Physical Origin of Proto-Information: Syntax, Semantics and Pragmatic Emergence in Prebiotic Protocell Clusters

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***Abstract*- The emergence of information and meaning before genes or enzymes existed is a key open problem in prebiotic research. This paper develops a physics-based framework for the rise of early information in protocell systems. We show that Casimir–Lifshitz interactions, acting under plausible primordial-soup conditions, generate stable dimers and ordered clusters in which nanometer-scale resonant gaps create structured fluctuation spectra and proton-rich reaction zones. On this basis, Computational Mechanics is used to describe the syntactic layer via ε-machines, functional semantics via lumping operations, and the pragmatic layer via emergent macro-ε-machines that execute cluster-level tasks in the sense of Construction Theory. Together these elements yield a coherent model of proto-biological meaning: one that explains prebiotic information structures without genes, enzymes, or biochemical networks and identifies a physical precursor to functional organization.**

***Keywords-Casimir*–Lifshitz coupling; computational mechanics; ε-machines; prebiotic information; construction theory; protocell clusters.**

I. INTRODUCTION

This is the fourth of seven papers in the series: "A Constructivist Proto-Bio-Information Theory: A Physically Grounded Nano-Systems Architecture for Prebiotic Emergence, Information, Proto-Semantic Function, and Sustainability of Protocell Aggregation and Cluster Formation".

Massoth [1] shows that Casimir–Lifshitz forces generate robust attraction and stable protocell clusters across 5–200 nm under realistic prebiotic conditions. These physically enforced mesoscale assemblies form the structural substrate in which this paper grounds the emergence of information and meaning.

Massoth [2] demonstrates that such clusters form reproducible mesoscale attractors with autonomous ε-machine dynamics. This attractor-based organization provides the computational and informational foundation that this paper develops into a physical account of proto-information and proto-semantics.

Massoth [3] shows that protocell clusters generate reproducible differences and functional meaning states through constructor-theoretic tasks. These proto-functional structures prepare the ground for this paper, which unifies syntactic, semantic, and pragmatic dimensions into a coherent framework of proto-biological meaning.

In addition, we integrate the 'Software in the Natural World' framework of Rosas et al. [4] with the Constructor Theory of Information [5] developed by Deutsch and Marletto, applying both to the hierarchical and task-based organization of protocell cluster dynamics.

The structure of the paper is as follows: In Section II, we review existing approaches to semantic information, Computational Mechanics, and Constructor Theory, highlighting the absence of a unified, physically grounded framework for prebiotic meaning. Section III introduces the physical and conceptual background of prebiotic protocell systems and formulates the central research questions concerning the emergence of syntax, semantics, and pragmatics prior to genetics. Section IV develops the physical and information-theoretic foundations of structured protocell dynamics, combining Casimir–Lifshitz coupling with Computational Mechanics, functional lumping, and constructor-theoretic task concepts. In Section V, we analyze the emergence of syntactic structure in protocell clusters, showing how reproducible fluctuation patterns are captured by ε-machines. Section VI addresses the transition from syntax to semantics, demonstrating how functional equivalence relations give rise to proto-semantic categories grounded in physical invariance. Section VII develops the pragmatic level, where entire protocell clusters form macro-ε-machines that perform reproducible tasks and qualify as prebiotic partial constructors. Section VIII answers the guiding research questions by synthesizing the syntactic, semantic, and pragmatic results within a unified physical framework. Finally, Section IX summarizes the conceptual contributions, situates the results within origins-of-life research, and outlines experimental and theoretical directions for future work.

II. RELATED WORK

Recent theoretical approaches to semantic information—most notably the work of Kolchinsky and Wolpert [15], Ruzzante et al. [16], and S. Bartlett et al. [17] - demonstrate that information is not intrinsically tied to genes or replication.

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Existing literature treats syntax (Computational Mechanics), semantics (semantic information), and function (Constructor Theory) largely in isolation. Even integrative discussions such as Rosas et al. [4] stop short of identifying a shared physical origin. A unified, prebiotically plausible framework linking all three levels remains absent.

This paper closes this gap by showing that syntax, semantics, and pragmatics emerge from the same Casimir–Lifshitz–shaped attractor landscape of protocell clusters. ε-machines capture syntactic structure, functional lumping defines semantic classes, and macro-ε-machines implement cluster-level tasks in the sense of Constructor Theory [5]. The result is a fully physical account of proto-biological meaning, in which information precedes replication and function precedes biochemistry.

III. PREBIOTIC EMERGENCE OF INFORMATION AND MEANING

How information, functional structure, and early meaning relations arose before genes, enzymes, or metabolic networks existed remains a major open challenge in origins-of-life research. The earliest protocells must already have exploited reproducible differences, produced functionally relevant states, and stabilized collective patterns; otherwise, the transition to biochemical evolution could not have occurred. Yet a mechanistic, physics-based model that explains how such proto-informational processes emerged is still largely missing.

Recent results show that Casimir–Lifshitz interactions can generate robust coupling between protocells under prebiotic conditions, forming stable dimers and ordered clusters. These clusters create nanometer-scale resonant gaps that structure the electromagnetic mode spectrum and produce characteristic energetic signatures—structured fluctuation spectra. The same gaps can host quantum-field-driven proton reservoirs, offering a physical precursor to chemiosmotic gradients.

These structured energy patterns may serve as substrates for proto-informational processes. To analyze them systematically, we use Computational Mechanics: ε-machines capture minimal predictive structure (syntax), lumping procedures define functional macrostates (semantics), and stable cluster geometries generate collective attractors (pragmatics).

Against this background, the paper addresses three central research questions:

RQ#1 Syntax: How does Casimir–Lifshitz coupling generate recurrent, predictable patterns describable by ε-machines?

This concerns the causally minimal states that arise from structured fluctuation profiles, gap geometries, and field modulations.

RQ#2 Semantics: Under which physical conditions do these syntactic patterns become functional categories with stable consequences for proton distribution, permeability, or adsorption?

Here we examine how lumping operations define semantic classes whose energetic signatures produce distinct physico-chemical effects.

RQ#3 Pragmatics: How do entire protocell clusters form emergent macro-ε-machines that perform reproducible tasks in the sense of Construction Theory?

This concerns proto-functional stability: when a dimer or tetrahedron becomes a coherent unit capable of repeated tasks such as stabilization, proton focusing, or exchange.

Together, these questions establish a physics-based framework for the emergence of prebiotic meaning—a transition from fluctuations to syntax, from functional consequences to semantics, and from cluster coherence to proto-pragmatic organization. This approach explains information formation before genetics and links concepts across biology, physics, and computer science.

IV. PHYSICAL AND INFORMATION-THEORETIC FOUNDATIONS OF STRUCTURED PROTOCELL DYNAMICS

The framework developed here is built on the coupling of two physical layers: (1) Casimir–Lifshitz–driven formation of structured fluctuation spectra between protocells, and (2) their representation as syntactic, semantic, and pragmatic information structures within Computational Mechanics and constructor-theoretic information.

A. Casimir–Lifshitz coupling as a generator of structured fluctuations

Between two protocells with radii R_1, R_2 and a gap L, Casimir–Lifshitz theory produces a mode-selective energy spectrum that structures local electromagnetic fluctuations. In the biologically relevant regime, 5 nm ≤ L ≤ 100 nm, the algebraic high-temperature term dominates:

$$F_{CL}(L) \approx -(A_{eff}/6) \cdot (R_{eff} / L^2), \text{ with } R_{eff} = (R_1R_2)/(R_1 + R_2),$$

and A_{eff} an effective Hamaker constant integrating the spectral dielectric response of the membrane-water-system.

The corresponding potential $U_{CL}(L) \propto -(A_{eff}/6) \cdot (R_{eff} / L)$ creates strong and reproducible nanometer-scale configurations that generate characteristic energetic signatures—structured fluctuation spectra. These signatures define proto-syntactic patterns because they restrict the system to a limited set of reproducible configuration classes.

In highly ordered protocell clusters (e.g., tetrahedral arrangements), the superposition of modes forms a topologically nontrivial attractor landscape. At the cluster center, this landscape produces quantum-field–induced proton enrichment zones—a physical mechanism for early functional gradients (Paper 5). Experimental protocell systems demonstrate that membrane-bounded compartments can indeed support such early functional gradients and stable microchemical domains [14].

B. Computational Mechanics and the mathematical structure of syntax

Computational Mechanics characterizes a system through the causally minimal, prediction-relevant states *S* derived from past observations $x(t{:}-\infty,0)$:

$$\varepsilon(x(t{:}-\infty,0)) = \{x' : P(x(t{:}0,+\infty) \mid x(t{:}-\infty,0)) = P(x(t{:}0,+\infty) \mid x'(t{:}-\infty,0))\}.$$

An ε-machine is thus a minimal state-based representation that captures all reproducible patterns required to predict a system's future behavior, without invoking symbolic codes or external control. It provides a mathematically well-defined notion of syntax as causal structure rather than symbolic description.

In this work, Computational Mechanics is not used as a generic modeling framework, but as a diagnostic tool to identify which physical degrees of freedom in protocell clusters give rise to reproducible, prediction-relevant macrostates. The observable process X_t corresponds to physically accessible quantities—such as inter-protocell distances, local field intensities, proton densities, or adsorption states—sampled over time in Casimir–Lifshitz–coupled assemblies. The resulting ε-states therefore do not represent abstract symbols, but equivalence classes of physical configurations that share the same conditional future behavior under field-mediated coupling.

The full set S of ε-states defines the syntactic level of the system. For protocell clusters, the ε-machine identifies reproducible fluctuation patterns and groups them into causally relevant states. Their temporal evolution is described by the stochastic transition matrix $T_{ij} = P(S_{t+1} = j \mid S_t = i)$.

The entropy rate $h_\mu = H\,[X_t \mid S_t]$ measures residual unpredictability within syntactically ordered patterns and quantifies the interaction complexity of protocell coupling.

This framework allows a principled distinction between mere structural order and genuine informational structure: only ε-states associated with distinct future consequences qualify as informational variables in the constructor-theoretic sense.

C. From syntax to semantics: lumping as functional category formation

Semantics arises when several syntactic states produce equivalent functional effects and can be grouped into macrostates Z_k via a mapping *A*:

$$Z_k = A(S_i, S_j, \ldots) \text{ if } \Phi(S_i) \approx \Phi(S_j),$$

where Φ(S) denotes a physical effect such as changes in proton distribution, adsorption profiles, or membrane permeability. A lumping is semantically valid if:

$$P(\text{Outcome} \mid S_i) \approx P(\text{Outcome} \mid S_j).$$

Semantics thus becomes a functional equivalence relation over energetic signatures. Examples:

- Protocell dimer:
  different fluctuation patterns that yield the same proton-focusing profile constitute a semantic microstate.
- Tetrahedral cluster:
  multiple syntactic field configurations producing the same central proton funnel.

D. Pragmatics: Emergence and Construction Theory

Construction Theory models functional possibilities as tasks: $A = \{x \rightarrow y\}$. A protocell cluster acts as a constructor when it performs a task repeatedly without losing functionality:

$$A(t{:}\ 0, +\infty){:}\ (x, C) \rightarrow (y, C), \text{ where } C \text{ is the cluster state.}$$

A task is physically possible if such a constructor can exist in principle.

For protocell clusters, we define proto-pragmatic tasks such as stable proton focusing, enhanced adsorption within the gap, and geometry-regulated exchange channels.

These tasks are described by macro-ε-machines, whose states correspond not to individual protocells but to entire cluster geometries (e.g., dimers or tetrahedra).

At the pragmatic level, this causal state structure extends naturally to macro-ε-machines that govern cluster-level tasks. Casimir–Lifshitz–coupled protocell clusters possess a finite set of causally relevant macrostates with distinct future consequences, thereby providing a physically grounded notion of syntax.

V. SYNTAX: PATTERN FORMATION AND E-MACHINES IN PROTOCELL CLUSTERS

In prebiotic protocell assemblies, syntax denotes the level of structured pattern formation that emerges from initially disordered fluctuations and becomes stabilized through physical coupling.

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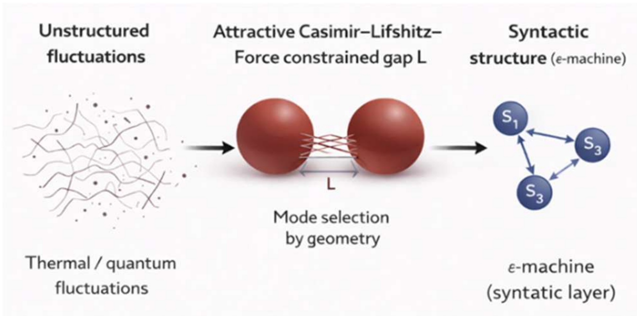

Figure 1. Physical origin of syntactic structure in protocell clusters.

In Figure 1, initially unstructured thermal and quantum fluctuations become geometrically constrained by attractive Casimir–Lifshitz coupling in a protocell dimer. Mode selection within the nanoscale gap reduces fluctuation diversity and gives rise to a finite set of reproducible causal states, represented as an ε-machine that constitutes the syntactic layer of prebiotic information.

Analysis of attractive Casimir–Lifshitz forces in single- and multi-cell geometries shows that protocells in saline environments generate characteristic regional fluctuation spectra that are neither random nor locally isolated. Casimir–Lifshitz interactions are fluctuation-induced forces that arise when electromagnetic vacuum fields are confined by material boundaries, here provided by adjacent protocell membranes, leading to reproducible, geometry-dependent coupling at nanometer scales.

Nanometer-scale gaps filter and modulate these electromagnetic modes so that specific field profiles recur. These energy patterns remain dynamic, yet they form spatially and temporally correlated sequences that exceed thermal noise. Such reproducible configurations constitute the syntactic basis of the system. Computational Mechanics provides a rigorous tool for reconstructing this structure.

The observable sequence $X(t{:}-\infty,+\infty)$ includes the relevant physical variables—distance dynamics, proton density, field strengths, and local permittivities. The ε-machine extracts the minimal state classes needed for prediction. Two histories are equivalent when they yield identical future distributions:

$$\varepsilon(x(t{:}-\infty,0)) = \{x' : P(x(t{:}0,+\infty) \mid x) = P(x(t{:}0,+\infty) \mid x')\}.$$

Each equivalence class defines a causal state S_t. The full set of these states forms the system's syntactic structure. While the underlying dynamics is continuous and high-dimensional, the ε-machine offers a discrete, reduced representation that preserves all information relevant for prediction.

In protocell clusters, recurring fluctuation motifs act as attractors of syntactic states. A dimer with a stable Casimir–Lifshitz gap generates characteristic sequences of distance-dependent field profiles; a tetrahedral cluster produces corresponding superposed near-field patterns. These ordered sequences are encoded in the transition matrix

$T_{ij} = P(S_{t+1} = j \mid S_t = i)$.

The emergence of such reproducible fluctuation sequences corresponds to the behavior of dissipative structures formed in far-from-equilibrium regimes [13].

Geometric fluctuations shift transition probabilities but remain confined to a limited set of robust patterns. Syntax thus arises from deterministic physical constraints combined with stochastic microscopic variability, which together permit only a finite number of causally meaningful patterns.

Syntactic order is quantified by the entropy rate

$h_\mu = H[X_t \mid S_t]$, where X_t denotes the next observable event (e.g., proton-density change or field-profile shift) and S_t the current syntactic state. The entropy rate measures the remaining unpredictability given the internal cluster state. Low values indicate that future behavior is strongly determined by syntax. Protocell clusters exhibit markedly lower entropy rates than isolated vesicles: Casimir–Lifshitz attraction channels the fluctuation spectrum and confines state dynamics to a few stable attractors.

Syntax is therefore not an abstract category but a direct physical consequence of cluster geometry, material-dependent mode structure, and feedback between proton distribution and electromagnetic fields. The ε-machine reveals this order and shows how protocell assemblies can exhibit structured "responses"—not through control or intention, but through reproducible organization within the fluctuation space.

VI. Semantics: Functional Category Formation in Protocell Clusters

In prebiotic protocell assemblies, semantics marks the transition from mere pattern formation to functional meaning. Syntax captures recurring fluctuation sequences; semantics emerges when such patterns produce systematically different physical effects. Proto-semantic structure is therefore defined as a relation between an energetic signature and its functional consequence.

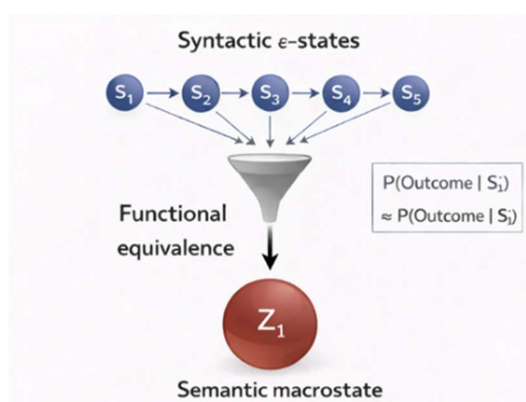

Figure 2. Semantic macrostates emerge by functional lumping of syntax.

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This corresponds to the principle of causal emergence, in which macro-level differences can exert greater causal specificity than their microstate constituents [11]. Meaning arises not through symbolic representation but through stable couplings between fluctuation patterns and measurable changes in proton distribution, membrane permeability, or adsorption dynamics.

In Figure 2, multiple syntactic ε-states with distinct transition structures are grouped through a lumping operation based on functional equivalence. When different syntactic realizations produce indistinguishable physical outcomes, they collapse into a single semantic macrostate. Semantics thus arises as an invariance of physical effects across syntactic diversity, not as symbolic encoding.

The mathematical basis is the lumping procedure of Computational Mechanics. Starting from syntactic ε-states S_t, semantics appears when several such states have equivalent effects. A semantic class Z_k is formed via a mapping A when $\Phi(S_i) \approx \Phi(S_j)$, where Φ denotes observable outcomes such as proton-density shifts or field-energy changes. Two syntactic states belong to the same semantic category if they yield the same macroscopic response. The condition

$$P(\text{Outcome} \mid S_i) \approx P(\text{Outcome} \mid S_j)$$

defines this functional equivalence: meaning emerges as invariance of physical effects across different syntactic realizations. The lumping criterion used here is mathematically equivalent to strong lumpability in Markov chains (Kemeny and Snell), but is interpreted physically in terms of functional equivalence of outcomes rather than state aggregation alone.

In dimers, distinct field-fluctuation patterns often lead to the same functional consequence, such as directed proton focusing in the gap. Quantum-field–induced mode selection creates resonance zones whose impact on proton dynamics remains similar despite syntactic variability. This yields a semantic class that groups all patterns producing the same proton-based effect.

Tetrahedral clusters generate a richer semantics. The four vesicles jointly form a three-dimensional energetic minimum at the cluster center, concentrating protons and acting as a proto-chemiosmotic reservoir. Different syntactic sequences—arising from minor distance fluctuations or altered mode superposition—produce the same functional macrostate: a stable proton-funnel geometry. Here, semantics appears as geometric invariance of functional effects. The semantic state is defined not by a single pattern but by all patterns that generate the same proton-reservoir dynamics.

In Computational Mechanics, such functional stability corresponds to a reduction of syntactic diversity into a small set of macrocategories. These lumped classes form a proto-semantic alphabet whose elements are defined by their effects. Meaning thus arises not from external coding but from the physical robustness of functional outcomes. Semantics becomes a direct consequence of energetic invariance, not a layer added on top of physics.

These invariances are experimentally accessible. Measurements of proton density in gap regions, membrane permeability, or field-intensity profiles offer observables whose outcome distributions can be compared under different syntactic excitations. If these distributions coincide, a semantic lumping class is identified. Prebiotic semantics thus becomes an empirically accessible, mathematically precise, and physically grounded layer. It marks the transition from structural order to functional efficacy and provides the foundation for later pragmatic and emergent organization in entire protocell clusters.

VII. Pragmatics and Emergence in Protocell Systems

The pragmatic layer of prebiotic protocell assemblies describes the processes through which syntactic patterns and semantic categories combine into collective functional units. Syntax captures the ordering of fluctuations, and semantics captures their functional effects.

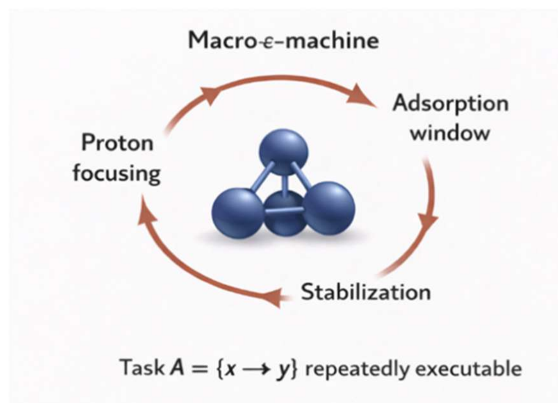

Figure 3. Macro-ε-machines implement repeatable prebiotic functional tasks.

In Figure 3, a tetrahedral protocell cluster is represented as a macro-ε-machine whose collective state enables the repeated execution of physical tasks. Proton focusing, adsorption windows, and stabilization form a closed task loop that persists despite microscopic fluctuations. The cluster thus functions as a prebiotic constructor in the sense of Construction Theory.

Pragmatics emerges only when whole protocell aggregates perform reproducible transformations that exceed the capabilities of individual vesicles. Such emergent task-capabilities mirror classical self-organizing processes in which new functional roles arise spontaneously from collective system dynamics [12]. At this level, protocell clusters act as physical constructors in the sense of Construction Theory: they carry out tasks repeatedly, robustly, and without losing their functional core. These emergent tasks arise not from biological programs but from the attractor dynamics of macro-ε-machines, whose states represent complete cluster geometries.

Dimers and tetrahedral clusters stabilized by Casimir–Lifshitz coupling form such macro-states. Their evolution is described by transition probabilities between geometrically defined macro-ε states. In dimers, coupling distance is the central state variable from which a reduced set of functional categories emerges. Tetrahedra possess an additional internal resonance zone, created by overlapping near fields, which forms a localized energetic subsystem. Both cluster types exhibit attractors with stable statistical signatures that persist despite microscopic noise. These macro-attractors carry proto-pragmatic meaning because they implement recurrent, functionally relevant tasks.

A Proto-Pragmatic-Functional (PPF) meaning category is: A stable, pre-biological macrostructure in protocell clusters that reliably performs a specific physical task and therefore has functional significance — without genes, enzymes, or chemical codes.

PPF-Meaning Category:
High Lipid Packing Density → Activation Mode

Regions of high lipid packing density reduce local permeability, stabilize nonpolar molecules, and form robust membrane patches. Despite microscopic variability, they produce recurrent patterns of compressed membrane modes that the ε-machine groups into one syntactic class. Functionally, this corresponds to an activation mode: these areas act as preferred sites for adsorption and structural coupling. Pragmatically, protocell clusters recreate such activation zones, supporting early precursor chemistry.
Syntax: Recurrent patterns of compressed membrane modes stabilized by Casimir–Lifshitz-induced pressure gradients.
Semantics: “High packing density means activation mode” - consistent adsorption and stabilization effects.
Functional value: Enhanced adsorption, structural stability, and energetic coupling; early hubs for precursor chemistry.

PPF-Meaning Category:
Resonant Modes → Preferred Adsorption

Resonant modes arise in dimers when specific distances and orientations amplify electromagnetic frequencies. Functionally, they lead to reliably increased adsorption of small molecules. Pragmatically, the dimer acts as a constructor that forms, maintains, and regenerates these adsorption windows under fluctuation. In the macro-ε-machine, the system returns to the same adsorption attractor despite varying microstates.
Syntax: Recurrent patterns of enhanced resonant modes in the fluctuation spectrum.
Semantics: “Resonant modes mean increased adsorption” - stable correlation between mode amplification and molecular attachment.
Functional value: More efficient adsorption, improved precursor chemistry, and faster local reaction kinetics.

PPF-Meaning Category:
Field Gradient → Preferred Proton Transfer

Field gradients created by mode selection concentrate protons in the gap and are a key functional feature. They arise through quantum-field-driven proton focusing and rest on stable syntactic patterns of damping and mode selection. Semantically, they represent facilitated proton transfer. Pragmatically, they create a proto-chemiosmotic space in which proton flow is more ordered than in isolated protocells. Such gradient zones act as energetic constructors because they repeatedly shape and stabilize reaction profiles.
Syntax: Recurrent patterns of stable field gradients and proton-focusing mode selection.
Semantics: “Field gradient means efficient proton transfer” - functional equivalence across syntactic variants.
Functional value: Improved energetics of simple redox and pH-driven reactions; proto-chemiosmotic precursors.

PPF-Meaning Category:
Energetic wells → Transfer Windows

Energetic wells form when dimers or tetrahedra generate local potential minima. These regions open transfer windows that ease passage or accumulation of specific molecules. Their syntactic patterns vary, but their functional impact remains stable. Pragmatically, these minima act as recurring resonance and transport zones and represent early proto-molecular channels in both pair and cluster geometries.
Syntax: Recurrent profiles of local potential minima in the near field of dimers or tetrahedra.
Semantics: “Energetic wells mean transfer windows” — consistently increased exchange and permeation probabilities.
Functional value: Earliest form of a proto-molecular channel; facilitated material transport between protocells.

PPF-Meaning Category:
Synchronization Mode → Cluster Stability

In larger clusters, pragmatics appears in collective attractors with new functional roles. When coupling strength integrates several protocells, synchronization modes arise that generate correlated oscillations across the assembly. These syntactically coherent patterns correspond semantically to increased cluster stability. Pragmatically, they reduce dissipation because synchronized membrane dynamics enable more efficient exchange processes. The macro-ε-machine thus captures a functional model that exceeds the sum of individual vesicles.
Syntax: Correlated oscillatory field modes that reproduce across multiple protocells.

Semantics: "Synchronous mode means cluster stability" - robust convergence to coherent dynamics.
Functional value: Reduced dissipation, more stable material cycles, coordinated adaptation to external fluctuations.

PPF-Meaning Category:
Interference Patch → Reaction-Enhancing Zone

Local interference patches ("hotspots") amplify selected electromagnetic modes and create energetic concentrations that promote reactions. Syntactically, they appear as stable condensation patterns; semantically, as zones of increased reactivity. Pragmatically, they function as recurrent reaction nodes: the cluster acts as a constructor that generates, stabilizes, and renews favored chemical microenvironments.
Syntax: Localized hotspots of energetic concentration stabilized by overlapping near fields.
Semantics: "Hotspot means reaction-enhancing zone" - strong coupling to increased adsorption and molecular retention.
Functional value: Local heating, higher reaction turnover, efficient chemical microdomains.

The proto-pragmatic-functional architecture of protocell systems thus emerges from the ability of dimers and tetrahedra to repeatedly occupy stable functional states. Macro-ε-machines formalize these emergent patterns, while Construction Theory clarifies their role as physical task realizers. At this level, the transition from physical fluctuation to proto-biological functionality begins: clusters become carriers of energetic, material, and informational tasks — early precursors of biological action systems.

VIII. Answering the Research Questions

RQ#1 Syntax: How does Casimir–Lifshitz coupling generate recurrent, predictable patterns describable by ε-machines?

Casimir–Lifshitz coupling generates syntax by constraining initially broadband thermal fluctuations into a restricted set of recurrent field and gap configurations that are well captured by ε-machines. In dimers, tetrahedra, and higher-order clusters, nanometre-scale gaps filter the mode spectrum and produce characteristic fluctuation and proton-density profiles that reappear with high frequency, so that Computational Mechanics reconstructs a small set of causal states with structured transition probabilities rather than a featureless noise process. These ε-states and their transitions define the syntactic layer: the minimal predictive patterns imposed by geometry, material parameters and field-mediated coupling.

RQ#2 Semantics: Under which physical conditions do these syntactic patterns become functional categories with stable consequences for proton distribution, permeability, or adsorption?

Semantics arises when subsets of these syntactic states are lumped into macrostates that share the same physico-chemical consequences. Under prebiotic saline conditions, different microscopic fluctuation patterns can produce indistinguishable proton-focusing profiles, adsorption propensities, or permeability shifts in the gap; such ε-states form semantic classes because they lead to the same outcome distributions for observables such as proton density or local reaction rates. In this view, meaning corresponds to energetic invariants: a semantic category is defined not by symbolic labels but by the robustness of its functional effects across underlying syntactic variability.

RQ#3 Pragmatics: How do entire protocell clusters form emergent macro-ε-machines that perform reproducible tasks in the sense of Construction Theory?

At the pragmatic level, entire dimers and tetrahedral clusters behave as macro-ε-machines whose states are cluster geometries and collective field configurations, and whose transitions implement reproducible tasks in the sense of Constructor Theory. Stable Casimir–Lifshitz attractors support repeated execution of proton focusing, adsorption enhancement, or exchange-channel formation without loss of cluster functionality, so that these aggregates qualify as prebiotic partial constructors. In this way, protocell clusters realize a proto-pragmatic architecture: from constrained fluctuations to syntax, from functional invariance to semantics, and from cluster-level attractors to emergent task spaces that constitute an early, fully physical notion of meaning before genetics.

IX. Conclusion and Future Work

This final section summarizes the conceptual contributions of the framework, situates the results within current origins-of-life research, and outlines experimentally and theoretically accessible directions for further investigation.

A. The Physical Emergence of Early Proto-Biological Information and Meaning

This work shows that prebiotic protocell assemblies can develop a structured, information-bearing organization even in the absence of genes, enzymes, or metabolic networks. The present study is conceptual and does not aim at a full numerical reconstruction of ε-machines; instead, it identifies the physical conditions under which syntactic, semantic, and pragmatic structures necessarily emerge.

Low-entropy structural order alone, such as crystalline lattices (e.g., NaCl), does not constitute information or meaning in the present sense. Information requires multiple reproducible macrostates with distinct future consequences and meaning requires that such differences gate physical tasks; crystalline systems realize a single attractor state and therefore lack informational and functional differentiation.

Unlike agent-based or viability-centered notions of semantic information [15], the present approach grounds meaning entirely in physical task realizability.

Casimir–Lifshitz coupling does more than merely stabilize protocell aggregates: it shapes the fluctuation landscape in nanometer-scale gaps, producing recurrent patterns, functional invariances, and collective attractors. From these physically constrained dynamics, syntactic, semantic, and pragmatic layers of proto-biological organization emerge in a unified manner.

Within this framework, syntax arises from ordered fluctuation patterns captured by ε-machines, semantics from functional invariance under syntactic variability, and pragmatics from cluster-level tasks reproducibly executed by macro-ε-machines. Meaning is therefore not introduced symbolically or biologically, but emerges as a physical property of structured, field-mediated interactions. Information precedes replication, and function precedes biochemistry.

This perspective complements existing origins-of-life models [15] that emphasize chemical or metabolic closure by identifying a prior stage of organization: closure at the level of physically stabilized task spaces. Protocell clusters act as prebiotic partial constructors in the sense of Constructor Theory, repeatedly realizing tasks such as proton focusing, adsorption enhancement, and exchange-channel formation without molecular machinery. Functional organization thus originates in field-structured geometries before genetic encoding becomes possible. By identifying field-structured task spaces as a precursor to biochemical organization, this framework offers a physically testable bridge between prebiotic physics and the emergence of biological function.

B. Future work

The framework developed here is experimentally and computationally accessible. ε-machines of syntactic fluctuation patterns can be reconstructed using near-field measurements, optical tweezers, pH-sensitive microsensors, and finite-element simulations of Casimir–Lifshitz interactions. Microfluidic platforms enable controlled assembly of protocell dimers and clusters, allowing systematic mapping of attractor landscapes and functional task stability.

At a theoretical level, future work should further integrate Computational Mechanics and Constructor Theory to characterize which macrostates qualify as constructors and how proto-pragmatic task spaces scale with cluster size and environmental complexity. Such integration may clarify the transition from field-mediated task organization to chemically driven metabolic networks.

More broadly, this approach suggests a revised narrative for the emergence of proto-liveliness: information is instantiated as reproducible field structure in confined gaps, while meaning and function emerge only at the cluster level—from field ordering imposed by geometric embedding and constrained by Casimir–Lifshitz boundary conditions across the coupled network of intermembrane spaces.

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