

BD is not a claim that nothing happens. A BD comparator may contain rich chemistry, motion, coupling, pattern formation, feedback-like behaviour, oscillation, growth, decay, self-organisation, and complex transients. It lacks only the specific organisation proposed to make the relevant distinction causally operative in downstream trajectory selection.

BD therefore separates lawful dynamics from non-trivial computation. It asks whether the proposed organisation makes a difference beyond what the system would do under comparable physical conditions without that organisation.

3.3. BD ablation family

BD comparators may be constructed through several intervention types. The appropriate comparator depends on the system, reference scale, operational horizon, and distinction under test.

Channel or interface ablation disables the pathway through which a distinction becomes available. If downstream outcomes remain unchanged, the claimed dependence on that distinction is weakened.

Alphabet or tokenisation ablation disrupts the physical equivalence classes by which alternatives are made distinguishable. If the system still produces the same outcomes when the proposed classes cannot be stably distinguished, the computation claim fails or must be revised.

Connectivity or organisation scrambling preserves components and driving as far as possible while disrupting the structure proposed to mediate distinction-conditioned dependence. If downstream selection collapses or changes, the claim gains support.

Reset or non-reuse control removes the persistence or availability of prior distinction where persistence or redeployment is claimed. If the downstream outcome does not change, the claimed retained-discriminator dependence is unsupported.

Bypass control tests whether the outcome depends on the proposed mediating organisation or instead on direct physical forcing, common cause, environmental correlation, external interpretation, or an unrecognised pathway.

Carrier microdetail control tests whether downstream difference tracks the relevant discriminable class rather than irrelevant carrier variation. A valid NTC claim must separate OA-class or symbol-class dependence from accidental microphysical detail at the reference scale.

Noise and drift control tests whether the distinction remains above threshold under the stated discrimination/noise regime and operational horizon.

These ablations need not all be available in every empirical domain. But a strong NTC claim requires an admissible comparator family adequate to the claim being made.

3.4. BD adequacy criterion

A BD comparator is adequate when it preserves enough of the relevant physical regime to make the comparison meaningful while selectively disrupting the organisation proposed to mediate distinction-conditioned outcome dependence.

A BD comparator is weak when it changes too much. If boundary conditions, driving, component inventory, scale, horizon, or noise regime are altered along with the target organisation, collapse may reflect general disruption rather than loss of NTC.

A BD comparator is also weak when it changes too little. If the proposed mediating organisation remains intact through a bypass route, hidden redundancy, external interpreter, or common-cause pathway, persistence of outcome dependence does not refute the NTC claim.

The comparator must therefore target the right organisation at the right scale.

3.5. Minimal comparability checklist

For a BD comparison to support or weaken an NTC claim, the following conditions must be specified as far as the domain permits:

1. the reference boundary;
2. the relevant component inventory;
3. the driving or throughput context;
4. the reference scale;
5. the operational horizon;
6. the discrimination/noise regime;
7. the distinction or symbol class under test;
8. the downstream outcome classes;
9. the mediating organisation proposed to make the distinction operative;

10. the ablation, scrambling, neutralisation, reset, or bypass-control intervention;
11. the expected collapse, degradation, change, or invariance under comparator conditions.

Where these cannot be specified, the claim may remain suggestive, exploratory, or descriptive, but it is not yet a strong NTC claim.

3.6. Information Processing Locus

Definition

An Information Processing Locus is the organisational locus whose integrity is required for downstream trajectory selection to depend on the relevant discriminable distinction under specified reference conditions.

IPL localises NTC. It identifies where distinction-conditioned organisation does the relevant work and therefore what a BD-family comparator must disrupt to test the claim.

An IPL may be a subsystem, boundary-channel arrangement, molecular network, regulatory pathway, morphology-environment coupling, artefact-system, machine architecture, institutional process, or distributed arrangement, provided that its organisation is required for downstream outcome dependence on the relevant distinction.

The IPL need not be conscious, cognitive, symbolic, centralised, or human-like. It is a localisation concept, not a psychology concept. What matters is whether the organised locus mediates the dependence between discriminable distinction and downstream trajectory selection.

3.7. IPL and bypass control

Without IPL discipline, explanation spreads.

A downstream outcome may appear distinction-conditioned because of an external interpreter, a background correlation, direct physical forcing, common cause, uncontrolled boundary variation, or a larger system in which the candidate locus is only passively embedded. In such cases, the apparent computation may not belong to the proposed system.

IPL prevents this drift by asking what must remain intact for the downstream dependence to hold. If the proposed locus is disrupted and the dependence persists through another route, the IPL was mislocalised or the claim was overbroad. If the dependence collapses when the locus is disrupted under adequate comparator conditions, the claim gains localisation support.

BD asks what changes under ablation. IPL identifies what is being ablated.

3.8. Computation as a testable physical regime

The combined function of NMF, BD, and IPL is to make computation a testable physical regime rather than an unrestricted description.

NMF grounds computation in nested physical constraints.

BD supplies comparator discipline.

IPL localises the mediating organisation.

Together they block the slide from lawful evolution to computation-as-universal-redescription. A system computes non-trivially only where distinctions are physically supported, made operative by organisation, and shown to condition downstream outcome classes under adequate comparator pressure.

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4. Pancomputation in conclusion

The TC/NTC distinction preserves what is useful in pancomputational language while preventing it from becoming vacuous.

TC acknowledges that lawful physical evolution can be computationally redescribed under an encoding. This is a broad representational fact about how physical trajectories can be mapped.

NTC identifies the narrower physical regime in which computation does explanatory work. A system exhibits NTC where discriminable distinctions become organisation-dependent determinants of downstream trajectory selection at a reference scale and operational horizon.

This distinction permits computation to remain continuous with physical law without collapsing into the claim that all physical change is computationally significant in the same sense.

A river may be computationally redescribed. A chemical reaction network may be computationally modelled. A crystal may instantiate regular structure. A flame may respond dynamically to fuel, oxygen, and airflow. None of these facts alone establishes NTC. NTC requires comparator-stable counterfactual dependence on discriminable distinctions mediated by identifiable organisation.

The result is a non-vacuous computational vocabulary. Computation, in the non-trivial sense, is neither a metaphor nor an observer's arbitrary encoding. It is a physically grounded, regime-relative property of organised systems whose outcomes depend on distinctions in a way that can be located and tested.

That result supplies the discriminator required for the definition of life.

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5. Life

5.1. Transition from NTC to life

Non-Trivial Computation is not itself life. A system may exhibit NTC without being alive. A signal-routing device, control system, regulatory circuit, chemical switch, or artificial process may produce distinction-conditioned downstream outcome dependence without maintaining itself as a living organisation.

Life requires a stricter condition. The distinction-conditioned organisation must contribute to the persistence of the system's own constraint-structured order under sustained driving.

A living system is therefore not merely a dynamic system, not merely a complex system, not merely a self-organising system, not merely a feedback system, not merely a system containing information, and not merely a system exhibiting NTC. It is a driven thermodynamic

organisation in which NTC is instrumental to maintaining the constraints that define the system as a persistent individual.[8]

This makes life a maintenance regime. Distinctions matter because they help preserve the organised conditions under which the system continues.

5.2. Life

Definition

Life is a Driven Thermodynamic System (DTS), embedded in Driven Thermodynamic State Space (DTSS), that contains an Information Processing Locus (IPL) whose Non-Trivial Computation supports maintenance of constraint-structured order (EBC/CTSS) over the relevant operational horizon, yielding a counterfactual order advantage over Baseline Dynamics (BD) under the same driving and boundary context absent that functional organisation.

In system-instance terms, life is a DTS whose expressed coarse-grained trajectory is maintained in a constraint-structured regime through IPL-mediated NTC over an operational horizon.

5.3. Operational test

A system qualifies as life, at the reference scale and operational horizon of interest, when all of the following are satisfied.

Driven embedding (DTSS in DTS)

The candidate is stably describable as a DTS embedded in DTSS, with sustained throughput at the reference boundary sufficient to support persistent departure from undriven relaxation over the operational horizon.

Constraint persistence (EBC/CTSS)

The system exhibits persistent component- and organisation-dependent EBC/CTSS restrictions maintained across typical perturbations relevant to the reference scale and operational horizon.

Computational maintenance (IPL present and selection-relevant)

The system contains an IPL such that disrupting it, scrambling it, disabling it, or replacing it with a BD-like locus produces systematically different downstream trajectory classes, specifically in the system's capacity to maintain its constraints.

Counterfactual order advantage over BD

Relative to an explicit BD comparator family, with the same relevant components and comparable driving and boundary context, interventions that disable the IPL cause order-maintenance to collapse, degrade, or change toward the BD trajectory class. The relevant collapse is loss of CTSS restriction or decay of EBC-dependent organisation.

All four conditions are required. Driven embedding without IPL-mediated NTC is not enough. Constraint persistence without computational maintenance is not enough. NTC without horizon-bound constraint maintenance is not enough. Apparent persistence without counterfactual order advantage over BD is not enough.[9]

5.4. Key characteristics

Non-Trivial Computation is the discriminator

Life is distinguished by a physically discriminable IPL whose informational state counterfactually modulates which macroscopic futures are realised. The discriminator is not complexity, feedback, morphology, reproduction, or chemical familiarity alone. It is distinction-conditioned maintenance of the system's own constraint regime.

Order is constraint-maintenance

The ordered structure relevant to life is persistent restriction of thermodynamic pathways: CTSS maintained against dissipation under driving. This order is not identified with any specific material substrate, morphology, visual organisation, or biological familiar appearance. It is order as maintained restriction of accessible macrostates.

Registration-to-maintenance coupling

The defining role of the IPL is that distinctions supported at the reference scale become causally operative in sustaining EBC/CTSS restrictions. Internal registration chains are a common mechanism, and later work may analyse them through more detailed registration-relay vocabulary. But extended, multi-step, endogenous reuse chains are not required as an axiom of the minimal life definition. Minimal non-triviality may be one-shot. Life is horizon-bound maintenance.

This does not detach life from distinction-conditioned organisation. It preserves the minimal threshold while allowing stronger living systems to involve memory, learning, regulation, repair, signalling, development, heredity, and complex internal registration.

Life is not NTC alone

A non-living system may compute non-trivially. It may route signals, switch states, classify inputs, or condition outputs on distinctions. It becomes life only where such distinction-conditioned organisation contributes to maintaining the system's own emergent constraints over the operational horizon.

Life is not persistence alone

A stable crystal, rock, vortex, flame, or autocatalytic pattern may persist under certain conditions. Persistence becomes life-relevant only where an IPL-mediated distinction-conditioned pathway is instrumental to the maintenance of the system's constraint-structured order.

Life is not feedback alone

Feedback may occur in many non-living physical and technical systems. Feedback becomes life-relevant only where discriminable distinctions are made operative in maintaining EBC/CTSS restriction under sustained driving.

5.5. Baseline comparator and failure mode

Under Baseline Dynamics, the boundary context, driving, component inventory, reference scale, operational horizon, and discrimination/noise regime are held comparable while the IPL's selection-relevant organisation is ablated, scrambled, neutralised, reset, bypass-controlled, or otherwise disabled.

An otherwise similar system then fails to maintain the same EBC/CTSS restriction. Its macroscopic order either decays toward undriven or weakly structured relaxation, or persists only incidentally, without being counterfactually keyed to prior distinctions.

The life claim gains support where disabling the IPL collapses, degrades, or changes the system's capacity to maintain its constraint regime. It weakens where the same order-maintenance persists without the proposed distinction-conditioned organisation, or where collapse results from general destruction of the system rather than targeted loss of the proposed IPL-mediated dependence.

5.6. Living System

Definition

A Living System is a DTS whose expressed coarse-grained trajectory exhibits IPL-mediated, non-trivially computed maintenance of EBC/CTSS restriction over the operational horizon, such that disabling the IPL collapses the trajectory toward the BD comparator class.

LS names the system-instance satisfying the life condition. Life names the regime condition. The Living System is the organised physical system whose trajectory is maintained in the relevant regime.

5.7. Life as minimally apparent

Describing life in minimally occurring states becomes tractable when candidate systems are not treated as bundles of biological familiarities, isolated physical properties, or chemically arbitrated gradients alone. They are evaluated as Driven Thermodynamic Systems whose Information Processing Locus performs Non-Trivial Computation making discriminable distinctions causally efficacious in selecting downstream trajectory classes that preserve the system's own constraint-structured order.

In this sense, being alive is not an honorific for complexity, feedback, adaptation, metabolism, reproduction, persistence, or life-like appearance. It is the presence, within a driven thermodynamic system, of IPL-mediated Non-Trivial Computation that supports horizon-bound maintenance of EBC/CTSS restriction under the stated reference conditions.[10]

The minimal life question is therefore:

Does the candidate system maintain EBC/DTS restriction under sustained driving through an IPL-mediated, distinction-conditioned pathway whose disruption collapses, degrades, or changes order-maintenance toward the relevant Baseline Dynamics comparator class?

This provides a clearer treatment of borderline cases.

A system with rich chemistry but no IPL-mediated distinction-conditioned maintenance remains chemistry, however complex.

A system with feedback but no comparator-stable dependence on discriminable distinctions does not yet meet the life condition.

A system with Non-Trivial Computation that does not contribute to its own constraint-maintenance may compute non-trivially without being alive.

A system that maintains organisation only because external conditions hold it in place, without its own IPL-mediated contribution to constraint persistence, does not satisfy the life discriminator.

A system whose apparent order survives targeted IPL disruption may be misdescribed, mislocalised, or not living under the proposed definition.

A system whose order-maintenance collapses, degrades, or changes under targeted disruption of the distinction-conditioned locus gains support as a living system at the specified reference scale and operational horizon.

5.8. Disciplinary unification

The definition gives physics, chemistry, and biology a shared discriminator without collapsing one into the other.

Physics supplies lawful microdynamics, boundary commitments, thermodynamic constraints, and nonequilibrium bookkeeping. It delimits what can persist, what must dissipate, and what can be maintained under sustained driving.

Chemistry supplies concrete inventories, reaction networks, material pathways, catalytic structures, molecular constraints, and gradient-coupled mechanisms by which physical constraints can be built, stabilised, transformed, and repaired.

Biology begins where organised information processing becomes a regime feature: where physically supported distinctions are registered or otherwise made operative in ways that maintain the constraints defining the system as a persistent individual.

This does not mean that biology leaves physics or chemistry behind. It means that chemical organisation has entered a further emergent regime: one in which chemical pathways, structures, and energetic couplings remain necessary, but are no longer sufficient to account for and audit life-status by themselves. The additional question is whether distinctions carried within the driven regime are made operative in maintaining the regime that carries them.

The sciences therefore do not need a checklist of biological familiarities to coordinate around the life question. They require a common operational language: constraints, discriminability, counterfactual dependence, maintenance, localisation, and comparator-guided ablation.

This does not settle every empirical case in advance. It supplies the discriminator by which cases can be tested.

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6. Conclusion

6.1. What the argument has established

The paper began with the problem of pancomputation. If every lawful physical process can be computationally described, then computation cannot by itself explain life. A river, flame, crystal, reaction network, or planetary orbit may be computationally redescribed under an encoding. That does not make it alive, and it does not make computation a sufficient discriminator.

The solution is to separate Trivial Computation from Non-Trivial Computation.

Trivial Computation is lawful state evolution redescribable under an encoding. Non-Trivial Computation is physically enacted discrimination: organisation-dependent downstream outcome dependence on discriminable distinctions under specified reference conditions.

The Nested Multiscale Framework grounds that distinction without adding new ontology. KMB supplies microphysical admissibility. BC delimits system and exchange. TSS supplies thermodynamic macrodescription. Thermodynamic Information Theory grounds the physical cost and embodiment of distinctions. EBC supplies organisation-generated constraint. CTSS describes restricted macrostate accessibility. DTS/DTSS describes sustained nonequilibrium maintenance under driving. SIT supplies channel-relative discriminability. NTC arises where physically supported distinctions become counterfactually efficacious in downstream trajectory selection.

Baseline Dynamics makes the claim testable. A BD comparator preserves the relevant physical regime while disrupting the proposed distinction-conditioned organisation. Information Processing Locus makes the claim localisable. IPL identifies where the relevant organisation must remain intact, or what must be disrupted, for downstream trajectory selection to depend on the distinction.

Life is the first major application of this discriminator architecture.

A living system is not merely complex, persistent, chemical, adaptive, feedback-driven, self-organising, reproductive, metabolic, or computationally redescribable. It is a driven thermodynamic system whose IPL-mediated Non-Trivial Computation supports horizon-bound maintenance of EBC/CTSS restriction, yielding a counterfactual order advantage over Baseline Dynamics under comparable driving and boundary conditions.

In compressed form:

Trivial Computation is physical evolution under an encoding.

Non-Trivial Computation is physically enacted discrimination.

Baseline Dynamics tests whether the distinction-conditioned organisation does the work.

Information Processing Locus localises where that work is done.

Life is driven thermodynamic constraint-maintenance supported by IPL-mediated Non-Trivial Computation.

The definition does not remove empirical difficulty. It changes its form. Instead of asking whether a candidate system resembles familiar life closely enough, the framework asks whether the system maintains its constraint-structured order through localisable, comparator-testable, distinction-conditioned organisation under specified reference conditions.

6.2. The origin of life as the physics–chemistry–life transition

The origin of life, in this framework, is not the origin of information in matter.

Informational distinction can occur before life. Physical systems can stabilise differences. Chemical systems can preserve structure, sequence, templating relations, catalytic selectivity, molecular recognition, compartmentalisation, copying, inhibition, amplification, and degradation pathways. RNA-like chemistry is not outside the informational continuum. It demonstrates that chemistry may already carry and transform distinctions before it becomes alive.

Nor is the origin of life the appearance of one privileged terrestrial scaffold. Membranes, mineral surfaces, wet-dry cycles, hydrothermal gradients, autocatalytic networks, genetic polymers, peptide systems, lipid compartments, and other chemical arrangements may support or instantiate the transition. They may be necessary in one planetary history and replaceable in another. They are candidate scaffolds, not the formal life threshold.[11]

The threshold is stricter.

Physics supplies lawful admissibility, dynamical constraint, boundary condition, and thermodynamic possibility. Chemistry is an emergent regime within physics: a level at which bonding, reaction pathways, catalysis, molecular structure, gradients, energetics, kinetics, and dissipative coupling become stable enough to be audited in their own terms. Chemistry does not leave physics. It is a higher-level abstraction made legitimate by regularities that physical dynamics can support.

Within chemistry, the sub-life information-processing layer names the descriptive region in which physically supported differences become discriminable distinctions and condition subsequent chemical pathways, without yet supporting maintenance of the driven constraint-bearing regime that carries them. Such processing may satisfy Non-Trivial Computation without satisfying the life discriminator; life begins only where IPL-mediated NTC supports that maintenance.

Life is the next emergent regime within physics and chemistry. It does not leave either domain behind. It arises where chemical organisation becomes a driven constraint-bearing regime whose future trajectory depends on physically enacted discrimination. At that point, chemistry remains necessary but becomes audit-incomplete for life-status attribution.

A chemical audit can track substrates, products, pathways, catalysts, gradients, rates, compartments, and energetic feasibility. It does not, by itself, track whether distinctions carried within the regime are made operative in maintaining the regime that carries them.

The present framework adds that missing life-discriminator question: do physically supported distinctions within the driven regime become causally operative in maintaining the constraint-structured order of that same regime, such that disruption of the relevant organisation collapses, degrades, or changes the order-maintenance trajectory toward Baseline Dynamics?

Where the answer is no, the system may remain rich or complex chemistry, including forms of sub-life information processing, self-organisation, catalysis, templating, feedback, or prebiotic scaffolding.

Where the answer is yes, the relevant driven chemical regime satisfies the Paper 1 life threshold. Which candidate frame, locus, class, or continuity output follows remains an attribution question for Papers 2 and 3.

This does not mean that the system chooses its future. It means that the system's organisation physically constrains which future trajectory classes remain accessible, stabilised, inhibited, repaired, redirected, reproduced, suspended, terminally completed, or closed under the stated reference conditions.[12]

The physics–chemistry–life continuum is therefore continuous in physical inheritance but discontinuous in regime condition. Each layer inherits the lower layer rather than escaping it. Each layer becomes separately auditable when a new class of stable, causally consequential behaviour appears. Biology, understood as the disciplined study of living systems, becomes warranted where chemical organisation enters this emergent regime: physically supported distinctions are made operative in maintaining and shaping the branching future of the driven thermodynamic system that carries them.

That is the origin of life in the present sense: not the first appearance of information, not the first appearance of chemistry, not the first appearance of complexity, and not the first appearance of an Earth-specific scaffold, but the emergence of a driven physical-chemical regime in which informational distinction becomes instrumental to the continued maintenance and future-branch structuring of the organisation that carries it.

Endnotes

[1] For the computational-implementation and triviality problem, see Chalmers (1996) and Horsman et al. (2014). Both motivate constraints beyond arbitrary physical-to-computational mapping; neither supplies the present TC/NTC discriminator. Lizier, Prokopenko, and Zomaya (2007) use the prior technical phrase “non-trivial computation” for distributed information dynamics in complex systems. That terminology and neighbouring problem are acknowledged here as provenance and comparator only: their information-storage, transfer, and modification framework does not supply the present organisation-mediated, comparator-tested NTC relation.

[2] Seifert (2012) is used here as a standard nonequilibrium and stochastic-thermodynamic reference for trajectory-level work, heat, entropy production, and driven open-system description. The NMF layer structure remains the present paper's construction.

[3] Shannon (1948) supplies the channel-relative mathematical framework for entropy, mutual information, alphabets, noise, and channel capacity used at this layer.

[4] Landauer (1961) provides the canonical physical-irreversibility result for logically irreversible information operations; Parrondo, Horowitz, and Sagawa (2015) provide the broader modern thermodynamics-of-information framework. These sources ground the physical cost and constraint claim, not the NMF layering itself.

[5] Woodward (2003) supplies the interventionist causal background used here. Baseline Dynamics is a stronger paper-specific comparator discipline: it additionally requires preservation of the relevant boundary context, driving, inventory, scale, horizon, and noise assumptions while the proposed mediator is selectively disrupted.

[6] Deacon, Srivastava, and Bacigalupi (2014) and Montévil and Mossio (2015) provide close organisational neighbours in which constraints are generated, maintained, or mutually dependent in nonequilibrium systems. They are acknowledged here without technical dependence: constraint organisation alone does not establish the present NTC/IPL burden.

[7] Bartlett (2024) independently formalises causal leverage by erasing or scrambling syntactic information and measuring divergence in future phase-space trajectories. This is an examined methodological adjacency to one possible BD-family intervention and readout; CLD does not by itself establish a physically supported alphabet, BD adequacy, or IPL localisation.

[8] For major organisation-centred life comparators, see Varela, Maturana, and Uribe (1974) on autopoiesis and Ruiz-Mirazo, Peretó, and Moreno (2004) on autonomy plus open-ended evolution. Kolchinsky and Wolpert (2018) provide a closer information-maintenance comparator by defining semantic information through the causal necessity of system-environment correlations for maintaining a physical system’s existence under counterfactual scrambling. The present local life threshold does not inherit that semantic-information or viability formalism and does not require autopoietic self-production or open-ended evolution as primitive discriminators; it instead requires driven constraint-maintenance supported by IPL-mediated NTC under the paper’s reference and Baseline Dynamics conditions.

[9] England (2015) provides a useful negative comparator: driven nonequilibrium self-assembly can exhibit structured dissipative adaptation without thereby establishing the IPL-mediated NTC maintenance relation required here.

[10] Cleland and Chyba (2002) argue that repeated counterexamples to trait definitions of life point toward the need for an underlying theory of living systems. The present discriminator is offered as an attempt at that theory-level task; the citation does not establish that the attempt succeeds.

[11] Hordijk and Steel (2015) develop autocatalytic-set models that explicitly incorporate boundaries. Such architectures are relevant candidate scaffolds in the chemistry-to-life transition, but their presence does not by itself establish the present life discriminator.

[12] Sharma et al. (2023) develop Assembly Theory as a formal account of historically contingent construction pathways, copy number, selection, and constrained exploration of assembly space. It is acknowledged here as a lower-ladder state-space and complex-chemistry adjacency, not as evidence of NTC or Life.

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