Membranes as the Earliest Entropy Resisting Structures in the Origin of Life

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A systems science perspective on boundary formation, local order, and life's emergence

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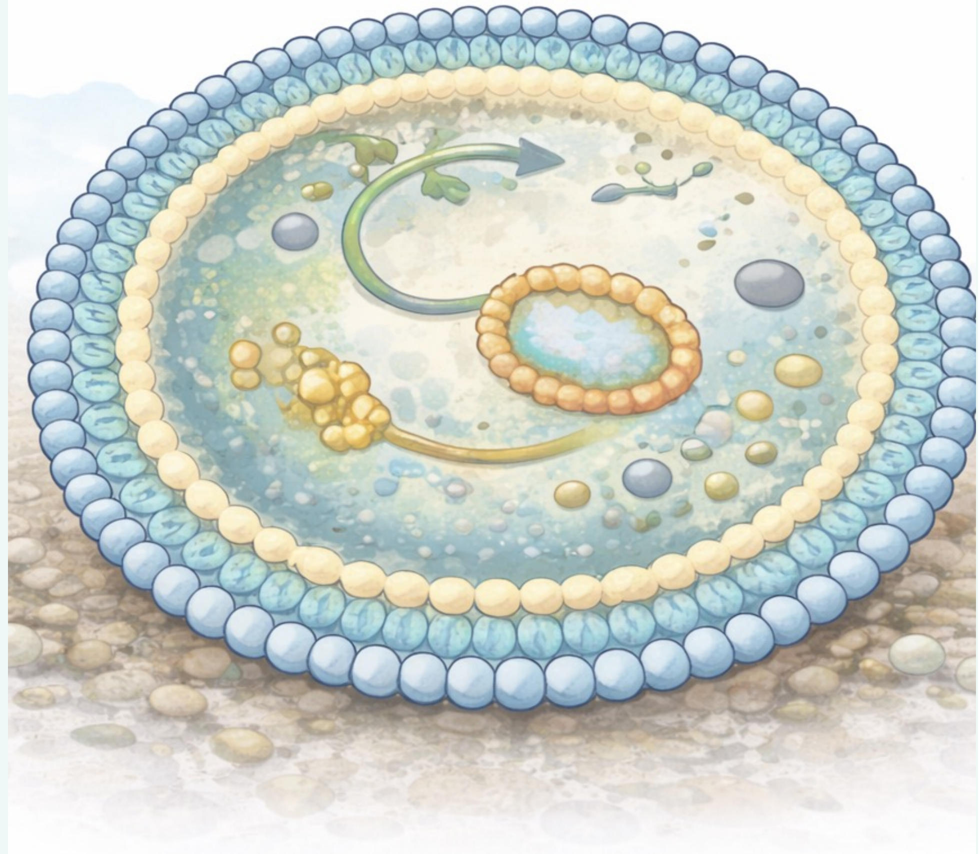


CRITICAL QUESTION

When does death becomes irreversible?

- Loss of homeostasis
- Metabolic activity stops
- Breakdown of genetic control mechanisms

STILL REVERSIBLE

- The decisive event is not a single ‘death molecule,’ but the collapse of the processes that preserve the membrane as a boundary.
- Once the boundary can no longer sustain selective permeability, gradients, and structural coherence, the system crosses from recoverable dysfunction to irreversible disintegration.”

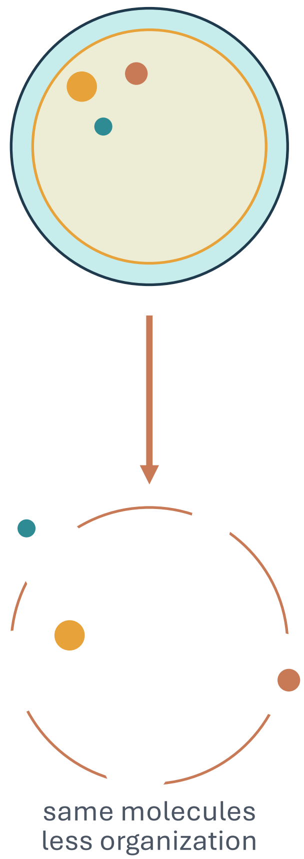
IRREVERSIBLE

OPENING QUESTION

“When a cell dies its chemistry may still be present but its boundary no longer sustains organized life”

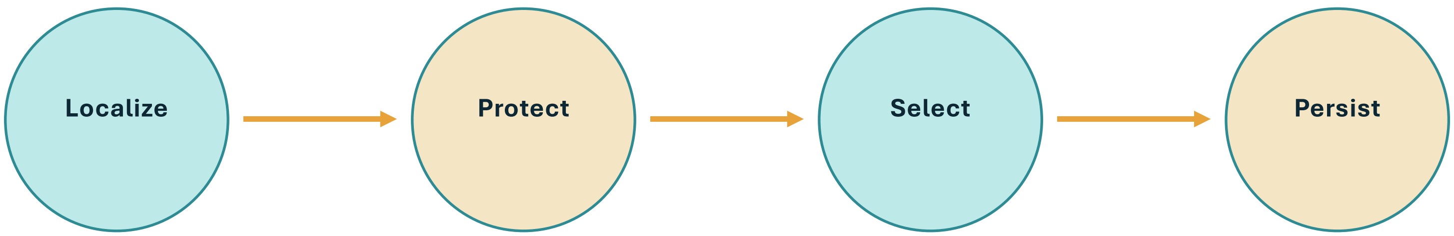
- Living systems maintain a low-entropy state in an open environment.
- Unlike inanimate systems, they sustain intricate molecular organization by constantly exchanging energy and materials with their surroundings.
- This capacity depends critically on the integrity of biological membranes: regulate the selective transport of molecules, maintain ion gradients, and provide a controlled reaction space for biochemical processes

- The puzzle is not chemistry alone
- The puzzle is organized persistence
- Membranes make persistence spatially possible



The thesis in one sentence

Before genetic evolution could stabilize information, and before metabolism could persist as a network, some boundary had to localize, protect, select, and maintain order.



Membranes are not life itself. They are a plausible early enabling architecture for life-like organization.

Membrane-bounded compartments have the capacity to sustain chemical differentiation over time under flux (e.g., cycling, gradients), thereby creating the preconditions for continued organization and selection-like persistence.

A route through a complex origin-of-life question

1. **The puzzle**
   Life as organized persistence
2. **The landscape**
   RNA first
   Metabolism first
   Membrane first
3. **The hypothesis**
   Membranes as entropy resisting boundaries
4. **The systems lens**
   Boundary feedback emergence selection-like persistence
5. **What follows**
   Predictions limits and implications

Three entry points into life's origin

Each highlights a real part of the puzzle

RNA first

Information and catalysis

How could replication and heredity begin?

Metabolism first

Reaction networks and energy

How could chemical cycles become self-sustaining?

Membrane first

Boundaries and persistence

How could order remain localized long enough to evolve?

Our theory does not replace the first two.
It asks what boundary conditions made them durable.

A systems shift in the question

From components to organization

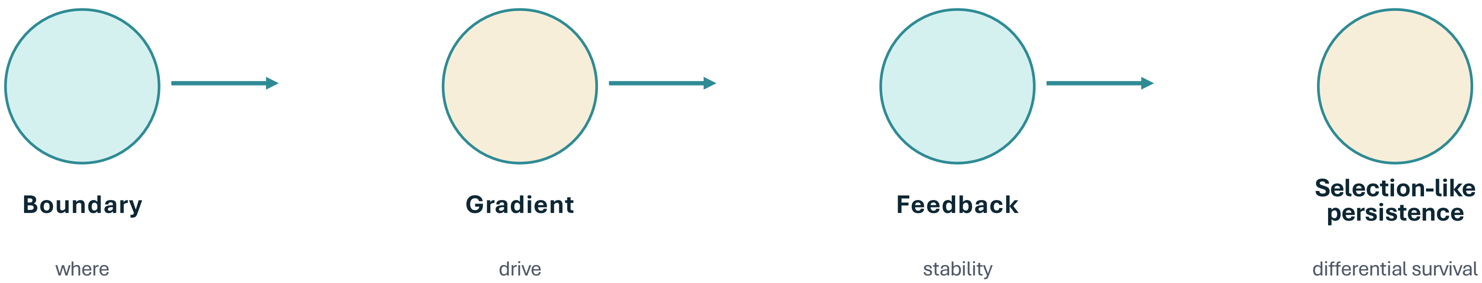
Molecule-first question

Which molecule came first?

→

Systems question

What made chemistry a persistent system?



Selection could have first acted on membranes, favoring those that:

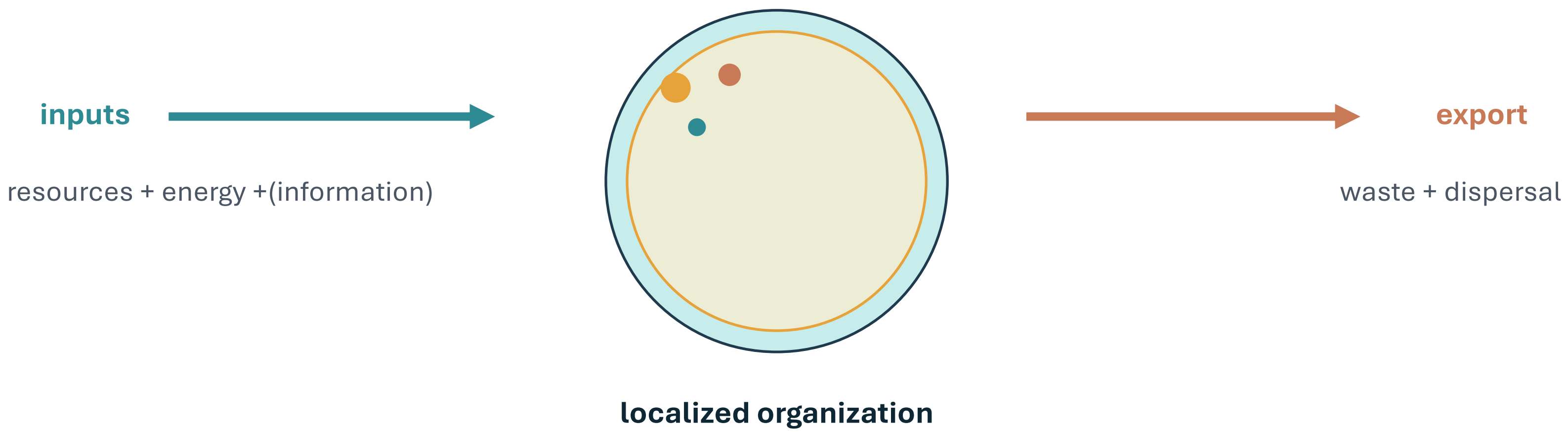
1. Maintained structural integrity longer in fluctuating environments
2. Incorporated amphiphiles that enhanced permeability for nutrient intake
3. Regulated energy gradients more effectively, enabling early metabolic-like reactions.

→ prebiotic membranes as first entities to undergo selection competing for stability and energy efficiency,

→ First “holons”

Entropy resisting does not mean violating thermodynamics

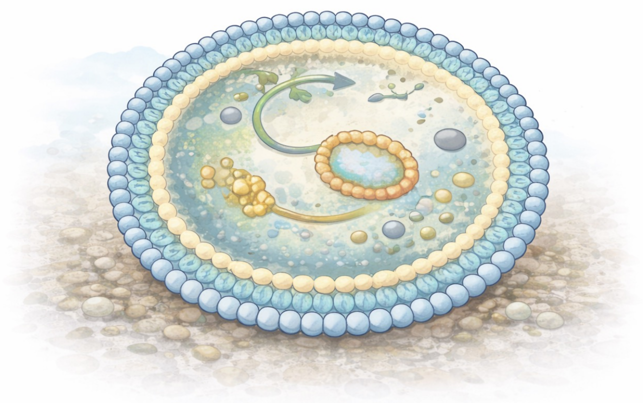
It means maintaining local order in an open far-from-equilibrium system



- Open systems can maintain local order by exchanging matter and energy
- Membranes create the inside–outside relation required for such exchange
- The hypothesis concerns early entropy resistance, not closed-system reversal

What membranes add to prebiotic chemistry

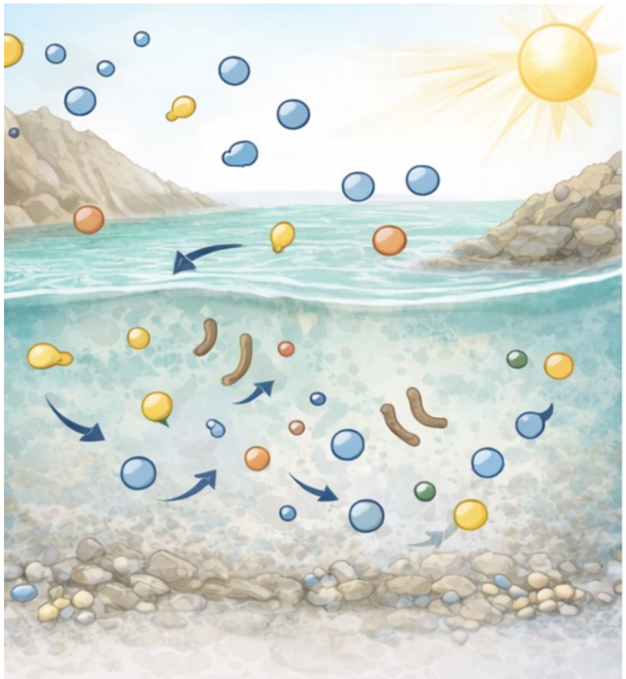
A boundary is not a passive container



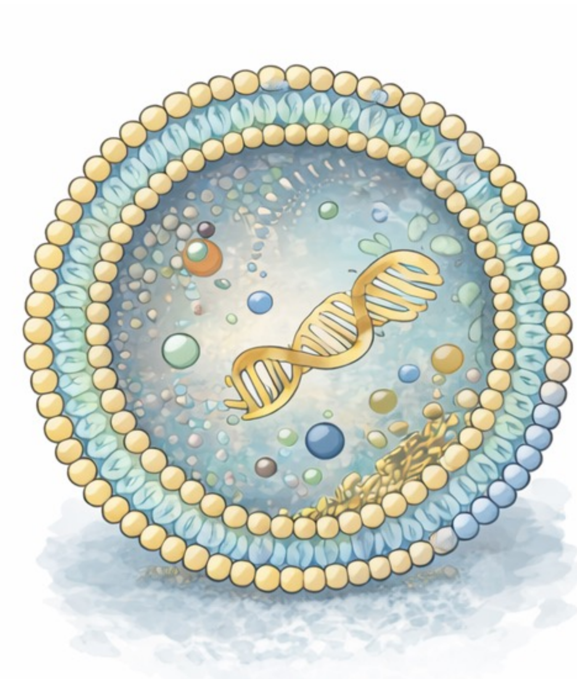
- Compartmentalization — keeps reactions together
- Selective exchange — filters flows
- Gradient support — stores difference
- Persistence — allows repeated interaction
- Differential stability — enables selection-like sorting

A membrane creates the conditions under which chemistry can become a system.

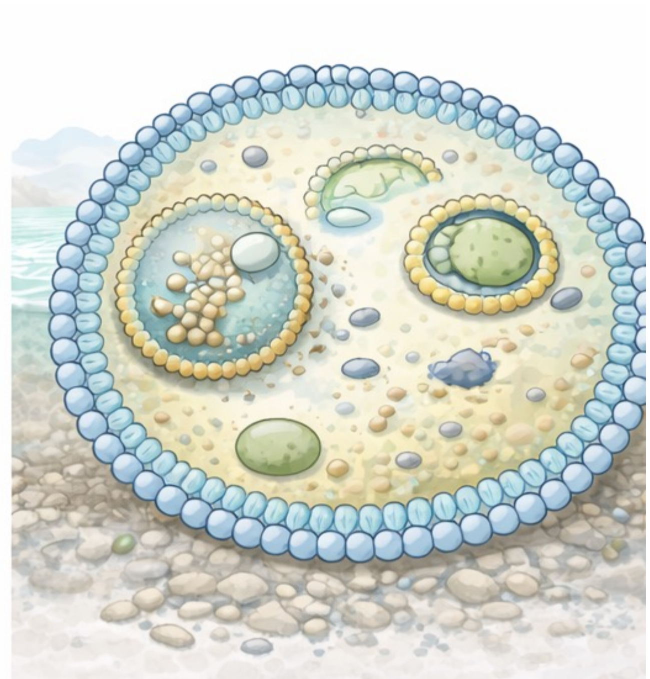
From uncontained chemistry to bounded systems



without boundary



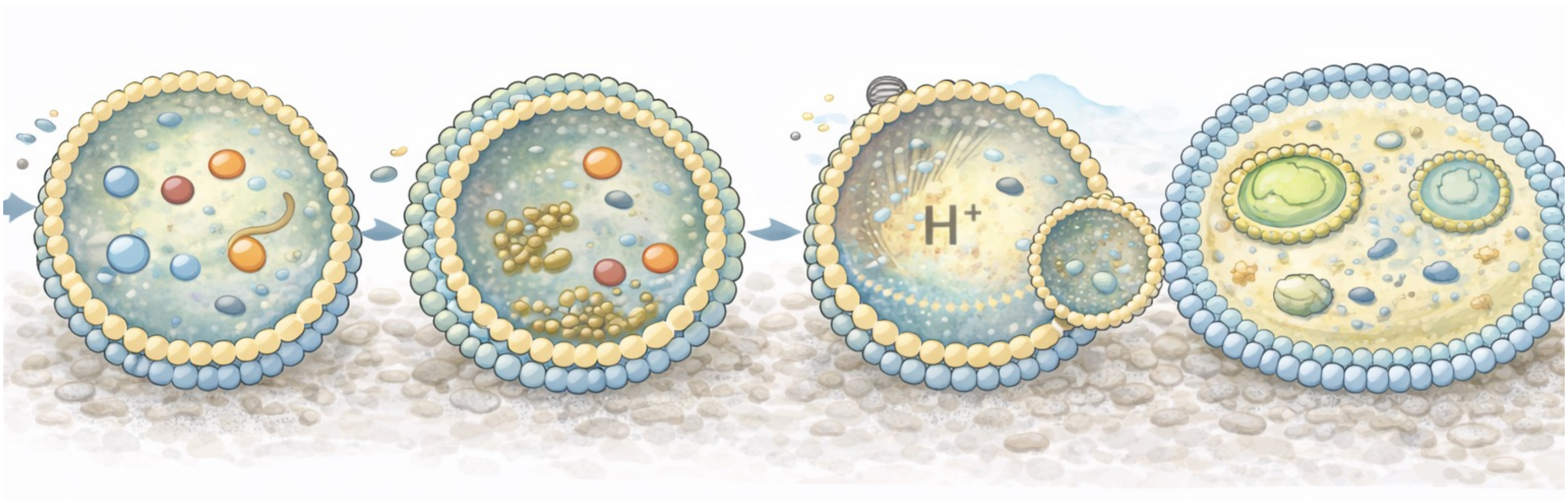
with boundary
Vesicle formations in a primordial soup



with internal organization

A plausible developmental sequence

From amphiphiles to membrane-bounded proto-organization



1 **assembly**

2 **encapsulation**

3 **gradients**

4 **growth and division**

The sequence is not a single proven pathway. It is a systems hypothesis about enabling transitions.

What the membrane-first lens adds

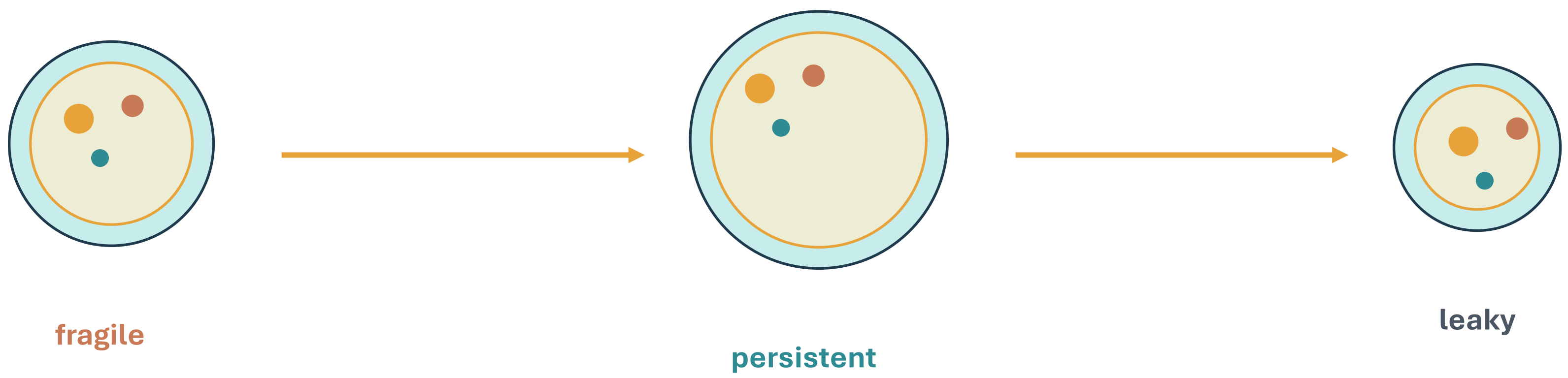
A compact comparison of three frameworks

	RNA first	Metabolism first	Membrane first
Primary focus	information	reaction cycles	bounded organization
Strength	heredity + catalysis	energy + networks	persistence + gradients
Open question	how RNA was sustained	how networks were contained	how inheritance emerged
Systems value	coding relation	metabolic coupling	inside–outside system

The membrane perspective is complementary: it asks how chemistry became locally durable.

Selection-like processes before genes

Differential persistence can begin before Darwinian heredity



- Some compartments remain intact longer
- Some retain useful molecules more effectively
- Some sustain gradients or reactions better
- These differences create pre-genetic sorting pressures

The systems-science vocabulary fits the problem

Membranes transform molecules into organized relations

Boundary

distinguishes inside from outside

Constraint

limits random dispersal

Gradient

stores organized difference

Feedback

stabilizes or amplifies patterns

Emergence

new system properties appear

Hierarchy

vesicles become substrates for higher organization

Life’s origin can be read as a transition from chemistry-in-space to system-across-time.

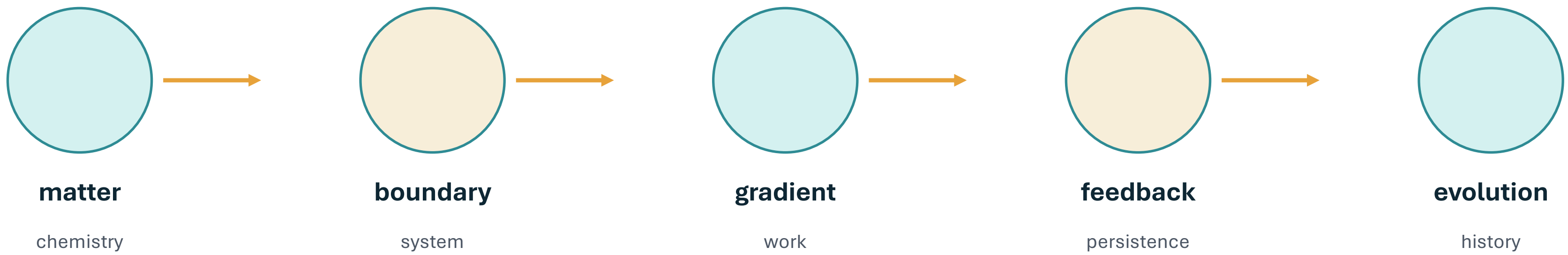
Grounding on systems science

1. **Laws of thermodynamics**: Membranes as the first entropy-regulating structures in open systems
2. **Autopoiesis**: Membranes enable self-maintaining organization prior to genetic inheritance
3. **Hierarchy and complexity**: Membranes create the first nested modular system (multi-level selection)
4. **Cybernetics**: Membranes introduce internal regulation and early selection pressures
5. **Evolutionary systems**: Membranes define the first proto-selection evolutionary unit, before molecular replication emerges

Why this matters for systems science

Origin of life as a case study in boundary-enabled emergence

Systems science contributes a language for transitions:



- ❖ It reframes life’s emergence as an organizational transition
- ❖ It connects thermodynamics with boundary formation
- ❖ It makes origin-of-life theory more explicitly systemic

Why this adds value beyond molecule-first accounts

It identifies enabling conditions rather than another privileged molecule

RNA and metabolism ask:

What began the internal machinery?

- Localization before accumulation
- Selective permeability before controlled exchange
- Gradients before bioenergetic machinery
- Compartment persistence before full heredity

Membranes ask:

What made machinery possible as a system?

A hypothesis should expose itself to possible failure

Vesicle stability →

Populations of prebiotic vesicles exposed to fluctuating environmental stresses (e.g., changes in salinity, pH, temperature, hydration cycles) should display differential persistence and growth depending on boundary composition and stability.

- ✓ Measurable distributions of vesicle lifetimes and division frequencies, with certain amphiphile mixtures becoming enriched over time.

Selective permeability →

Protocells with intermediate permeability will outperform both highly leaky compartments (which cannot maintain internal reaction networks) and overly impermeable ones.

- ➢ can be quantified experimentally by relating membrane composition to reaction yields, concentration gradients, and long-term persistence.

Gradient coupling →

Primitive membranes interacting with mineral catalysts or redox couples should, under suitable conditions, sustain localized ion or chemical gradients that bias reaction fluxes inside vesicles relative to the surrounding medium.

- ➢ Detect persistent gradient-coupled reaction rates

Compositional inheritance →

Vesicles that grow and divide while maintaining characteristic lipid or catalyst mixtures bias the properties of their progeny.

- ✓ Could be tested by tracking vesicle lineages in microfluidic or cycling environments and quantifying whether chemical compositions persist across multiple growth–division cycles.

Threshold-like behavior →

Once boundary stability, resource flux, and internal reaction coupling exceed critical values, protocells should transition sharply from transient chemical assemblies to long-lived, self-maintaining units.

- ✓ Explore broad parameter spaces may therefore reveal phase-transition-like regimes in which persistence, internal organization, and adaptive responses increase non-linearly.

What this hypothesis does not yet solve

Scientific caution is part of the argument

Lipid supply

Were enough amphiphiles available in plausible early environments?

Permeability balance

Could vesicles both retain useful molecules and admit resources?

Inheritance

How much compositional continuity is enough before genes?

Historical pathway

Many routes may have existed rather than one universal sequence

**The claim is not that membranes explain everything.
The claim is that they explain a neglected enabling level.**

What should remain 24 hours later

1. **Life is not chemistry alone** — It is organized persistence.
2. **Membranes create the inside–outside relation** — This makes local order and selective exchange possible.
3. **Entropy resistance is a systems property** — Open systems maintain local order through flows.
4. **Membranes complement RNA and metabolism** — They supply an enabling architecture, not a replacement theory.
5. **The hypothesis is testable and limited** — Its value lies in guiding better experiments and clearer theory.

Closing line:

Life may have begun when chemistry acquired a boundary capable of resisting dispersal long enough to have a history.

Thank you

Questions and discussion

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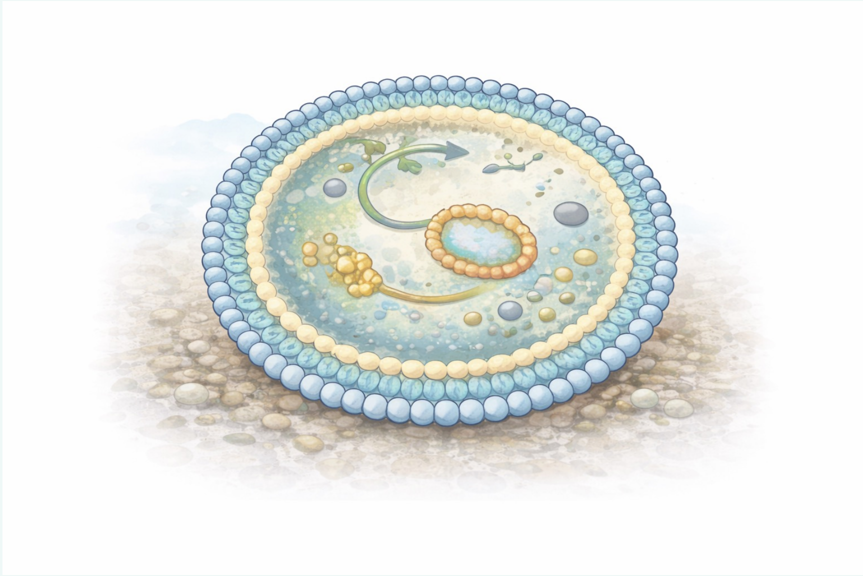

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Others' Work

Scientific caution is part of the argument

Trevors and Psenner

- Emphasized on Role of lipid membranes in early life: encapsulation
- Rather than regulatory or selective roles of membranes

We: systemic, thermodynamic, or evolutionary implications of membrane formation.

Dreamer

Boundary formation is not a late "packaging step," but a physically enabling condition that makes protocellular evolution experimentally tractable in plausible early-Earth settings.

No exclusivity

Mineral surfaces, porous geological structures, and coacervate-like systems could also have supported localized chemistry prior to cellular life.

Koestler

Membranes as the first "holons"