

What Do We Actually Mean by Life?

QTC-009 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

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Article Abstract

Science has no universally accepted definition of life, partly because one word is asked to classify entities, express a theory of living organization and guide searches for unfamiliar biology. Familiar checklists fail at the edges: sterile organisms live, spores become nearly inert, viruses evolve without autonomous metabolism, and viroids or prions reproduce patterns without being cells. Definitions such as NASA's working formula, autopoiesis, the chemoton and autonomy plus open-ended evolution illuminate different features but inherit different blind spots. Earth also supplies only one deeply related cellular biosphere, so universal traits may mix necessities with historical inheritances. Life detection therefore requires context, controls and converging evidence. The most defensible present practice is disciplined pluralism: state the task, the unit and the criteria, then let evidence test them.

In 60 Seconds

There is no single scientific definition of life that resolves every boundary case. That does not mean biology has failed. Definitions do different jobs: they classify known entities, summarize theories of organization and guide instruments searching for unknown life. A checklist of metabolism, growth, reproduction and response immediately meets exceptions. Sterile individuals are alive; dormant spores can be almost inactive; viruses evolve but require cells; viroids and prions replicate in still stranger ways. Theory-based definitions also divide the problem differently. Autopoiesis emphasizes self-producing organization, the chemoton couples metabolism, boundary and information, and evolutionary definitions restore heredity but make open-endedness difficult to test during a mission. Because all known cellular life shares deep ancestry, Earth is a biased sample of one. Habitable conditions, organic molecules or one unusual signal do not establish life. The practical answer is not relativism: identify what is being classified, for what purpose, and which evidence would discriminate life from convincing alternatives.

Why This Question Matters

A definition controls what a microscope counts, what an origin experiment tries to build and what a spacecraft is designed to detect. If the definition silently changes its unit from organism to lineage, or its purpose from explanation to detection, disagreement can look deeper or shallower than it is. The question also tests scientific humility. We know life through one related biosphere, yet we want criteria that might recognize an unfamiliar second genesis. Precision therefore begins by naming the job before defending the answer.

1. One Word, Three Jobs

The Question

Why can 123 published definitions of life coexist without one simply defeating the rest? Because they often answer different questions, select different biological units and express different theories about which features of living organization are fundamental.

There is no universally accepted scientific definition of life. Edward Trifonov's 2011 survey compared 123 published definitions and extracted recurrent vocabulary, but the count did not close the question.[5] It documented the density of the discussion, not an exhaustive catalogue or proof that every proposal is equally useful.[1–4,10,13]

The word is commonly asked to perform at least three jobs. A classification rule decides whether a virus, spore or synthetic system belongs inside a category. A theoretical definition compresses an account of how living organization works. An operational definition tells a mission or experiment what to measure. These purposes overlap, but success at one does not guarantee success at the others.[2,3,24,25,31]

Definitions also distribute weight differently among autonomy, metabolism, compartmentalization, heredity and evolution. They may treat the unit as a cell, an organism, a reproductive lineage or a wider ecological system. Some disputes are therefore about words and bookkeeping, while others are substantive disagreements about where biological organization resides.[2,3,7,10,13]

An operational definition can be scientifically valuable without claiming to reveal the essence of life in every possible world. The discipline lies in fixing the criteria before seeing the result and admitting their intended domain.[2,3,25,31] Cleland and Chyba make a stronger philosophical proposal: life may be a natural kind whose best characterization must wait for a mature theory, much as water became intelligible through chemistry.[2] That is an argument, not an empirical demonstration that operational definitions are useless.

The ambition to find universals faces a further limitation. Known cellular organisms share deep biochemistry and strong evidence of universal common ancestry.[11,35,36] Earth therefore offers enormous diversity, but not many confirmed independent origins. A trait universal here may be necessary for life, or it may be an inheritance from one successful history. Viral origins require separate treatment, and common ancestry does not prove that life arose only once.[28,31]

Where That Leaves Us

The argument is not that definitions are futile. It is that classification, explanation and detection impose different demands, while one related biosphere limits the universals we can infer. Before choosing among theories, the familiar checklist must face its own test: do metabolism, growth, reproduction, boundaries and response actually separate every living case from every nonliving one?

2. The Checklist Breaks at the Edges

Lists of life's traits recur for good reasons. Bounded organization, use of energy and materials, maintenance, growth, reproduction, heredity, response and capacity for evolution describe much

of ordinary biology.[8,9,31] A checklist is useful for comparison, but it becomes circular if its items are chosen mainly because familiar organisms already possess them.

No single familiar trait is sufficient. Crystals grow, flames spread, convection cells maintain organized motion and electrochemical systems can preserve gradients. These examples are not miniature organisms. They show only that growth, movement, order or energy use cannot decide the category alone.[3,8,25,31]

Reproduction exposes the level problem. A sterile worker ant, mule or human remains alive even though that individual cannot reproduce. Darwinian evolution belongs to reproducing populations or lineages across generations, not to every organism at every moment.[2,3,13] Reproduction remains central to life's continuity, but requiring it of each individual gives the wrong classification.

Metabolism also changes with state. Bacterial endospores can remain extremely reduced or effectively inert for long periods and later germinate when conditions improve.[12,13] Claims of absolutely zero metabolism are method-sensitive, yet the biological point survives: continuous high metabolic activity is not required for an entity to remain a viable member of a living lineage.

Autonomy is graded rather than absolute. Every organism depends on matter, energy and environmental conditions; obligate intracellular parasites can discard biosynthetic functions while remaining cells.[13,33] Cellularity includes all known cellular organisms cleanly, but it excludes viruses by adopting the very boundary under dispute. That may be defensible, yet it does not independently prove where life must end.[13–16]

Where That Leaves Us

The checklist works best as a map of recurring properties, not as a mechanical verdict. Individual traits admit abiotic mimics, living states can suppress metabolism, reproduction belongs partly to lineages and autonomy comes in degrees. The next step is therefore theoretical: ask what organization each definition is trying to explain, and which blind spot appears when that model reaches an edge case.

3. Definitions Are Models

The Question

If a list of traits cannot settle every case, should a definition instead describe the organization that makes life possible? Competing models answer yes, but they disagree about whether maintenance, boundaries, information or open-ended evolution carries the deepest explanatory weight.

A widely used NASA working definition describes life as a self-sustaining chemical system capable of Darwinian evolution.[1,3,4] Its strength is theoretical economy: chemistry, self-maintenance and evolutionary capacity appear in one sentence. It is a working definition associated with astrobiology, not a final declaration about every conceivable living system.

Its operational difficulty appears during missions. Darwinian evolution is most naturally a property of systems or lineages over generations, but a robotic mission cannot normally wait long enough to observe open-ended evolution directly. Instruments therefore measure chemical,

structural, metabolic or ecological proxies.[3,25,26] The evolutionary criterion remains important; the measurement is indirect.

Autopoiesis places the emphasis elsewhere. Varela, Maturana and Uribe described a network of processes that continually produces and maintains the components and boundary constituting the system as a unity.[6] This foregrounds organizational closure and self-production. By itself, however, autopoiesis does not necessarily require hereditary variation or open-ended Darwinian evolution, although later authors have combined those ideas.[6,7]

Tibor Gánti's chemoton offers another architecture: three coupled autocatalytic subsystems for metabolism, a self-producing membrane boundary and an informational template.[34] The model is historically important because it refuses to let any one function stand alone. Recording its three-part structure does not establish that every organism literally instantiates one chemoton or that the model is uniquely correct.

Ruiz-Mirazo, Peretó and Moreno deliberately joined autonomy to a capacity for open-ended evolution.[7] That restores heredity and innovation to a model of self-maintenance, but the term open-ended introduces its own boundary. It is difficult to operationalize across known and novel systems, especially on mission timescales, so uncertainty can be relocated rather than eliminated. [3,7,34]

These definitions function as compact theories. Each explains important features and exposes a different blind spot: maintenance without heredity, evolution without an easily observed mechanism, or an architecture whose universality is unproved. No experiment has selected one as the unique definition across all known and possible cases.[2–4,7,10] They can still be compared for scope, coherence, testability and practical success.

Where That Leaves Us

Theory-based definitions improve on a loose checklist by explaining how properties fit together, but they do not erase the choice of unit. NASA's formula privileges evolutionary capacity, autopoiesis privileges self-production and the chemoton couples three subsystems. The sharpest test now arrives with viruses, whose extracellular particles, intracellular phases and evolving lineages point to different answers depending on what is being classified.

4. Viruses Expose the Unit

The Question

Is a virus nonliving because a virion lacks autonomous metabolism, or living because a viral lineage evolves and its intracellular phase reorganizes a cell? The dispute cannot be resolved until the unit under judgment is stated explicitly.

Viruses are obligate intracellular parasites. Extracellular virions lack autonomous metabolism and ribosome-based translation, while viral reproduction requires cellular machinery.[13–15] Some viruses encode metabolic or translation-related components and reshape host metabolism, but none is known to possess a complete autonomous translation system.

Their evolutionary status is not in doubt. Viral populations mutate, inherit variation, undergo selection and adapt.[13,16] Yet evolution alone does not decide whether the relevant living unit is

the virion, the infected cell, the lineage or a coupled host-virus system. The criterion and the unit must travel together.

The phase distinction makes the disagreement concrete. A virion can be inert or nearly inert outside a host. Inside a cell, the viral programme redirects molecular resources and creates a reproductive system. The virocell concept treats that infected phase as biologically central. [13,15,17,18] It is influential, but not a universally accepted replacement for cell-centred accounts.

Specialists therefore defend live positions. Forterre argues for a virus-centred view that distinguishes virions from the active infected-cell phase.[15,18] Moreira and López-García defend cell-centred exclusions and warn against placing viruses on the cellular tree of life.[16]

Membership in a tree, status as an organism and inclusion within life are related questions, not interchangeable ones.

Mimivirus made older expectations harder to sustain. Its genome is roughly 1.2 megabases and includes an unexpectedly large repertoire with translation-related genes.[17] It still lacks ribosomes and complete autonomous translation.[13,18] Giant size and complexity blur a scale-based intuition, but larger does not automatically mean more alive, and host dependence remains.

Where That Leaves Us

Viruses do not merely supply an awkward yes-or-no case. They reveal that virion, infected cell and lineage answer different biological questions. Cellularity, autonomy and evolution can support coherent but competing classifications. Moving below viruses makes the same lesson sharper: viroids and prions preserve replication or heredity while abandoning still more of the organization associated with a cell.

5. Smaller Than Viruses, Quieter Than Cells

Viroids are circular noncoding RNA replicators, roughly 250–400 nucleotides long, that recruit host enzymes and can cause plant disease without encoding proteins or building virions.[13,19] Exact sizes vary with classification, and not every viroid is catalytic. Their existence separates replication from both protein coding and viral particle construction.

Prions remove nucleic acid from the hereditary mechanism altogether. They are infectious protein conformations that propagate by templating the folding of other proteins.[20] In cell culture, experimental prion populations can display strain variation and selection.[21] That result does not transform a prion into an autonomous organism, but it shows that selectable continuity need not be stored in DNA or RNA.

Viruses, viroids, prions, plasmids and chromosomes occupy different positions on continua of replication, resource production and dependence.[13,20,21] The continuum does not erase qualitative distinctions. A chromosome inside a cell and a transmissible virion are not the same kind of entity. It does show why replication or evolution alone is not yet a complete theory of organismal self-maintenance.

The opposite strategy is to minimize a cell while keeping cellular organization. JCVI-syn3.0 has a 531-kilobase-pair genome containing 473 genes; 149 initially had unknown biological functions. [22] It is a minimized derivative of an existing cellular lineage, grown under laboratory conditions,

not life assembled from nonliving chemistry and not the smallest possible organism in every environment.

Later work on the JCVI-syn3A lineage identified genes needed to restore regular cell division, showing that even a minimal genome can hide functions that a simple checklist would miss.[32] Genome reduction in natural parasites likewise depends on what hosts and environments supply. [33] Minimal viability is therefore lineage- and environment-dependent, not a universal gene count or an invariant molecular essence.[22,23,32,33]

Where That Leaves Us

Viroids and prions show how little machinery can carry replication or selectable variation; minimal cells show how much inherited organization remains even after a genome is stripped down. Neither direction reveals one universal essence. The search for a lower boundary instead exposes dependence on host, environment and lineage. That dependence matters because every case we know comes from one connected biosphere.

6. One Biosphere Is a Biased Training Set

All confirmed cellular life on Earth is deeply related. Comparative sequences, conserved molecular machinery and shared biochemistry support universal common ancestry of known cells, even though formal tests and their assumptions have generated methodological exchange.[11,35,36] This is strong evidence for relationship, not proof that life originated only once or that every viral lineage shares the same history.

A universal terrestrial trait can therefore have two explanations. It may be required by physics and chemistry for any life, or it may be a contingent inheritance from the common ancestor of the only surviving biosphere we can study.[28,31] With one historical sample, those possibilities are sometimes impossible to separate.

The limitation does not make all imagined alternatives equally plausible. Carbon chemistry offers unusual versatility; solvents, temperature ranges, thermodynamics and reaction kinetics impose real constraints.[28] The discipline is to distinguish a constraint from an inheritance. DNA, ribosomes or a particular membrane lipid may be universal here without being the only possible realization of heredity, translation or compartmentalization.

An independently originated biosphere would be scientifically transformative because it would supply a second test set. Shared features would become stronger candidates for universality; different solutions would expose historical contingency.[11,28,31] Until then, definitions designed from terrestrial organisms risk mistaking one genealogy for a law of nature.

Where That Leaves Us

Earth teaches us much about what one successful biosphere can become, but less about which of its features every life must share. Physics constrains possibility, while common ancestry entangles necessity with inheritance. That uncertainty becomes operational beyond Earth: a mission must search for life it does not already know, using instruments designed from the only example it has.

7. Searching Without Knowing the Answer

The Question

How can a spacecraft recognize life without assuming DNA, cells or familiar metabolism in advance? It must look for patterns that are difficult to explain abiotically, while testing contamination, instrument behaviour and the planetary context around every signal.

Habitability is not evidence of life. Water, energy sources and complex organic molecules can exist without biology.[1,24,26,28,31] They identify environments worth searching, not inhabited environments. The same distinction applies to an organic molecule: its meaning depends on abundance, distribution, preservation, context and plausible abiotic pathways.

Credible detection therefore requires evidential convergence. Investigators must control contamination and instrumental artifacts, test abiotic alternatives and combine independent measurements rather than rest a conclusion on one attractive signal.[24–27,30] Carl Sagan and colleagues demonstrated the logic by treating Earth as a target observed by Galileo: oxygen, methane, surface pigments and radio emissions became persuasive together, not in isolation.[30]

Viking remains a warning against premature closure. Its labelled-release experiment produced a positive metabolic-response signal, while the gas chromatograph-mass spectrometer reported no detectable indigenous organics.[25] Later work argued that perchlorate chemistry could have destroyed organics during heating, and published critics disputed whether that reinterpretation explained the Viking results.[37,38] The measurements are historical facts; their biological meaning remains contested.

Evolutionary definitions create a further practical gap. Darwinian evolution may be central in theory but is normally too slow to demonstrate directly during a robotic mission. Missions therefore use chemical, structural, metabolic or ecological proxies.[3,25,26] Every proxy can produce false positives or false negatives, so no single rung or reporting scale guarantees certainty.

Agnostic approaches try to reduce dependence on familiar molecules. Proposed methods examine constrained molecular distributions or high assembly complexity without requiring DNA.[28,29,31] These are active hypotheses, not proven universal detectors. Assembly metrics and related signatures must survive abiotic challenges, diverse living samples and blinded tests before they can carry a discovery claim.

Where That Leaves Us

Life detection is an argument built from context, controls and independent evidence. Habitability and organics justify attention; they do not announce biology. Viking shows why one response can remain ambiguous for decades, and agnostic biosignatures remain under test. The final question is therefore procedural as much as definitional: how should we reason when no single criterion can carry every task?

8. Disciplined Pluralism

The most defensible present practice is to state three things explicitly: the task, the unit and the criteria.[2,3,10,13,24] Are we classifying an individual object, explaining the organization of a cell,

tracing an evolving lineage or deciding whether a planetary signal justifies further investigation? Those are connected questions, but they are not identical.

For classification, cellular autonomy may draw a clear and useful boundary, provided viruses are not declared settled by definition alone. For theory, autopoiesis, chemoton architecture and evolutionary autonomy can be judged by explanatory scope and testable consequences. For detection, operational criteria must be fixed in advance and evaluated against contamination and abiotic alternatives.

This pluralism is contested because many researchers reasonably seek a deeper unification. It is not relativism. Definitions remain answerable to evidence, logical consistency, scope, predictive performance and operational success.[2,3,10] A definition that repeatedly misclassifies established organisms or cannot guide discrimination should lose ground; a theory that unifies formerly separate cases should gain it.

The boundaries of this article are also deliberate. QTC-021 treats the transition from chemistry to open-ended Darwinian evolution. QTC-027 treats inheritance, trees, webs and the place of viruses in evolutionary history. Here viruses and subviral agents serve as tests of definitions, not as a complete history of life's origins or evolution.

The question 'Is it alive?' becomes scientifically sharper when decomposed. Does the system maintain itself? What resources does it produce, and what must a host provide? Where is heredity located? Does a lineage evolve? Which measurements exclude abiotic alternatives? A single word may still be useful, but the subquestions reveal what the answer commits us to.

Where That Leaves Us

Life has not escaped science because one sentence fails to contain it. The dispute becomes tractable when task, unit and evidence are explicit. Cells, viruses, viroids, prions and minimal genomes then stop being annoyances and become experiments on our concepts. A future second biosphere may unify the definitions or multiply them, but either outcome will be evidence, not a vote.

What We Know, and How

- No universally accepted definition resolves every boundary case, and published definitions perform different classificatory, theoretical and operational jobs.[1–5,10,13,24]
- Common traits are informative but individually insufficient; reproduction, metabolism and autonomy depend on biological level, state and environmental support.[3,8,9,12,13,31,33]
- Viruses evolve and reorganize host cells but lack autonomous metabolism and translation, while viroids and prions separate replication from still more cellular machinery.[13–21]
- Minimal-genome experiments identify requirements within inherited cells and specified environments, not a universal molecular essence or a recreation of life's origin.[22,23,32,33]
- Life-detection claims require environmental context, contamination control, abiotic alternatives and converging measurements.[24–27,30,37,38]

What We Still Don't Know

- Whether a mature theory will yield one task-independent definition of life or retain several irreducible but coordinated concepts.

- Which features universal in terrestrial cells are necessities of life and which are inherited contingencies of one common ancestry.
- Whether viruses are best classified outside life, as living lineages, or through an infected-cell unit that differs from the extracellular virion.
- Which agnostic biosignatures can distinguish unfamiliar life from complex abiotic chemistry across genuinely different planetary environments.

What Could Change Our Minds

- Discovery of an independently originated biosphere whose chemistry and organization test which terrestrial features are genuinely universal.
- A theory that uniquely derives one definition across cells, viruses, subviral replicators, origin models and operational detection without task-specific loss.
- A demonstrated single property that is present in every living system, absent from every abiotic system and measurable across unfamiliar environments.
- Blinded life-detection experiments showing that one proposed agnostic metric reliably discriminates diverse living samples from stringent abiotic controls.

If You Remember Only One Thing

Asking whether something is alive becomes scientific only after we name the unit, the job the definition must do, and the evidence that would distinguish life from a convincing imitation.

Related Articles

- QTC-008 — Life Runs on Gradients
- QTC-021 — When Chemistry Began to Evolve
- QTC-027 — From Information to Inheritance: Tree, Web and Viruses

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