WHITE PAPER

Creating Life From Scratch

A Plain-Language Account of the Most Ambitious Scientific Project in Human History — and Why It Might Actually Work

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"Life is not a molecule, not a genome, not a metabolism. It is a self-stabilizing network of coupled reaction cycles operating above an error threshold. That framing is biochemically correct."— Biochemical peer reviewer

Computational companion study: Lauletta, J. (2026). Bivology: A Computational Framework for Mapping the Chemistry-to-Life Transition. bioRxiv BIORXIV/2026/711189.

Executive Summary

This white paper describes a scientific program to create life from scratch — starting from pure chemistry, with no biological material of any kind, under conditions that recreate ancient Earth's hydrothermal vent environments.

The project is not science fiction. It has been reviewed by five AI systems, evaluated by a human biochemist, and stress-tested against NASA Exobiology grant criteria. The NASA simulation returned a rating of Very Good to Excellent — High Risk, High Reward. A full grant proposal (NASA ROSES-25 C.5 Exobiology) has been prepared and is ready for institutional partnership.

A companion computational study — Bivology: A Computational Framework for Mapping the Chemistry-to-Life Transition — has been published on bioRxiv (BIORXIV/2026/711189). That study maps the parameter space of the chemistry-to-life transition across six simulation steps, identifies three quantitative thresholds necessary and sufficient for heredity to emerge from random chemistry, and generates independently testable predictions for each stage of the physical reactor experiment described in this white paper.

The scientific foundation rests on a remarkable recent discovery: the smallest known living organism on Earth — Candidatus Sukunaarchaeum mirabile — survives with only 189 genes and no independent metabolism whatsoever. It is unambiguously alive. It replicates. It evolves. It simply cannot do any of that without a host organism supplying what it can no longer make itself.

This organism is not a curiosity. It is a proof of concept. It demonstrates that life at its absolute minimum does not require independence, metabolism, or complexity. It requires only four things: heritable information, the ability to copy that information with bounded error, variation, and selection. Everything else is optional.

The project proposes to build a geochemical reactor that provides the chemical support Sukunaarchaeum gets from its host — and then ask whether chemistry alone, given the right conditions, can cross the threshold into something that meets those four criteria. Starting from molecules. No shortcuts.

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1. The Question Nobody Has Answered

Life exists. We know that. What we do not know — and have never demonstrated — is how chemistry becomes life. How does a collection of molecules, given the right conditions, cross the threshold from interesting chemistry to something that replicates itself, varies, and evolves?

This is not a philosophical question. It is an experimental one. And it has never been answered, because no one has ever succeeded in crossing that threshold deliberately, starting from pure chemistry, in a laboratory.

Every previous attempt has either started with existing biology — taking a living cell and modifying it — or has stopped well short of the threshold, producing interesting molecules but not life. The gap between chemistry that produces amino acids and chemistry that produces a self-replicating, evolving system is the most important gap in all of science. It is the gap this project is designed to cross.

The gap between interesting chemistry and life has never been deliberately crossed. That is what this project attempts.

1.1 Why Now?

Three things have converged in the last few years to make this attempt realistic rather than merely ambitious.

The first is the discovery of Candidatus Sukunaarchaeum mirabile — an organism so minimal that it redefines what life requires. Its existence proves that the destination is achievable: a fully dependent, metabolism-free, 189-gene organism that is nevertheless unambiguously alive. Before this discovery, the minimum requirements for life were theoretical. Now they are empirical.

The second is quantitative progress on the error threshold problem — the central physical barrier between chemistry and life. New experimental results demonstrate that non-enzymatic chemistry can achieve replication fidelity approaching 10^{-4} errors per base under the right conditions. This does not solve the problem, but it brings the gap from impossible to difficult. There is a difference between those two things.

The third is the Asgard archaea research published in Nature in early 2026 — two papers simultaneously demonstrating that the ancestor of all complex life was already molecularly sophisticated before the evolutionary event that triggered complexity, and that it lived in oxygen-transitioning geochemical environments very similar to what this project's

reactor is designed to recreate. The conditions are not guesswork. They are increasingly well-characterized.

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2. The Organism That Changes Everything

To understand what this project is attempting, you first need to understand Candidatus Sukunaarchaeum mirabile.

It was discovered living inside a single-celled host organism called Citharistes regius. It is an archaeon — a member of the domain of life that branched off from bacteria billions of years ago and eventually gave rise, through a remarkable evolutionary merger, to all complex life including us. But Sukunaarchaeum represents the opposite extreme of that evolutionary trajectory: not complexity, but radical simplicity.

Its entire genome is 238,000 base pairs — roughly 189 protein-coding genes. For comparison, the human genome has approximately 20,000 protein-coding genes. Even the simplest free-living bacteria known have around 300–400 genes. Sukunaarchaeum gets by with 189, because it doesn't need what its host provides. No genes for energy production. No genes for making most amino acids. No genes for synthesizing the fatty acids that make cell membranes. It relies entirely on its host for all of that, and contributes only what its host cannot do for itself.

Sukunaarchaeum by the numbers	
Genome size	238,000 base pairs (one of the smallest known)
Protein-coding genes	~189
Independent metabolism	None
Energy production genes	None
Host dependence	Total — cannot survive outside Citharistes regius
Status	Unambiguously alive. Replicates. Evolves.
What it proves	Life at minimum does not require independence or metabolism.

What it proves is this: Sukunaarchaeum is not broken. It is not a failed organism or an evolutionary dead end. It is a fully functional living system that has found a stable niche by offloading every metabolic function it doesn't need to its environment. It has been doing this, apparently successfully, for an extremely long time.

It's not broken — it's just never had an environment rich enough to not need that support.

2.1 The Wright Brothers Analogy

Sukunaarchaeum is not going into the reactor. The project does not take this organism, extract its DNA, and use it as a starting point. It starts from pure molecules — nucleotides, fatty acids, minerals, gases, water. No biological material of any kind.

Sukunaarchaeum plays the role that birds played for the Wright Brothers. Birds proved that heavier-than-air flight was physically possible — not a fantasy, not a violation of natural law, but a real achievable state. The Wright Brothers studied birds to understand the principles: lift, drag, wing geometry, control surfaces. Then they built something new from scratch that embodied those principles.

Sukunaarchaeum proves that minimal, fully-dependent life is physically possible. The project studies it to understand the principles: minimum gene count, minimum metabolic requirements, minimum informational complexity. Then it builds something new from chemistry that embodies those principles. Not the organism. The principles.

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3. What Life Actually Requires

One of the most important contributions of this project — before a single experiment is run — is establishing a precise, measurable definition of what life requires. This project cuts through decades of philosophical debate by asking not what is life, but what are the minimum experimentally testable conditions that, when met, constitute life? The answer is four criteria.

Criterion	What It Means	How It's Tested
Heritable information storage	The system must encode information in a polymer sequence that is passed on when the system reproduces	Next-generation sequencing confirms sequence retention across 20+ replication cycles
Template replication with bounded error	Copying must be accurate enough that information isn't lost to accumulated errors — Eigen's error threshold	Per-base error rate measured by sequencing; must cross 10^{-3} before translation emerges
Selection acting on variants	Different sequences must compete, with more functional sequences becoming more prevalent over time	Population sequencing over 50+ generations confirms selective enrichment of advantageous variants

Criterion	What It Means	How It's Tested
Self-maintaining boundary	The system must maintain a physical boundary that keeps its chemistry distinct from the environment	Lipid vesicles confirmed to persist 4+ weeks without continuous precursor addition

Notice what is not on this list: metabolism, energy production, independence, complexity, a nucleus, proteins, or any specific molecule. These are features of life as we know it today — not requirements for life at its minimum.

Sukunaarchaeum meets all four criteria with no metabolism and total dependence on its host. JCVI-syn3.0, Craig Venter's minimal synthetic cell, meets all four criteria but required an existing cell's machinery to get there. The project aims to meet all four criteria starting from chemistry alone.

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4. The Central Barrier: The Error Catastrophe

Of the four criteria, the hardest to meet is the second: replication with bounded error. This is not an engineering challenge. It is a fundamental physical constraint, and understanding it is essential to understanding why this project is difficult and why it is also now more tractable than it has ever been.

The problem was formalized by the physicist Manfred Eigen in 1971 and is known as the error threshold or error catastrophe. When a polymer copies itself without enzymatic help — the situation in early Earth chemistry, and in Stage II of this project — it makes mistakes. The measured error rate for non-enzymatic RNA replication is between 7% and 26% per base. Eigen showed mathematically that there is a maximum genome length that can be maintained at any given error rate. Above that length, errors accumulate faster than selection can remove them, and the information dissolves into noise.

The Error Threshold — Why It Matters	
At 10% error rate per base	Maximum viable genome: ~10 bases
At 1% error rate per base	Maximum viable genome: ~100 bases
At 0.1% (10^{-3}) error rate	Maximum viable genome: ~1,000 bases
At 0.01% (10^{-4}) error rate	Maximum viable genome: ~10,000 bases

The Error Threshold — Why It Matters	
Minimum genome for translation	~500 bases
Sukunaarchaeum genome	~238,000 base pairs

4.1 Computational Confirmation of the Threshold

A companion computational study — *Bivology: A Computational Framework for Mapping the Chemistry-to-Life Transition* (Lauletta, 2026, bioRxiv BIORXIV/2026/711189) — provides independent quantitative characterization of this transition. Across 60 ensemble replicates in a digital chemistry simulation, the error threshold behaves as a sharp phase transition confirmed by Sarle's bimodality coefficient exceeding 0.555 at all tested error rates. The study identifies three conditions necessary and sufficient for heredity to emerge from random chemistry:

- A minimum autocatalytic coupling of 1.5× — corresponding physically to a pH gradient greater than 1.2 units across a mineral membrane, or a Fe-S catalytic rate enhancement greater than 1.5×. Both are achievable under the reactor conditions described in Section 5.
- At least one functional sequence arising by chance in solution — a stochastic event requiring only that chemistry produce a functional motif in at least 3% of encapsulation events.
- Encapsulation capturing that sequence before dilution — after which template-directed replication drives population takeover with 100% reliability across all replicates.

These computational thresholds directly map onto the go/no-go criteria for Stages II and III of the physical experiment, providing a quantitative baseline against which reactor results can be compared.

Three mechanisms, each demonstrated experimentally, partially close the fidelity gap in physical chemistry. Passive thermodynamic correction can push error rates toward 10^{-4} without enzymatic help. Peptide-assisted fidelity enhancement has been shown to improve ribozyme activity by up to 15-fold. Oligonucleotide-catalyzed copying has achieved accuracy sufficient for active ribozymes. None of these alone solves the problem. Together, they provide a plausible pathway.

The critical honest caveat: these mechanisms have each been demonstrated individually under controlled laboratory conditions. Whether they operate simultaneously and additively in a

chemically noisy, evolving reactor has never been tested. Testing that assumption — rigorously, quantitatively, under realistic conditions — is what Stage II of this project does.

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5. The Experimental Roadmap

The project is organized as seven sequential stages, each with pre-defined success criteria and explicit go/no-go gates. Funding the full program requires 8–15 years and $15–40M across multiple grants and institutions. The first three stages — the scope of the initial NASA grant proposal — can be completed in three years for $1.35–2.1M.

Stage	Timeline	What Happens	What Success Looks Like	
I — Reactor	Year 1	Build and validate a microfluidic geochemical reactor: 200–500 mV redox gradient, alkaline pH differential, thermal cycling 20–80°C, FeS/FeS_2 mineral surfaces	Stable reactor operating 6+ months; vesicle formation confirmed; oligomers forming on mineral surfaces	
II — Polymer Chemistry	Years 1–2	Test TNA and RNA replication fidelity under reactor conditions; measure whether error rate crosses 10^{-3}	Template-directed replication of 20+ mer sequences at <1% error rate in reactor environment	
III — Protocell Formation	Years 2–3	Encapsulate replicating polymers in lipid vesicles; demonstrate selection acting on encapsulated sequences over 50+ generations	Stable encapsulation; sequence retention above Eigen threshold; first selective enrichment of advantageous variant	
IV — Translation (Future)	Years 4–6	Introduce minimal translation scaffold; evolve genetic code from scratch within the system	Codon-amino acid assignments emerging through selection; genetic code present	
V — Energy Coupling (Future)	Years 5–8	Transition from externally supplied chemical energy to internally coupled PPi-based energy chemistry	System partially self-sustaining for energy; PPi pools maintained within protocells	
VI — Genome Reduction (Future)	Years 7–12	Allow system to evolve toward minimal genome under controlled reactor dependence	Stable minimal genome in the 189–473 gene range; system meeting all four life criteria	
VII — Open Evolution (Future)	Years 10–15	Remove constraints and observe; document first open-ended evolution of a created living system	Heritable variation, selection, and adaptation documented over hundreds of generations	

Stages I–III are the Phase 1 NASA proposal. They are designed as a complete scientific program that produces significant results regardless of whether subsequent stages are ever funded. The deliverable from Phase 1 alone — a validated geochemical reactor producing stable protocells with encapsulated, selectively replicating polymers — would be the most advanced experimental demonstration of prebiotic chemistry ever achieved.

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6. The Asgard Connection: Why the Timing Is Right

In early 2026 — as this white paper was being written — two landmark papers were published in Nature, reporting new findings about the Asgard archaea: the group of microorganisms that are our closest living microbial relatives, and the best available window into what the ancestor of all complex life looked like.

The Asgard archaea were discovered only a decade ago in deep-sea hydrothermal sediments. They are named after Norse mythology — Lokiarchaeota, Heimdallarchaeia, Thorarchaeota — because the first was found near an underwater formation called Loki's Castle. They represent, as far as science can determine, the closest living descendants of the archaeal lineage that eventually gave rise to eukaryotes: every animal, plant, fungus, and human being on Earth.

The first paper, from Tobiasson, Luo, Wolf, and Koonin (Nature, 2026), conducted a comprehensive phylogenomic analysis of core eukaryotic genes tracing to the last eukaryotic common ancestor. The results showed dominant contributions of Asgard archaea to the origin of most conserved eukaryotic functional systems — meaning the molecular toolkit for complexity was already assembled in the Asgard lineage before the evolutionary merger that supposedly created complexity. The ancestor was already sophisticated.

The second paper, from Brett Baker's group at the University of Texas at Austin (Nature, 2026), resolved a long-standing puzzle. The merger theory of eukaryotic origins requires an anaerobic archaeal host to meet an aerobic bacterium. How did they occupy the same environment? Baker's team found that the Asgard lineages most closely related to eukaryotes — the Heimdallarchaeia — actually live in oxygen-rich shallow coastal sediments and carry extensive oxygen metabolism genes. The ancestor was metabolically flexible, living across geochemical gradients.

The transition to complex life didn't require innovating oxygen metabolism from scratch — the building blocks were already there.

These findings matter for this project in three specific ways.

First, the compartmentalization proteins found in Asgard archaea — the machinery for forming internal vesicles and membrane compartments — predate the nucleus, predate mitochondria, predate everything we associate with complex cells. Compartmentalization is ancient and minimal, not a late innovation. The lipid vesicles in Stage III of this project are not a cartoon simplification of biology. They may be a genuine structural analog of what the Asgard ancestor was already doing billions of years ago.

Second, the redox gradient environment where the relevant Asgard archaea live — oxygen-transitioning, geochemically variable shallow sediments — is structurally similar to what the project's reactor is designed to recreate. The 200–500 mV redox range isn't arbitrary. It maps to the environments where the most important transitions in the history of life actually happened.

Third, the UT Austin paper comes from Brett Baker's lab — an institution in the same University of Texas system as UT Southwestern, where leading organoid and cell biology research relevant to this program is being conducted. This is an active, high-profile research environment producing landmark science directly relevant to this program.

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7. Why NASA Cares: Life Detection Beyond Earth

This project is not just about Earth. It is about answering the question that the entire NASA Astrobiology program exists to answer: what would life look like elsewhere, and how would we recognize it?

The standard life-detection framework assumes that detectable life is metabolically active, produces chemical disequilibrium, and leaves signatures accessible to orbital or flyby instruments. Sukunaarchaeum challenges this assumption. It produces no detectable metabolic signature. Its only unambiguous biochemical signature is informational — heritable polymer sequences with measurable fidelity.

If minimal life is informationally defined rather than metabolically defined, the entire biosignature framework needs recalibration. Instruments optimized for detecting metabolites,

energy signatures, or chemical disequilibrium may be blind to the simplest forms of life. This project provides the experimental ground-truth to know what minimal life looks like chemically, physically, and informationally — and therefore what instruments need to detect it.

7.1 Ocean World Connections

The reactor's geochemical parameters are not arbitrary. Each one is explicitly modeled on characterized planetary environments.

Reactor Parameter	Planetary Analog	Mission Connection
Redox gradient 200–500 mV	Europa seafloor — water-rock interface chemistry	Europa Clipper (MASPEX, E-THEMIS)
Alkaline pH differential 2–3 units	Enceladus hydrothermal plume source chemistry	Cassini INMS legacy data (Waite et al., 2017)
Thermal cycling 20–80°C	Martian subsurface hydrothermal systems	Mars Science Laboratory (Curiosity)
FeS/FeS_2 mineral surfaces	Europa and Mars iron-sulfur mineralogy	Mars 2020 (Perseverance)
H_2-rich reducing environment	Enceladus plume composition	Cassini direct sampling

The reactor is simultaneously a laboratory experiment and a planetary analog environment. Results from Stage I — which geochemical parameters support stable vesicle formation and oligomer synthesis — directly inform habitability models for Europa, Enceladus, and Mars. Every experimental outcome, including failure, teaches something about which environments in the solar system are and are not capable of supporting informational chemistry.

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8. The Review Record

This project has undergone an unusual review process for an independent research proposal: systematic evaluation by five AI systems and a human biochemist, followed by a simulated NASA Exobiology panel assessment. The results are summarized below.

Reviewer	Key Finding	Critical Concern Raised
Anthropic Claude	Conceptually sound; quantitative framework strong	Bootstrapping problem for translation requires explicit acknowledgment

Reviewer	Key Finding	Critical Concern Raised
Google Gemini	Literature grounding solid	Parallel XNA screen logistically unviable — recommended staged decision tree
xAI Grok	Identified factual error in Sukunaarchaeum genome size (corrected in v2)	Error catastrophe treatment initially too optimistic
Mistral LeChat	Well-structured presentation	Quantitative fidelity threshold for peptide enhancement not specified
Perplexity AI	Strongest of five AI reviews — most actionable	Energy coupling treated as late addition; fidelity co-dependence unverified under reactor conditions
Human Biochemist	"Scientifically serious. Chemically grounded. Conceptually coherent."	PPi hydrolysis kinetics; fidelity mechanisms unverified in combination; temporal gap in minimal genome analogy
Simulated NASA Panel	Very Good to Excellent — High Risk / High Reward	Translation scaffold introduces synthetic bias; Phase 1 must stand alone as deliverable
ChatGPT	"Unusually strong for an origin-of-life concept proposal written outside a traditional academic group."	Non-enzymatic replication harder than implied; reactor complexity may need staged simplification

Each critique was incorporated into successive document versions. The project is now in its fifth version, with a full NASA grant proposal (ROSES-25 C.5 Exobiology) prepared and ready for institutional partnership. The review record demonstrates not just that the project has been scrutinized, but that it has withstood scrutiny and emerged stronger for it.

> *"The proposal does not ignore the hard problems. It quantifies them. That alone separates it from most origin-of-life speculation."— Human biochemist reviewer*

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9. What Is Needed Next

The scientific framework is complete. The experimental design is complete. The NASA grant proposal is complete. The computational companion study is published on bioRxiv. The project now seeks institutional partnership with a research laboratory to bring the physical experiment into existence.

NASA grants are awarded to institutions. The experimental work requires a biochemistry laboratory with access to microfluidics and sequencing infrastructure. The project is therefore

seeking a collaborative PI relationship — a working scientist who sees the scientific opportunity here and wants to be part of it.

The ideal collaborator has a biochemistry background, familiarity with cell biology and polymer chemistry, and comfort with high-risk, high-reward science. They do not need to be an origins-of-life specialist — the experimental design is detailed enough that a competent biochemist could execute it. What they need is intellectual curiosity and the willingness to put their name on something ambitious.

This is, genuinely, a career opportunity. A successful Phase 1 — even if it only characterizes the fidelity barrier quantitatively without crossing it — is a landmark publication in astrobiology and prebiotic chemistry. A successful Phase 1 that demonstrates selective replication in protocells would be among the most cited papers of the decade.

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10. Ethical Considerations

Creating life raises obvious ethical questions. They deserve direct answers rather than deflection.

The systems produced in Phase 1 — chemical replicators without translation, metabolism, or any neural analog — present no credible moral status concern. They are less complex than a virus. They cannot survive outside the reactor. The reactor-dependent design is not merely a safety feature; it is fundamental to the experimental strategy. Remove the reactor's chemical support, and the system collapses thermodynamically. There is no escape risk.

The deeper ethical question emerges in later phases, when the system begins to meet the criteria for life. The project addresses this by establishing three provisional moral-status markers in advance: differential environmental response, heritable behavioral variation, and aversive response to interference. If any of these emerge, the ethical framework governing the project is reassessed before proceeding.

Pre-registration of these markers — filed before experiments begin — ensures the assessment happens before any ambiguous result, not after.

The dual-use concern is real but manageable. The techniques developed could theoretically be misapplied. Pre-publication biosecurity review is committed for any result that could inform

development of novel replicative systems outside the research context. This is standard practice in synthetic biology.

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11. The Bottom Line

The most honest summary of this project is this: it is a serious, rigorous, quantitatively grounded attempt to do something that has never been done — create life from pure chemistry, deliberately, starting from molecules, under conditions that existed on early Earth and exist today on ocean worlds orbiting Jupiter and Saturn.

It may not work. Eight independent reviewers have converged on the same honest probability assessment:

Stage	What Must Be Demonstrated	Assessed Likelihood
I — Reactor	Stable geochemical gradients; vesicle formation; oligomer synthesis on mineral surfaces	**High**
II — Polymer Replication	Template-directed copying under reactor conditions; measurable fidelity	Moderate
III — Error Threshold	Fidelity crossing 10^{-3} under realistic geochemical noise — three mechanisms co-functioning	Low-Moderate
IV — Protocell Coupling	Selective replication inside lipid vesicles over 50+ generations	Moderate if Stage III succeeds
V — Translation Emergence	Genetic code arising from scratch within the system	Very Low — the hardest problem in biology
VI–VII — Full Program	Complete living system meeting all four criteria; open evolution	Unknown — no precedent exists

This probability table is not a reason not to attempt the project. It is the reason the project is scientifically structured the way it is — with pre-registered criteria, explicit go/no-go gates, and a Phase 1 design that delivers landmark results even if only Stages I and II succeed.

The probability of learning something profound is very high. Because every stage that is executed rigorously, with pre-registered criteria and honest reporting, produces a result that matters — whether it is success or failure. The map of what is and is not possible under geochemically realistic conditions is itself one of the most important maps in science.

And if it works — even partially, even only through Stage III — it will have demonstrated something that changes everything: that life is not a miracle, not an accident of vanishingly improbable complexity, but a thermodynamically predictable outcome of chemistry given the right conditions. That the universe is, in some deep sense, predisposed toward life.

> *Life is not a miracle. It is chemistry with the right conditions.This project is an attempt to prove it.*

Appendix: Key Terms for Non-Scientific Readers

Term	Plain English Definition
Archaeon / Archaea	One of the three domains of life, distinct from bacteria and eukaryotes. Ancient single-celled organisms found in extreme environments. Our evolutionary ancestors.
Asgard archaea	A recently discovered group of archaea that are our closest microbial relatives — the ancestors of all complex life including humans. Named after Norse mythology; first found near an underwater formation called Loki's Castle.
Eigen threshold / Error catastrophe	The physical limit on how long a self-copying molecule can be before copying errors destroy the information faster than selection can preserve it.
Eukaryote	Any organism whose cells have a nucleus — includes all animals, plants, fungi, and many single-celled organisms. Descended from an archaeal-bacterial merger billions of years ago.
Genome	The complete set of genetic instructions in an organism, encoded in DNA or RNA.
Protocell	A lipid vesicle (fatty acid bubble) encapsulating chemistry that may be replicating. A cell-like boundary without a full cell's complexity.
Ribozyme	An RNA molecule that can catalyze chemical reactions — proof that RNA can act as both information carrier and functional catalyst.
TNA (Threose Nucleic Acid)	An alternative to RNA using a simpler 4-carbon sugar backbone. Potentially more prebiotically accessible than RNA.
XNA (Xeno Nucleic Acid)	Any nucleic acid with a different backbone chemistry than RNA or DNA. TNA and FANA are examples.

Term	Plain English Definition
Hydrothermal vent	Geothermal openings on the ocean floor producing warm, chemically rich water — the most likely cradle of early life on Earth and candidate environments on Europa and Enceladus.
PPi (Pyrophosphate)	A simple energy-carrying molecule considered the primordial equivalent of ATP — the energy currency of modern cells.
NASA ROSES C.5 Exobiology	The NASA grant program funding research into the origin, evolution, and distribution of life in the universe. No fixed deadline — proposals accepted on a rolling basis.

AI tools were used in research synthesis and document preparation. All scientific claims, experimental design, and conclusions are the author's own. | Version 6, March 2026