Mass, Entropy, and the Structural Advantages for LUCA of Protons as Charge Carriers

D.J. Goosen

August 15, 2025

Abstract

This paper proposes that the Last Universal Common Ancestor (LUCA) did not win the evolutionary lottery primarily through biochemical elegance or catalytic superiority, but through survivability under physical entropy. Specifically, the author argues that LUCA persisted because it utilized proton gradients not just for electrochemical energy, but for their mechanical and thermodynamic advantages. The mass of the proton (∼1836x that of an electron) simultaneously demanded and conferred structural stability, pressure, and thermal inertia in a chaotic prebiotic environment. These properties buffered LUCA against entropy-driven collapse. The author introduces the concept of LUCA as a "minimum entropy-budgeted replicator" and reframes proton gradients as spatial constraints that imposed structure before biological design existed. This theory extends Nick Lane's bioenergetic model by emphasizing the physical role of proton mass in early life's resilience. This framework may inform origin-of-life modeling, synthetic bioengineering, and astrobiological search strategies focused on gradient-based resilience.

Note

This paper was partially inspired by two non-academic essays by the author: *"The First Principles of AI Optimism"* and *"If I'm Wrong About AGI and UBI Has to Happen"*, which feature entropy's unavoidable effects on physical and human systems alike. Both essays were published on Substack in April 2025. Available at:

- `https://djgoosen.substack.com/p/the-first-principles-of-ai-optimism`
- `https://djgoosen.substack.com/p/if-im-wrong-about-agi-and-ubi-has`

1 Introduction

The origin of life is often approached as a biochemical puzzle, with a focus on how complex molecular systems could emerge from prebiotic conditions. One of the most compelling models in this space, championed by Nick Lane [1], suggests that life began by harnessing naturally occurring proton gradients in alkaline hydrothermal vents. These gradients provided a source of energy that could drive proto-metabolic processes before the evolution of sophisticated molecular machinery.

This paper builds on Lane's foundational model but introduces a thermodynamic dimension that remains underarticulated in the literature: the structural consequences of using a comparatively massive particle—specifically, the proton—instead of the smaller electron, as a charge carrier in early bioenergetics. Lane not only emphasizes the centrality of proton gradients in early bioenergetics, but also openly wrestles with their physical difficulty—acknowledging that proton transport is energetically costly and counterintuitive compared to electron flow. He highlights the oddity of evolution relying on protons at all, given their mass and the challenge of moving them across membranes. But he frames it as a metabolic puzzle rather than a prebiotic selection filter.

Moreover, what Lane stops short of suggesting is that these very costs may have simultaneously demanded and conferred an early consequential advantage. This paper argues that the costliness of protons was not a barrier, but a condition that selected for biological survivability under entropy. The mass of the proton—often treated as a mechanistic inconvenience—offered something electrons could not: mechanical pressure, thermal inertia, and entropy buffering. These qualities may have helped LUCA persist through instability and drift. In this view, proton mass wasn't an obstacle to overcome—it was a condition for survival in high-entropy prebiotic environments.

Lane exposed the tension. This paper proposes that the tension *was the point*.

What exerts more force rolling downhill toward a door: a bowling ball or an acorn?

The answer is obvious. And so is the consequence:

> The heavier the particle, the more force it applies in motion.
> The more force, the more structure the environment must develop to constrain it.

So ask: what kind of framing, what kind of wall, must emerge to withstand the persistent force of the bowling ball—not once, but continually?

Now ask: which of the two is more thermodynamically resilient?

- The acorn, lightweight and low-impact, is easily scattered.
- The bowling ball, with its greater mass and momentum, is harder to dislodge, harder to change.

The proton is more relatively resistant to fluctuation than the electron. As a result, the proton tends to create more of a kind of entropy buffer. Thus, using it as a charge carrier buys emergent life more time to replicate.

Which suggests:

- Proton mass wasn't a liability in the bioenergetics of early life—it was a structural forcing function.
- Life as we know it didn't just emerge under pressure—it may have emerged *because* of it.

This is the key insight Lane set the stage for. He saw the size of the proton and wondered at it.
This paper proposes: the proton's size was helping to shape the lifeform we call LUCA, while providing a buffer against entropy, long enough for that lifeform to replicate.

2 Positioning: Extending Lane's Bioenergetic Model Through Mass and Entropy

Lane's proton gradient model frames the origin of life as an energy-first problem, where ambient electrochemical gradients powered early metabolism [2]. He accepts that LUCA likely emerged in vent environments where such gradients were stable and abundant, and that energy dynamics preceded genetic encoding.

While Lane [1] treats protons as charge carriers generating voltage for LUCA, this paper highlights an underexamined property: *mass*. Protons are $\sim$1836 times more massive than electrons. In chaotic prebiotic environments, that mass had consequences.

This paper proposes that proton mass contributed to:

- Osmotic and mechanical pressure, imposing compartmentalization
- Thermal inertia, stabilizing reactions against fluctuation
- Entropy buffering, allowing partial failure without systemic collapse

This reframes LUCA as the first structure to persist—not due to elegance or efficiency—but because it could survive long enough for evolution to take over. It wasn't just powered by proton gradients. It was *shaped* by them.

3 The Problem with Electrons

Electron-based redox chemistry dominates modern metabolism, but electrons present serious challenges for prebiotic survival:

- They tunnel, radiate, and emit photons.
- They require specific carriers to control.
- They are highly reactive, easily excited.

These properties make electrons efficient charge carriers in evolved systems—but fragile in chaotic environments. Any early prebiotic systems built on electron transport likely collapsed under their own volatility.

The infinitesimal electron defies position. You can never know where it is going to exist in spacetime.

The proton, while also being delocalized and probabilistic, has far fewer "places" to hide within an atom. Thus you can better approximate where it may exist at any moment in spacetime.

And in the earliest biological systems, it may not have been the relative ease of movement of a charge carrier that mattered most for long-term survival—it may very well have been the relative *resilience* of that charge carrier.

4 The Structural Consequences of Proton Mass

Protons, comparatively, are:

- More massive, creating mechanical pressure.
- More predictable, hopping through water in constrained paths.
- More thermally inertial, storing heat and resisting fluctuation.
- More constrained, reinforcing spatial boundaries through charge and force.

Where electrons react, protons resist. Their pressure across a membrane or porous structure isn't just electrical—it's *physical*.

While other ions such as sodium (Na^+) and potassium (K^+) are also common in biological systems and participate in membrane transport in modern cells, they do not possess the same combination of physical and chemical properties that make protons uniquely suited as early charge carriers. Protons are both highly abundant in hydrothermal vent environments and exceptionally small in mass and ionic radius, allowing them to move rapidly through aqueous media and across narrow boundaries via the Grotthuss mechanism.

Unlike larger cations, protons contribute not only to electrochemical gradients but also impose meaningful mechanical pressure due to their mass-to-charge ratio and high local concentration. Additionally, the ubiquity of proton gradients across extant life forms suggests a deep evolutionary entrenchment that likely reflects early selective advantages in entropy-buffered structural persistence.

5 Mass as Entropy Buffer

A charge-carrier's entropy resilience isn't about subatomic invincibility—it's about tolerating loss without collapse. And a proton's mass offers charge-carrier systems greater margin:

- Protons can absorb more perturbation than electrons.

- Protons can persist better through wobble than electrons.
- Protons can also hold gradients longer than electrons, delaying equilibrium.

LUCA likely wasn't the most energy-efficient emergent lifeform. It was rather the most buffered. Using the mass of the proton as a charge carrier gave it time. This buffering function delayed thermodynamic collapse long enough for molecular recursion—replication—to stabilize.

6 Gradient as Structure Imposer

A proton gradient represents a spatial separation of charge across a boundary. This separation creates an electrochemical potential, driven by the thermodynamic tendency toward equilibrium. When proton concentrations differ across a membrane or porous interface, the system is under electrochemical pressure to equalize that imbalance.

This pressure is not abstract—it generates measurable force. The movement of protons down their concentration gradient produces directional stress on local molecular structures, especially in systems lacking evolved transport mechanisms. In such contexts, the gradient itself becomes a mechanical constraint that can shape or stabilize early structural features.

- The presence of a gradient imposes directionality and localized pressure.
- Proton flow across boundaries requires those boundaries to persist under load.
- Structural features in early systems likely emerged in direct response to this sustained electrochemical force.

When the gradient is equalized, no net force remains. The pressure drops to zero, and the system reaches thermodynamic equilibrium—functionally equivalent to a level plane with no directional work possible.

Without a gradient, the floor is level.
With a gradient, the system has slope—directional potential that can be harnessed or that must be resisted.

Proton mass amplifies this effect. Compared to electrons, protons exert more mechanical pressure through both charge and inertia. The resulting force had structural consequences. LUCA may have persisted not because it exploited this gradient more efficiently, but because its configuration could absorb and withstand this pressure long enough to maintain coherence in a high-entropy environment.

For example, a pH gradient of 3 units across a 5 nm membrane corresponds to an electrochemical potential of $\sim$177 mV (via the Nernst equation), which—when scaled to molecular surface area—imposes measurable ionic pressure on early boundary structures. This potential is non-negligible at molecular scales and supports the argument that proton gradients could physically shape prebiotic compartments.

7 LUCA as Survivor, Not Designer

The author does not contend that LUCA was the first. Instead, it was the last one that didn't die before replicating.

- It could drift and recover.
- It could endure entropy long enough to stabilize.
- Its architecture may have been shaped more by mass and pressure than by catalytic design.

This makes LUCA a thermodynamic outlier—a biologic structure that resisted decay until evolution could refine it. In this model, replication is not the origin point—it is the consequence of surviving the slope of entropy long enough to reproduce under it.

Note: Even while claiming that the proton offered evolution negentropic advantages, it is also important to acknowledge that the pH gradient between alkaline vent fluids and mildly acidic seawater creates a naturally stable proton motive force. Unlike pure water or lab solutions, seawater's ionic richness supports persistent gradients—especially favorable to proton transport.

8 Implications

- **Origin-of-Life Models:** Must account for structural pressure, not just energy potential.
- **Synthetic Biology:** Design for mass-based buffering in prebiotic analogs.
- **Astrobiology:** Search for life where mass-stabilized gradients are possible.
- **Systems Thinking:** Reassess survivability as a function of entropy resistance, not efficiency.

9 Hypothesis and Empirical Testing Pathways

Hypothesis

This hypothesis builds on prior work demonstrating the plausibility of proton gradients across natural barriers in alkaline hydrothermal systems, where mineral membranes and steep pH differentials could have supported early compartmentalization and energy harvesting [3, 4, 5].

These studies support the idea that membrane-like structures, formed through mineral interfaces in hydrothermal vents, could have facilitated selective proton flow and maintained gradients capable of exerting structural and energetic constraints—consistent with the entropy-buffering framework proposed here.

Early replicating systems using more massive charge carriers (e.g., protons vs. electrons) were more resilient to entropy-induced degradation. Proton-driven systems tolerated environmental fluctuation, structural drift, and partial collapse more effectively than electron-based analogs—due to the mechanical and thermodynamic buffering effects of proton mass.

This hypothesis predicts that mass-constrained, gradient-driven systems persisted longer under high-entropy conditions and were more likely to support stable molecular recursion and replication.

Testable Pathways

1. Synthetic Protocell Experiments

Construct two types of protocell analogs:

- **System A:** Powered by proton gradients
- **System B:** Powered by electron transport chains (e.g., redox couples)

Control for:

- Membrane composition
- Environmental constraints
- Energy inputs

Measure:

- Duration of system persistence under entropic stress (e.g., thermal fluctuation, ionic interference)
- Replication fidelity or internal structure retention over time
- Tolerance to gradient collapse or perturbation

Prediction: Proton-gradient systems will show greater structural resilience and longer functional duration before collapse.

2. In Silico Simulations of Entropy Budgeting

Build computational models (agent-based or thermodynamic simulations) of minimal replicator systems:

- **System A:** Uses low-mass charge carriers (electrons)
- **System B:** Uses high-mass charge carriers (protons)

Parameters:

- Gradient strength

- Maintenance cost
- Environmental noise or perturbation rate

Outputs:

- Time to thermodynamic collapse
- Rate of replication drift or fidelity decay
- Structural entropy over time

Prediction: Systems using higher-mass charge carriers will exhibit greater entropy tolerance and slower degradation curves.

3. Comparative Bioinformatic Analysis

Mine microbial and extremophile databases for organisms that:

- Rely primarily on proton-motive force
- Inhabit high-entropy environments (e.g., hydrothermal vents, acidophilic zones, high-salinity habitats)

Search for correlations between:

- Gradient type (proton vs. electron-based energy systems)
- Traits associated with entropy resilience:
  - Mutation buffering
  - Membrane integrity
  - Starvation tolerance
  - Structural redundancy

Prediction: Proton-reliant species will exhibit more entropy-resilient phenotypes, especially in highly fluctuating or thermodynamically unstable environments.

Falsifiability: If systems using electron gradients demonstrate greater persistence under entropy than proton-based systems, this would falsify the claim.

10 Conclusion

LUCA didn't survive due to its bioenergetic efficiency. It survived because of its thermodynamic resilience. The proton didn't just power life. It created an entropy buffer for LUCA. It bought LUCA time to replicate. By shifting our attention from electrochemical abstraction to mechanical resilience, we uncover a new way to think about what is needed to energize life—and how life on Earth first held itself together.

Author's note: This paper was developed through a process of large language model-accelerated formalization. All core insights, original syntheses, and theoretical framings originated from the author.

References

[1] Lane, N. (2015). *The Vital Question: Energy, Evolution, and the Origins of Complex Life*. W. W. Norton & Company.

[2] Mitchell, P. (1961). Coupling of phosphorylation to electron and hydrogen transfer by a chemi-osmotic type of mechanism. *Nature*, 191, 144–148.

[3] Russell, M. J., Barge, L. M., Bhartia, R., *et al.* (2014). The drive to life on wet and icy worlds. *Astrobiology*, 14(4), 308–343. `https://doi.org/10.1089/ast.2013.1110`

[4] Sojo, V., Herschy, B., Whicher, A., Camprubi, E., & Lane, N. (2014). The origin of life in alkaline hydrothermal vents. *Astrobiology*, 14(2), 119–133. `https://www.liebertpub.com/doi/10.1089/ast.2015.1406`

[5] Westall, F., Hickman-Lewis, K., Hinman, N., *et al.* (2018). A hydrothermal-sedimentary context for the origin of life. *Astrobiology*, 18(3), 259–293. `https://doi.org/10.1089/ast.2017.1680`