

When Chemistry Began to Evolve

QTC-021 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

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Epistemic profile: Open Problem

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Article Abstract

Chemistry began to evolve when differences could persist, be copied imperfectly and alter the success of descendant lineages. Replication alone was not enough. Autocatalytic molecules can multiply without accumulating adaptations; compartments can grow and divide without transmitting useful differences; reaction networks can sustain themselves without becoming hereditary. Experiments have nevertheless rebuilt powerful parts of the threshold. RNA can act as both record and catalyst, molecular populations evolve in test tubes, compartments restrain parasites, and sequence-dependent chemistry can change protocell growth. Recent ribozymes even sustain open-ended RNA replication under controlled cycles. Yet every integrated system still inherits substantial machinery, substrates or selection rules from researchers or modern biology. The transition from geochemical chemistry to autonomous Darwinian evolution remains an open problem, not an empty one.

In 60 Seconds

Evolution is not a synonym for change. For chemistry to evolve cumulatively, some entity or lineage must persist or reproduce, variants must differ, relevant differences must be inherited, and those differences must alter success. Template copying gives sequences a direct route to heredity, but errors create a limit: if copying is too inaccurate, information dissolves faster than selection can maintain it. Catalytic RNA makes an RNA-world stage plausible because one polymer can carry sequence and perform chemistry, yet it does not prove that an all-RNA era occurred. Autocatalytic networks show collective self-maintenance; model and experimental work also shows that maintenance is not automatically heredity. Compartments localize benefits and parasites, allowing selection among chemical packages. In laboratories, RNA systems have mutated, competed, coevolved and formed cooperative networks for hundreds of generations. The caveat is load-bearing: those systems begin with evolved polymerases, ribozymes, translation components, designed fragments, activated substrates or managed transfers. We have rebuilt selection from prepared parts. We have not yet watched geochemical inputs bootstrap an autonomous, open-ended evolutionary lineage.

Why This Question Matters

Origin-of-life accounts often declare victory as soon as a molecule copies itself or a vesicle divides. The harder boundary is causal: can differences survive the cycle, affect descendants and accumulate under selection? That question separates chemistry that merely repeats from chemistry that can improve. It also makes laboratory caveats informative rather than embarrassing. Every supplied enzyme, fragment, transfer and selection rule identifies a function that nature once had to provide. Mapping

those dependencies turns disconnected demonstrations into a precise research programme and prevents the first evolvable chemistry from being confused with the first cell.

1. What Has to Start Evolving

The Question

A crystal grows, a flame propagates and a chemical cycle repeats. None thereby accumulates adaptations. What additional causal link lets one successful difference survive reliably into descendants and become a platform for the next improvement?

Darwinian evolution needs more than motion through chemical state space. A population of entities or lineages must persist or multiply, differ in relevant ways, pass some of those differences forward, and experience different survival or reproductive success because of them.[1] These criteria do not demand cells, DNA, sex or a modern genetic code. They demand causal continuity. If a variant's useful feature vanishes at every cycle, selection can sort one generation but cannot accumulate an adaptation across generations.

Heredity at this boundary is therefore a functional relation, not the name of a molecule. Sequence copying is one powerful form. A compartment can also inherit a composition, and a reaction network can return to one of several persistent organizations.[3,20,22] But the strength of inheritance matters. A vague resemblance produced by the same environment is not equivalent to descendants being shaped by their parent. Weak memory may permit a few adaptive steps; open-ended evolution requires enough fidelity and variation for improvements to remain available while new ones arise.

Three tempting substitutes fail separately. Autocatalysis makes a product accelerate its own formation, but faster production need not create alternative inherited types.[17,20] Metabolic turnover can keep a network away from equilibrium, yet a maintained flow need not remember which variant worked better.[20,36] A vesicle can grow and split through ordinary membrane physics while distributing contents randomly or carrying no consequential contents at all.[24,27] Multiplication, maintenance and enclosure are ingredients of evolvability, not interchangeable definitions of it.

The unit exposed to selection is equally important. A rapidly copying molecule may prosper while destroying the network that supplies its catalyst. A compartment may reproduce faster because its contents generate membrane material, even when one molecule inside copies more slowly.[22,23] Selection can act at both levels, and their interests can conflict. The origin problem is thus not only how the first replicator appeared. It is how molecular success became coupled to the persistence of a larger chemical organization.

This gives the article an evidence ladder. We can ask whether a system copies, whether copying generates inherited variants, whether success depends on those variants, whether the process continues through many cycles, and whether the machinery for each step is internal rather than supplied by an experimenter.[2,12,16,30,34] Many experiments reach several rungs. None begins with geochemical feedstocks and climbs them all autonomously. That is why the epistemic profile is Open Problem even though much of the underlying laboratory science is established.[16,35,36]

Where That Leaves Us

The threshold is not a mystical spark between non-life and life. It is a chain of testable dependencies: persistence, variation, inheritance and differential success, joined strongly enough for improvements to accumulate. The most direct way to preserve a chemical difference is to copy its sequence, so the next step follows the first molecular lineages built on templates.

2. Copying Creates a Lineage

A template does something chemically unusual: it makes the order of units in an existing polymer influence the order assembled in a new one. Complementary copying can alternate plus and minus strands, while ligation can assemble a copy from larger fragments.[2,12,37] Either route creates descent with modification if copying sometimes changes sequence. It also separates heredity from mere abundance. Two molecules can be equally numerous, but only the one whose structure helps determine its descendants carries sequence information forward.

Sol Spiegelman's laboratory made that distinction vivid using the RNA bacteriophage Q β . In 1967 Donald Mills, Robert Peterson and Spiegelman repeatedly transferred RNA into fresh mixtures containing Q β replicase and activated nucleotide substrates.[2] Variants that replicated well under that regime came to dominate. The experiment placed molecular populations under a defined ecology: copying time, dilution and recognition by the enzyme determined fitness. Evolution occurred outside a cell because inherited sequence differences altered success across transfers.

The famous shortened RNAs produced in this research are often called Spiegelman's monsters. Their lesson is not that evolution inevitably simplifies. It is that fitness answers a local question: successful at what?[2,5] In a tube where the protein replicase and substrates are free, an RNA that discards viral functions can copy faster. Inside a virus, losing capsid and infection functions would be disastrous. Selection optimizes performance under the environment actually imposed, not progress toward life or complexity.

This caveat applies to modern in vitro evolution. Researchers begin with a population, define a target such as binding or catalysis, retain successful molecules and amplify them with sophisticated enzymes.[9–11] The result can reveal functional regions of sequence space and show how mutation and selection move through them. It cannot by itself explain where the first selectable population, amplification chemistry or environmental criterion came from. The experimenter temporarily performs several roles that an autonomous system would have to internalize.

Copying is also chemically plural. Complementary nucleotide oligomers can promote one another's formation, peptides can template assembly of peptide copies, and RNA enzymes can cross-replicate from supplied fragments.[12,18,37] These demonstrations prevent the origin story from being reduced to one inevitable molecule. They also expose a common bottleneck: products bind templates, fragments must be activated, and catalysts often recognize only narrow substrates. A lineage exists only if copying outruns decay and dilution over repeated cycles.

Where That Leaves Us

Template copying makes ancestry chemically legible, and the Q β experiments prove that molecular populations can adapt outside cells. Yet every copied bit carries a cost: mistakes generate novelty

while also eroding what selection has retained. Once sequence becomes a record, the next question is quantitative—how inaccurate can copying be before the record ceases to survive?

3. Fidelity Sets an Information Limit

The Question

Without copying errors, a lineage cannot discover new sequence functions. With too many, it cannot preserve the functions already found. How could primitive chemistry cross that moving boundary before accurate enzymes themselves could be encoded?

Manfred Eigen formalized the central trade-off in 1971. If a sequence is copied with some probability of error at each position, the chance of an entirely correct copy falls as sequence length grows.[3] Selection can maintain a favored sequence only when its reproductive advantage compensates for mutational loss. The resulting error threshold is not one universal number. It depends on length, per-unit fidelity, fitness differences and the structure of the replicating population.[3,4] Primitive information capacity was therefore an ecological and kinetic quantity, not merely a property of a molecule.

The phrase error catastrophe can mislead when treated as a dramatic synonym for mutation. In idealized models, crossing a threshold delocalizes a population from a favored sequence; finite populations, neutral mutations, recombination and changing fitness landscapes can smooth or alter the transition.[3,4] The durable point is simpler. Information is physically maintained by repeated, sufficiently faithful production. A long sequence cannot remain a stable instruction merely because it once formed. It must continually win a race among accurate copying, erroneous copying, degradation and replacement.

Real RNA populations supplied an empirical counterpart. Esteban Domingo and colleagues sequenced descendants from a cloned Q β phage and found a heterogeneous population rather than one invariant genome.[5] Mutation and selection maintained a cloud of related sequences. Such observations helped motivate quasispecies theory, but the label should be used carefully: not every variable viral population satisfies every mathematical assumption. For origins research, the important fact is that heredity can reside in a structured population even when no molecule is copied perfectly.

Error also interacts with selfishness. Short templates can copy quickly and exploit catalysts made by longer functional sequences. In bulk, they may erase the very system that enables them. [2,31,32] Increasing fidelity does not solve that conflict; it can faithfully reproduce a parasite. Spatial structure, linkage and compartments become relevant because they make the effects of a sequence fall more heavily on nearby partners and descendants. Information capacity is thus limited by ecological organization as well as chemical accuracy.

The bootstrap problem is often called Eigen's paradox. Accurate polymerases could support longer sequences, yet the instructions for accurate polymerases are themselves long.[3,16,36] Candidate escapes include short early genomes, information distributed among cooperating molecules, crude catalysts improved stepwise, and selection among compartments. None is absurd, and none is established as the historical route. A solution must show not merely that high fidelity can exist, but how a low-information system could reach it without losing continuity along the way.

Where That Leaves Us

Fidelity turns replication into a channel with finite capacity. Too little variation freezes novelty; too much dissolves ancestry; parasites can exploit either regime. A promising early polymer would therefore need to carry information and help execute the chemistry that preserves it. The discovery that RNA can catalyze reactions made that double role experimentally real.

4. RNA Can Be Catalyst and Record

The Question

Modern cells divide labor among DNA, RNA and proteins, making their joint origin look circular. If one polymer alone could both store sequence and perform chemistry, could it provide a bridge before that division existed?

In 1982 Kelly Kruger, Thomas Cech and colleagues showed that an intervening RNA sequence from *Tetrahymena* could excise and cyclize without a protein enzyme performing the key reaction.[6] In 1983 Cecilia Guerrier-Takada, Sidney Altman and colleagues showed that the RNA component of bacterial RNase P could catalyze RNA cleavage under specified ionic conditions.[7] These were not self-replicating primordial molecules. They were decisive demonstrations that RNA is not confined to carrying messages: its folded structure can create catalytic function.

Walter Gilbert named the RNA world in 1986: a stage in which RNA could have combined genotype and phenotype before DNA became the principal archive and proteins the principal catalysts.[8] The idea solves a logical division of labor, not the whole origin. It leaves precursor synthesis, activation, polymerization, strand separation, fidelity and compartmentalization to be explained. Catalytic RNA is evidence that such a world is chemically possible. It is not geological proof that Earth passed through a pure or universal all-RNA era.[6–8]

Laboratory selection expanded the catalytic catalogue. Starting from vast random-sequence pools, David Bartel and Jack Szostak isolated new ribozymes; Ronald Breaker and Gerald Joyce then observed a replicating species emerge within an RNA evolution reaction.[9,10] Continuous selection can improve function across cycles.[11] These results show that RNA sequence space contains reachable catalysts. Their machinery also matters: protein polymerases, reverse transcription, PCR, prepared substrates and investigator-defined selection supplied steps that the selected RNA did not perform.

RNA polymerase ribozymes have since crossed striking milestones. They have transcribed active ribozymes, amplified diverse RNA templates and used trinucleotide building blocks to invade structured templates.[13–15] In 2025 James Attwater and colleagues coupled activated triplets to pH and freeze–thaw cycles, obtaining exponential copying of both strands, partial copying of the polymerase ribozyme and open-ended evolution of sequence pools.[16] The strand-separation problem was attacked by the substrates themselves, which trapped dissociated strands before rapid reannealing.

The achievement narrows the gap without erasing it. The 2025 catalyst was an artificial heterodimeric ribozyme evolved in vitro and supplied with activated triplets, primers and managed environmental cycles.[16] Lincoln and Joyce's earlier cross-replicating RNA enzymes amplified without proteins, but each partner assembled the other from four supplied oligonucleotide substrates.[12] These systems demonstrate replication and selection from prepared

parts. They do not yet show how a geochemical mixture makes the catalyst, its activated feedstock and the cycle that sustains both.

Where That Leaves Us

RNA can unite record and catalytic action, and current ribozymes perform feats that were speculative a generation ago. The historical inference remains bounded by what laboratories supply. Nor is templated replication the only proposed route to organized chemistry: entire reaction networks can close upon themselves, sustain their components and raise a different question about inheritance.

5. Autocatalytic Networks Are Not Yet Heredity

A molecule need not make a literal copy of itself for a system to be autocatalytic. In a collectively autocatalytic set, products catalyze reactions that, through a network, regenerate the set from an external food supply. Stuart Kauffman and J. Doyne Farmer explored how such closure can appear once modeled catalytic connections become sufficiently dense.[17] The proposal matters because organization can be distributed: no master replicator needs to contain instructions for every reaction. The network as a whole maintains the capacity to rebuild its members.

Closure, however, answers a production question before it answers an evolutionary one. A network may always relax to the same composition after disturbance. If alternative organizations are not reliably transmitted, selection has nothing stable to compare.[20] Growth rate alone is insufficient when a faster state cannot seed descendants resembling itself. Autocatalytic sets therefore offer a possible metabolism and a possible unit of reproduction, but heredity must be demonstrated rather than smuggled in through the word self-organization.

Peptide experiments make the distinction concrete. In 1996 David Lee and colleagues built a peptide that templates assembly of copies from two fragments.[18] A later system formed a hypercyclic network in which distinct peptide replicators promoted one another, an experimental form of molecular symbiosis.[19] These were genuine chemical feedbacks. They used prepared sequences and fragments, and they did not spontaneously generate an indefinitely expanding repertoire of inherited functions. Self-replication and cooperation were present; open-ended Darwinian evolution was not.

RNA networks can go further. Niles Vaidya and colleagues mixed fragments that assembled into self-replicating ribozymes and observed cooperative catalytic cycles.[21] A three-member network grew more effectively than selfish autocatalytic cycles, and in vitro selection altered network behavior. The result shows that molecular cooperation can itself affect success. It does not show that the participating fragments arose together on early Earth: the system descended from a modern group I intron and was configured so the relevant interactions could be tested.

A valuable negative result came from Vera Vasas and colleagues. In their models, conventional autocatalytic sets did not accumulate adaptations merely because they were self-sustaining.[20] Evolvability required special alternative cores, rare transitions and compartments that allowed selection among different chemical organizations. The conclusion is not that metabolism-first schemes are impossible. It is that any scheme must identify its hereditary states, show how descendants preserve them, and demonstrate that selection can move the population toward cumulative improvement.

Where That Leaves Us

Autocatalytic networks explain how production can be collective, while experiments show that molecular cooperation is chemically attainable. Their weakness is diagnostic: without distinct heritable organizations, self-maintenance has no evolutionary memory. Compartments offer one way to create that memory by keeping products, costs and descendants together long enough for selection to compare whole chemical packages.

6. Compartments Make Selection Local

In a well-mixed solution, a useful catalyst may help every nearby replicator, including parasites that contribute nothing. A compartment changes the accounting. Benefits and costs become concentrated among a limited set of molecules, and division sends samples of that local chemistry into descendants.[22,23] The same boundary creates hazards: partners may be separated, rare components lost and nutrients excluded. Compartmentalization is not automatically beneficial. Its evolutionary value depends on size, permeability, mixing, growth and how contents are partitioned.

Simple membranes already perform several required physical operations. Martin Hanczyc, Shelly Fujikawa and Jack Szostak showed that fatty-acid vesicles can encapsulate RNA, grow and divide under laboratory conditions.[24] Ting Zhu and Szostak coupled membrane growth to filament formation and division without a protein cytoskeleton.[27] Kensuke Kurihara and colleagues later combined amplification of encapsulated DNA with reproduction of giant vesicles.[29] Each system joined important functions, but external supplies or interventions still drove parts of the cycle.

A particularly revealing experiment linked internal polymers to competition. Irene Chen, Richard Roberts and Szostak loaded fatty-acid vesicles with nucleic acids. Their osmotic pressure increased membrane tension, causing stressed vesicles to acquire fatty acid from relaxed competitors and grow.[25] The polymer did not encode a membrane enzyme; ordinary physics connected content abundance to compartment phenotype. If better copying produced more trapped polymer, a replicator could in principle make its own compartment more competitive without first inventing modern metabolism.

Other experiments joined copying or catalysis to the inside. Sheref Mansy and colleagues showed that activated nucleotides could cross suitable fatty-acid membranes and extend a genetic template inside.[26] Katarzyna Adamala and Szostak encapsulated a catalyst whose reaction products changed membrane growth, giving catalyst-containing protocells a competitive advantage.[28] These results create pieces of a genotype–phenotype link. The templates or catalysts were installed by investigators, however, and neither system autonomously reproduced the internal function and membrane through indefinite generations.

A 2026 experiment added another physical bridge. Akiko Baba and colleagues measured how defined peptide sequences changed the growth rates of decanoic-acid vesicles, revealing a sequence-dependent fitness landscape and epistasis.[35] The authors explicitly used growth as a proxy: the vesicles did not complete division, and the prepared peptides were neither synthesized nor inherited by the system. That limitation is the point. Sequence can already alter compartment performance; an evolutionary lineage would still need a way to reproduce the sequence and couple growth to descendants.

Where That Leaves Us

Compartments can convert private chemistry into selectable package-level consequences. Membranes grow, divide, admit substrates and respond to their contents, while sequence can alter growth. Yet localization also creates competitors that exploit shared machinery. The strongest test is therefore not an isolated protocell but a population containing cooperators, parasites and descendants across many cycles.

7. Cooperation, Parasites, and Experimental Evolution

Parasites are not a late complication added after evolution begins. They are an immediate consequence of shared copying machinery. A shorter RNA that retains polymerase recognition while abandoning the cost of producing polymerase can outrun its functional host.[2,31] In bulk, the parasite's advantage spreads globally and may collapse the system. In compartments, some hosts find themselves with few parasites, reproduce, and seed the next round. Local assortment makes system-level function visible to selection.

Theory anticipated this effect. The stochastic-corrector model of Eörs Szathmáry and László Demeter showed how competition among compartments can maintain several necessary replicators despite competition within each one.[22] Later spatial models compared discrete packages with limited dispersal and found parameter regions where higher-level selection stabilizes cooperation.[23] These are not universal guarantees. Compartments that are too large resemble bulk; those too small lose indispensable partners. Selection operates through a quantitative window of assortment, growth and mixing.

Experiments have now entered that window. Shigeyoshi Matsumura and colleagues placed functional and parasitic RNAs through repeated cycles of transient droplet compartmentalization and mixing. Functional replicators survived instead of being eliminated by parasites.[32] The result demonstrates that permanently reproducing cells are not the only possible population structure. It also used Q β replicase, a designed ribozyme-bearing RNA, microfluidic droplets and managed selection. Natural aerosols, pores, ice veins or vesicles remain proposed analogues, not demonstrated historical sites.

Norikazu Ichihashi and colleagues built an RNA genome encoding a Q β replicase subunit inside water-in-oil droplets and followed roughly 600 generations. Mutations accumulated and variants with improved replication dominated.[30] Yohsuke Bansho and colleagues then added parasitic RNA. Bulk populations collapsed, whereas compartmentalized populations showed host-parasite oscillations and evolved coexistence.[31] These are rich Darwinian and ecological dynamics. Their engine included a reconstituted *Escherichia coli* translation system, modern factors and researcher-controlled transfers.

Longer experiments revealed cooperation as well as conflict. Ryo Mizuuchi and Ichihashi sustained two functional RNAs that helped one another replicate despite parasites, and cooperation improved during evolution.[33] Extending the lineage further produced several host and parasite lineages and a network in which one RNA helped replicate the others.[34] The network was not fully designed in advance; interactions emerged through mutation and selection. Yet the ancestral host, Q β -derived replicase, translation machinery and droplet regime were inherited from biological engineering rather than prebiotic chemistry.

Where That Leaves Us

Experimental molecular ecosystems now mutate, adapt, oscillate, resist parasites and evolve cooperation. They prove that compartments can turn chemical copying into sustained ecology. Their inherited laboratory infrastructure marks the remaining distance rather than diminishing the result. The final question is whether all essential functions can bootstrap from plausible chemistry without an experimenter supplying the missing organism.

8. The Threshold Has Not Been Rebuilt

The Question

No single gap remains called the origin of evolution. Instead there is an integration test: under plausible early-Earth conditions, can feedstocks, copying, catalysis, energy, compartment reproduction and selection sustain one another without hidden biological subsidies?

The experimental landscape is no longer a list of isolated ingredients. Copying has been joined to selection; RNA sequence to catalytic phenotype; internal polymer or catalyst to vesicle growth; compartments to parasite control; and long-term selection to cooperative molecular networks. [12,25,28,30–35] These couplings make older declarations that the problem is experimentally inaccessible obsolete. They also make vague declarations that life has been created untenable. Every result specifies both what was internal and what the apparatus still supplied.

The 2025 triplet-polymerase experiment is the clearest example of progress changing the question. It overcame a major strand-separation barrier, copied both RNA strands exponentially and let random sequence pools change without a preset final sequence.[16] Yet the ribozyme had already been evolved in the laboratory, and activated triplets, primers, pH changes and freeze–thaw timing were provided. The next problem is not whether RNA replication can be open-ended under any conditions. It is how the catalytic system and its operating cycle become self-supplied and heritable together.

The 2022 RNA ecosystem illustrates a complementary achievement. From one engineered host lineage, mutation and selection generated several persistent host and parasite lineages with cooperative interactions.[34] That is genuine complexification, not merely repeated amplification. But it began downstream of translation, an encoded protein replicase, prepared nutrients and managed droplets. It demonstrates what an evolvable molecular ecology can do once a powerful platform exists. It does not explain the transition from the chemistry of QTC-020 to that platform.

Current theory explores alternative orders. A 2026 model by Raquel Nunes Palmeira and colleagues found conditions in which sequences supporting protocell growth emerge before sequences supporting copying, because faster growth expands access to monomers and sequence space.[36] The result reverses a simple information-first narrative, but it follows from a model that assumes rudimentary metabolism, random polymers, copying, translation and mappings from polymer properties to function. It is a testable proposal about ordering, not a recovered history of early Earth.

The demanding benchmark is now explicit. Begin with bounded geochemical inputs; generate a persistent replicating organization; produce inherited variation; link variants to compartment or network success; and sustain open-ended adaptation without importing evolved enzymes or an external selection algorithm. [16,20,35,36] Nature need not have done this in one vessel or one leap.

A staged route across environments would count if matter and function remain traceable. No experiment yet meets either form of the test. QTC-022 therefore begins after this unresolved threshold, with the first cells inferred from evidence we did not witness.

Where That Leaves Us

Chemistry began to evolve when success left a transmissible trace that could be improved again. Experiments now reconstruct that logic with extraordinary precision, while their supplied parts reveal the unfinished bootstrap. The next article moves from the threshold to its descendants: cells whose beginnings were never observed and must be inferred from rocks, genomes and shared molecular machinery.

What We Know, and How

- Molecular populations can undergo mutation, selection and adaptation outside cells when copying and transfer conditions are supplied.[2,9–12]
- RNA can store sequence and catalyze reactions, and evolved ribozymes can sustain increasingly general RNA copying.[6–8,13–16]
- Autocatalytic molecules and networks can self-maintain or cooperate without thereby guaranteeing cumulative heredity.[17–21]
- Compartments can link internal chemistry to growth and can protect functional replicators from parasites.[22–35]
- No system yet bootstraps sustained, open-ended Darwinian evolution from bounded geochemical inputs without evolved biological machinery.[16,20,35,36]

What We Still Don't Know

- Which chemical entity or organization first supplied heredity strong enough for cumulative selection.
- How early copying crossed the fidelity–information barrier before accurate catalysts could be encoded.
- Whether template replicators, autocatalytic networks, metabolism and compartments arose in sequence or co-developed.
- Which natural population structures controlled parasites before reproducible cellular division existed.
- How geochemical feedstocks, energy and environmental cycles became an autonomous evolutionary ecology.

What Could Change Our Minds

- An autonomous replicator that forms from geochemically bounded inputs and sustains inherited adaptation without evolved enzymes.
- A protocell lineage that couples internal copying, useful catalysis, membrane growth and division across many generations.
- Direct experimental bootstrapping of copying fidelity and information capacity from a simpler low-fidelity system.
- Naturalistic compartments or spatial structures that repeatedly suppress parasites without microfluidic management.

- A mass-balanced, staged experiment linking prebiotic environments to an open-ended evolutionary molecular ecosystem.

If You Remember Only One Thing

Chemistry evolves only when inherited differences alter descendant success and accumulate.

Laboratories have rebuilt copying, catalysis, compartments and selection in powerful combinations, but not their autonomous bootstrap from geochemical inputs.

Related Articles

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- QTC-009 — What Do We Actually Mean by Life?
- QTC-020 — Before Life: A Planet Full of Chemistry
- QTC-022 — The First Cells We Never Saw

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