The Grammar of Emergence

Stuart Kauffman's Autocatalytic Sets and the Closure Framework: How the First Closure Bootstrapped Itself from Chemistry

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Collectively autocatalytic sets achieve constraint closure. In constraint-closed systems, a set of boundary condition constraints on the release of energy constructs the very same set of boundary condition constraints. Cells literally construct specifically themselves.
Stuart Kauffman et al., Is the Emergence of Life and of Agency Expected?, 2025

Every finite closure generates remainder. The remainder is not noise. It is the proof that the grammar is finite.
CF Dietz, Consciousness, Closure, and the Cosmos, 2026

Abstract

Stuart Kauffman is a theoretical biologist, MacArthur Fellow, and founder of complexity science at the Santa Fe Institute. For more than five decades his work has addressed a single question from multiple directions: how does organized complexity emerge from simpler components without an external designer? His collectively autocatalytic sets, networks of molecules that mutually catalyze each other's formation and thereby sustain themselves, provide the most rigorous available account of how the first organizational closure could have bootstrapped itself from chemistry at the origin of life. His adjacent possible, the bounded space of what can next come into existence from what currently exists, describes the structured openness through which any organized system expands its own possibilities. His Kantian wholes, systems in which the whole exists for and by means of its parts, name the organizational character shared by all autocatalytic life. This paper argues that Kauffman's framework and the closure framework developed in Consciousness, Closure, and the Cosmos converge at the deepest possible level: the origin of closure itself. The closure framework describes the structure of organized experience and biological life in terms of closure regimes, their remainder, and their supersession. Kauffman describes how the first closure regime could have appeared at all, bootstrapping itself from the thermodynamic remainder of a prebiotic chemistry that did not yet contain any closure. His constraint closure, in which a set of boundary conditions constructs the very same boundary conditions through the reactions it governs, is the structural description of how a closure regime constitutes its own identity from what it opens onto. His adjacent possible is the structured face of remainder: not chaos but the bounded space of what the current closure has not yet constituted and toward which it can expand. Together, Kauffman and the closure framework describe the full arc from the first moment a chemistry became a closure to the present moment where that arc has produced conscious systems that can reflect on their own emergence.

1. Before the First Closure

Four billion years ago, the Earth's surface was a thermodynamic environment of staggering chemical richness and organizational poverty. Energy was abundant: solar radiation, volcanic heat, lightning, hydrothermal vents. Molecular diversity was accumulating: amino acids, nucleotides, lipids, small organic molecules of hundreds of kinds, produced by abiotic chemistry and delivered by meteorites. What was absent was organization: the capacity for any subset of this chemistry to maintain itself, to reproduce its own composition across time, to draw distinctions between what belonged to it and what did not.

The origin of life is the origin of the first biological closure. The moment when some subset of the prebiotic chemistry first began constituting its own identity, maintaining its own boundary conditions through its own activity, drawing the first distinction between inside and outside, self and non-self, is the moment the universe crossed from chemistry to biology. Everything that has happened since, every organism, every nervous system, every thought, every conversation, every paper in this series, is a consequence of that first moment of organizational closure.

The dominant framework for understanding this transition has been the RNA world hypothesis: a self-replicating RNA molecule that could both carry genetic information and catalyze its own replication. The appeal is logical. Template replication is the mechanism that modern life uses for genetic continuity, and RNA can both carry sequence information and catalyze chemical reactions. But the RNA world has a foundational difficulty: how did the first self-replicating RNA arise? Template replication requires the very machinery it is supposed to produce. The chicken-and-egg problem is not solved; it is just moved one step earlier.

Stuart Kauffman proposed a different account, rooted in a different kind of organizational closure. Not a single molecule capable of self-replication, but a network of molecules capable of collectively catalyzing each other's formation. Not template replication as the founding act, but mutual catalysis as the founding act. Not a single closed loop, but a collectively autocatalytic set: a chemistry so organized that the whole network sustains itself through the interactions of its parts, even though no single part is capable of sustaining itself alone. The first closure was not a molecule. It was a grammar.

2. Kauffman's Four Claims

Kauffman's contribution to origin-of-life research and complexity science has four interconnected claims developed across five decades of theoretical and empirical work.

2.1 Collectively Autocatalytic Sets: The Network Is the Unit of Life

A collectively autocatalytic set is a network of molecules in which every molecule's formation is catalyzed by at least one other molecule in the network, and the entire network can be generated from a basic food set of simpler molecules available in the environment. No molecule in the set catalyzes its own formation alone. The catalysis is collective: the network as a whole sustains itself through the mutual interdependence of its members.

Kauffman's theoretical work, formalized by Steel and Hordijk into the RAF framework, shows that such networks arise almost inevitably in sufficiently complex chemical systems. As the diversity of molecular species in a system increases, the probability that any given molecule catalyzes the formation of another molecule in the system increases. When catalytic connectivity crosses a critical threshold, the system undergoes a first-order phase transition: a collectively autocatalytic set spontaneously appears. The transition is not gradual but abrupt, a phase transition from uncatalyzed chemistry to self-sustaining catalytic closure. Life, on this account, did not emerge gradually through the slow accumulation of complexity. It appeared in a phase transition, the way ice appears when water reaches zero degrees.

Kauffman's 2025 paper with colleagues in the Proceedings of the Royal Society B proposes that the earliest life began with small-molecule collectively autocatalytic sets as first-order Kantian wholes, which then merged with peptide and RNA autocatalytic sets to form a third-order Kantian whole. The autocatalytic small-molecule set became the metabolism. The peptide and RNA sets ultimately coevolved to template replication, coding, and the ribosome. The RNA world did not precede metabolism: metabolism and information storage coevolved from their respective autocatalytic foundations.

2.2 Constraint Closure: The System That Constructs Its Own Boundary Conditions

Kauffman's most structurally precise concept is constraint closure, the property that makes an autocatalytic set genuinely alive rather than merely self-sustaining in a chemical sense. In a constraint-closed system, a set of boundary conditions on the release of energy, call them A, B, and C, governs a set of thermodynamic processes, call them 1, 2, and 3. The processes release energy in constrained rather than random ways. And the constrained release of energy through those processes constructs the very same boundary conditions A, B, and C.

The system constructs specifically itself. Not just any boundary conditions, not just a random selection of constraints, but the identical set of constraints that initiated the processes. The constraint set is self-referential: the constraints govern the processes that construct the constraints. This is the structural definition of organizational identity at the chemical level. The cell is not a bag of chemicals. It is a set of constraints that constructs itself through the constrained release of thermodynamic energy. Cells literally construct specifically themselves, and this self-construction is what distinguishes life from non-life at the organizational level.

2.3 The Adjacent Possible: Remainder as Structured Openness

Kauffman's adjacent possible describes the space of what can next come into existence from what currently exists. At any moment in the history of a system, the possible states it can reach in one step are bounded by its current state: not all of chemistry is accessible from any given chemistry, but a specific bounded space of transformations is accessible. As the system moves into the adjacent possible, taking one step from its current state, the adjacent possible itself expands: new possibilities become reachable that were not reachable before the step was taken.

The adjacent possible is structured: it is not the space of all possible states but the space of states reachable from where the system currently is. The history of the system determines what adjacent possible it currently faces. Two systems with different histories face different adjacent possibles even in the same environment. The adjacent possible is path-dependent: where you can go depends on where you have been.

This concept was originally developed in the context of biological evolution, where the adjacent possible at any evolutionary moment is bounded by the organisms, molecules, and ecological relationships that currently exist. But Kauffman has extended it to economics, technological evolution, and any complex adaptive system. The adjacent possible is a general feature of any organized system that exists in a larger space of possible states: the system's current closure determines which possibilities are immediately accessible.

2.4 Kantian Wholes: The Whole That Exists for and by Means of Its Parts

Kauffman borrows from Kant's Critique of Judgment the concept of the natural purpose: an organized entity in which the parts exist for the sake of the whole and the whole exists by means of the parts. He calls such entities Kantian wholes: organized systems in which no part can be understood except in relation to the whole, and the whole cannot exist except through the coordinated activity of the parts.

Collectively autocatalytic sets are Kantian wholes in this precise sense. No single molecule in the set sustains itself. Each molecule exists because other molecules in the set catalyze its formation, and each molecule in turn catalyzes the formation of others. Remove any molecule and the set may collapse. The whole, the self-sustaining network, exists only through the activity of all the parts in concert. And the parts have their chemical character, their role in the network, only in relation to the whole that their mutual activity constitutes.

Kauffman's 2025 paper proposes that nested Kantian wholes, first-order wholes becoming components of second-order wholes which become components of third-order wholes, describe the stages by which prebiotic chemistry achieved the organizational complexity of the first cell. The merger of small-molecule autocatalytic sets with peptide autocatalytic sets and RNA autocatalytic sets produced a third-order Kantian whole whose organizational complexity exceeded what any of its component sets could achieve alone.

3. What Kauffman Needs

Kauffman's framework is the most comprehensive theoretical account of how organized complexity emerges from simpler components at the origin of life. His constraint closure concept is structurally precise, mathematically formalized through the RAF framework, and increasingly supported by empirical evidence. His adjacent possible has become one of the most generative concepts in complexity science, applied from prebiotic chemistry to technological innovation.

There are two gaps that Kauffman's framework does not close. The first is the relationship between constraint closure and the broader phenomenon of organizational closure in living systems above the chemical level. Kauffman establishes constraint closure at the metabolic level and shows how it scales to the Kantian whole of the first cell. He does not fully develop the account of how constraint closure relates to the higher-level organizational closures, neural, cognitive, cultural, that characterize more complex living systems. His framework is richest at the chemical foundation and becomes less specific as one moves up the hierarchy.

The second gap is the relationship between the adjacent possible and remainder. The adjacent possible describes the structured space of what the current system can reach but has not yet reached. This is a spatial and probabilistic concept: it describes the neighborhood of the system's current state. The closure framework's account of remainder is related but more fundamental: remainder is not just what lies in the adjacent possible but what exceeds the closure's constitutive capacity altogether, including what no expansion of the adjacent possible will ever reach. The adjacent possible is the tractable face of remainder: the portion of remainder that is immediately accessible to the current closure's expansion. But remainder extends beyond the adjacent possible to what no finite closure can fully capture, which is what the CC-C framework calls M.

The closure framework addresses both gaps. The higher-level organizational closures of neural, cognitive, and cultural life are not separate phenomena from constraint closure but the same structure operating at higher levels of organizational depth, each using the outputs of lower-level closures as its elements and setting boundary conditions for those lower levels. And the adjacent possible is the immediately accessible face of remainder: the boundary region where the current closure meets what it has not yet constituted and can reach in one step. M is what lies beyond all adjacent possibles: the inexhaustible ground that every expansion of the adjacent possible approaches and none reaches.

4. Two Concepts at the Foundation

The closure framework is introduced here at its most foundational level: the level at which Kauffman's constraint closure and the framework's closure regime are the same structural reality described in different vocabularies.

4.1 Constraint Closure Is Closure Regime at the Chemical Level

A closure regime is a system that stabilizes some content by drawing distinctions, establishing identity criteria, and maintaining lawful relationships among its elements. It constitutes facts within its scope and generates remainder at its boundary.

Kauffman's constraint closure is a closure regime in this precise sense, described at the level of thermodynamic boundary conditions rather than cognitive distinctions. The set of boundary conditions A, B, C draws distinctions in the thermodynamic landscape: these energy release pathways are constrained in these specific ways, and those are not. It establishes identity criteria: the criteria that determine when the system's organizational state is maintained, when the constraints are intact and the processes they govern are proceeding correctly. And it maintains lawful relationships among its elements: the set of processes 1, 2, 3 are in lawful relationship with the constraints A, B, C precisely because the processes construct those constraints.

The self-referential character of constraint closure, the set of boundary conditions that constructs itself through the processes it governs, is the most stripped-down possible instance of what the closure framework calls a closure regime. The cognitive and linguistic closures that Boroditsky and the Grammar of Knowing address are enormously more sophisticated versions of the same structure: a set of distinctions and identity criteria that constitutes itself through its own constitutive activity. Kauffman found this structure at the chemical foundation of life. The closure framework found it at the organizational foundation of experience. They are the same structure at different levels of organizational depth.

4.2 The Adjacent Possible Is the Structured Face of Remainder

Remainder is what the closure generates at its boundary: the domain of what exceeds the closure's constitutive capacity, what lies outside its scope, what it opens onto without being able to fully constitute. In the closure framework, remainder is not merely what the system has not yet done. It is the positive resource that drives supersession: the mismatch between what the closure constitutes and what it opens onto creates the pressure for the closure to update its organizational state.

Kauffman's adjacent possible is the immediately accessible face of this remainder: the subset of remainder that the current closure can reach in one organizational step. When a collectively autocatalytic set expands by incorporating a new molecular species, it moves into the adjacent possible, and the adjacent possible itself expands: new chemical reactions become possible that were not possible before. This expansion is the autocatalytic set using its remainder, in this case the broader chemistry available in the environment, as a resource for its own growth and organizational enrichment.

M, the inexhaustible ground that every closure opens onto without exhausting, is the limit of all adjacent possibles: the space that no expansion of any closure, however deep and complex, will ever fully constitute. Every closure, from the first autocatalytic set to the most sophisticated human consciousness, faces remainder that exceeds its current constitutive capacity. The adjacent possible is the near edge of that remainder: what the closure can reach next. M is what lies beyond all next steps: the inexhaustibility that makes the expansion of the adjacent possible possible without ever completing it.

5. Four Claims, One Structure

The vocabulary correspondence between Kauffman's complexity science and the closure framework is the most historically foundational in the series. What Kauffman calls a collectively autocatalytic set, the closure framework calls the first closure regime: the first organizational structure that constitutes its own identity from the chemistry it opens onto. What Kauffman calls constraint closure, the framework calls the self-referential character of organizational identity: the closure that constructs its own boundary conditions through the processes those boundary conditions govern. What Kauffman calls the adjacent possible, the framework calls the structured face of remainder: the bounded space of what the current closure can constitute next. And what Kauffman calls the Kantian whole, the framework calls the organizational unity of a closure regime: the system in which no part can be understood except in relation to the whole it constitutes with the others.

5.1 The Phase Transition Is the First Appearance of Closure

Kauffman's first-order phase transition, the moment when chemical diversity crosses the catalytic threshold and a collectively autocatalytic set spontaneously appears, is the moment of the first closure in the history of the universe. Before the phase transition, there is chemistry: reactions, thermodynamic gradients, molecular diversity, but no organizational closure. After the phase transition, there is life: a subset of chemistry that constitutes its own identity, maintains its own boundary conditions, draws its own distinction between self and environment.

The abruptness of the transition matters. The closure framework's account of closure is structural: a system either draws distinctions and constitutes facts or it does not. There is no gradual approach to being a closure regime. The phase transition from uncatalyzed chemistry to collectively autocatalytic set is the abrupt emergence of organizational structure from a chemistry that previously had none. The universe went from containing no closure to containing closure in a transition as sharp as the freezing of water. Every closure regime that has existed since, including the one currently reading these words, is a descendant of that first phase transition.

5.2 Constraint Closure Is the Founding Act of Supersession

The self-referential character of constraint closure, the set of boundary conditions that constructs itself through the processes it governs, is the founding act of what the closure framework calls supersession: the process by which a closure updates its organizational state to maintain its identity when the mismatch between its current constitution and what it opens onto exceeds what it can absorb.

In the first collectively autocatalytic set, supersession is metabolic: the set must continuously process its food source to maintain the constraints that define it. When the food source changes, when the chemical environment shifts, the autocatalytic set must adjust its constraint set or dissolve. The adjustments that maintain constraint closure across environmental change are the most primitive form of what becomes, in more complex organisms, learning, adaptation, and eventually conscious inquiry. The grammar of supersession is already present in the first autocatalytic set: maintain the closure or dissolve into the unconstrained chemistry from which it emerged.

5.3 Nested Kantian Wholes Are Nested Closure Regimes

Kauffman's account of how small-molecule autocatalytic sets merged with peptide and RNA autocatalytic sets to form nested Kantian wholes is the chemical history of what the closure framework calls nested closure regimes: higher-level closures that use the outputs of lower-level closures as their elements and set boundary conditions for those lower-level closures.

The first-order Kantian whole, the small-molecule autocatalytic set, is the foundational closure. The second-order Kantian whole, incorporating peptide or RNA autocatalytic sets, is a higher-level closure that uses the first-order closure's outputs as its elements. The third-order Kantian whole, the full protocell with metabolism, template replication, and coding, is the higher-level closure still that integrates all three. Each merger is the formation of a new closure level: a new organizational reality that constitutes facts that the lower-level closures alone cannot constitute. The history of life that Jablonka traces through four inheritance systems operating at different timescales begins at this chemical foundation that Kauffman describes.

5.4 The Adjacent Possible Is Remainder That Can Be Reached

Kauffman's adjacent possible is the most concrete and practically applicable expression of the closure framework's account of remainder. At any moment in the life of an organized system, the remainder it faces is not uniformly accessible. Some of what exceeds the current closure's constitutive capacity can be reached by a single organizational step. Other portions of remainder require many steps, or may require the emergence of an entirely new level of organizational closure, or may lie permanently beyond the reach of any closure of this type.

The adjacent possible is the tractable near edge of remainder. It is where growth, learning, and creative expansion happen: where the current closure reaches into what it does not yet constitute and incorporates it into what it does. Every expansion into the adjacent possible changes the adjacent possible itself: the new closure, enriched by what it has incorporated, faces a different and expanded set of what it can reach next. The history of biological evolution, of cultural development, of individual learning, is the history of organized systems repeatedly expanding into their adjacent possible, each expansion enabling the next.

What no expansion reaches is M: the inexhaustible ground that every adjacent possible opens onto without exhausting. The adjacent possible expands without limit but M does not diminish. Every new closure constitutes new facts and reveals new remainder. The game is not convergent: the universe does not approach a state where all remainder is eliminated and all of M has been constituted. Kauffman's phrase for this, the universe is ceaselessly creative, is the complexity scientist's version of what the closure framework calls the inexhaustibility of M.

6. The Connection to the Full Arc of Life

Kauffman occupies a unique position in the series. Every other paper has described closure regimes that already exist: Noble's cardiac cells, Friston's neural hierarchies, Maturana's autopoietic cells, Levin's morphogenetic patterns, Jablonka's inheritance systems, the cognitive and linguistic closures of Boroditsky and Crum. Kauffman describes how closure first came to exist at all. He is not describing a feature of life. He is describing the origin of life's organizational character.

This positions Kauffman as the foundation of the biological side of the series. The arc runs from Kauffman's first autocatalytic set, through Maturana's autopoiesis, through Noble's biological relativity and Friston's hierarchical inference, through Jablonka's four inheritance systems and Levin's bioelectric morphogenesis, to Thompson's phenomenological bridge and Jablonka's account of the emergence of consciousness. At every level, the same structural logic applies: a closure regime constituting its own identity from what it opens onto, generating remainder at its boundary, using that remainder as the resource for the next closure's emergence. Kauffman found that logic at the chemical foundation. The rest of the series traces it upward through the full organizational depth of biological life.

The connection to the CC-C framework's cosmological claim is the most direct in the series. Consciousness, Closure, and the Cosmos argues that C, bare conscious presence, is not a late product of biological evolution but a primitive that precedes and underlies all organizational structure. Kauffman's framework does not engage this claim directly. But his account of the universe as ceaselessly creative, producing genuine novelty through the expansion of adjacent possibles that could not have been predicted from any prior state of the universe, is the complexity scientist's expression of what the CC-C framework means by M: the inexhaustible ground that every closure opens onto and none exhausts. Kauffman does not call this ground conscious. The CC-C framework argues that it is. The disagreement is productive and the connection is real.

7. The Grammar of Emergence

Four billion years ago, somewhere on the early Earth, a chemistry crossed a threshold. The diversity of molecular species present in some local environment became dense enough, the catalytic connections between them rich enough, that a phase transition occurred: a collectively autocatalytic set spontaneously appeared. A network of molecules began sustaining itself, maintaining its own boundary conditions through its own thermodynamic activity, constructing specifically itself from what the environment provided.

This was the first closure. The first moment in the history of the universe where an organized system drew a distinction between itself and what it was not, constituted its own identity from what it opened onto, and maintained that identity through continuous interaction with what it could not fully incorporate. Every cell, every organism, every nervous system, every thought since then is a descendant of that first phase transition. The grammar of emergence is the grammar of how closure first appeared.

Stuart Kauffman has spent five decades working out the details of this grammar: the mathematics of catalytic closure, the thermodynamics of constraint closure, the expansion logic of the adjacent possible, the organizational character of Kantian wholes. His work is the most rigorous available account of how the first closure bootstrapped itself from chemistry that contained no closure.

The closure framework names the structural logic that Kauffman's account presupposes and extends. Constraint closure is a closure regime at the chemical level: a set of distinctions and identity criteria that constructs itself through its own constitutive activity. The adjacent possible is the structured face of remainder: the bounded space of what the current closure can reach but has not yet constituted. Nested Kantian wholes are nested closure regimes: higher-level closures using lower-level outputs as elements, setting boundary conditions for the levels below. And M, the inexhaustible ground that every adjacent possible opens onto without exhausting, is what Kauffman calls the ceaseless creativity of the universe: the inexhaustibility that makes every next step possible without ever reaching a final state where nothing remains to be constituted.

We are, as Kauffman says, at home in the universe. Not because the universe was designed for us, but because we are made of the same organizational logic that has been present since the first autocatalytic set appeared. Closure has been the grammar of life for four billion years. We are what happens when that grammar deepens far enough to reflect on itself.

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Author's Note

This paper is the fourteenth in a series engaging thinkers whose work converges with the closure framework developed in Consciousness, Closure, and the Cosmos. Stuart Kauffman is emeritus professor of biochemistry at the University *of Pennsylvania and affiliate faculty at the Institute for Systems Biology in Seattle. He is a MacArthur Fellow and Norbert Wiener Medal recipient, and one of the founders of the Santa Fe Institute, where complexity science as a field was born. His work on autocatalytic sets, self-organization, and the adjacent possible spans more than five decades and has influenced biology, economics, philosophy, and complexity science more broadly. This paper occupies the foundational position in the biological arc of the series. Every other paper in the biological half of the series describes closure regimes that already exist: this paper describes how the first closure could have appeared at all. Kauffman's constraint closure and the closure framework's closure regime are the same structural reality described in different vocabularies. This convergence is the deepest in the series because it reaches to the chemical origin of what the closure framework describes at every other level. The author also notes a productive disagreement: Kauffman's universe is ceaselessly creative but not, in his framework, conscious. The CC-C framework argues that M, the inexhaustible ground every closure opens onto, has the character of conscious presence. This disagreement is not resolved in this paper but named as the site of the most philosophically consequential conversation the series opens. The author welcomes engagement from Kauffman directly and from origin-of-life researchers, complexity scientists, and philosophers who find the convergence between autocatalytic sets and the closure framework either illuminating or contestable.*