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*Hypothesis*

# The Carbon-Based Evolutionary Theory: A Conceptual Framework Unifying Chemical, Biological, and Social Evolution

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## Abstract

What mechanisms drive and shape the stepwise evolution from simple carbon-based materials (CBMs) to complex organisms and societies? This fundamental question remains unresolved because chemical, biological, and social evolution have often been studied in isolation. Here we propose the Carbon-Based Evolutionary Theory (CBET), which is grounded in rigorous integrative reasoning and supported by extensive empirical evidence, mathematical modeling, resilience to falsification, and cross-hierarchical explanatory power. CBET extends the natural selection mechanism from Darwinian theory and introduces the spirodynamic feedback mechanism. These dual mechanisms respectively drive and shape CBM evolution, resolving the aforementioned fundamental question for the first time and explicitly explaining the increasing orderliness in biological and social systems. Furthermore, CBET reveals the natural balances of competition versus collaboration, elimination versus inclusiveness, selfishness versus altruism, and individual versus collective interests. It thus establishes an evolutionary foundation for the social sciences and fosters the core ethics for harmonious societal development.

**Keywords:** carbon-based material; mechanism; chemical evolution; biological evolution; social evolution; natural selection; theory

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## 1. Introduction

Why have simple carbon-based materials (CBMs), such as carbon atoms, methane, and carbon dioxide, evolved stepwise to the complex, diverse, and ordered organisms and societies we observe today? This fundamental question has long fascinated scholars but remains unresolved [1–8]. It involves the chemical evolution of organic molecules [5], the biological evolution of organisms, and the social evolution of animal and human societies [7,8]. Traditionally, these three domains have been studied in isolation [1–8], and thus theories developed in one domain often fail to apply to others. For instance, while Darwinian theory provides a robust account for biological evolution, it does not address chemical or social evolution.[1,2] Consequently, it offers neither a foundational explanation for life's origin nor reliable insights for understanding societal development.[1–4] Notably, Social Darwinism—an improper extension of Darwinian concepts to societal contexts—has been misused to rationalize harms like selfishness, slavery, and colonialism [2,4]. Additionally, certain biological phenomena, such as epigenetic changes and neutral mutations have not been seamlessly integrated into Darwinian theory.[2] To bridge these gaps, here we propose the Carbon-Based Evolutionary Theory (CBET), which aims to unify chemical, biological, and social evolution within a single coherent framework.

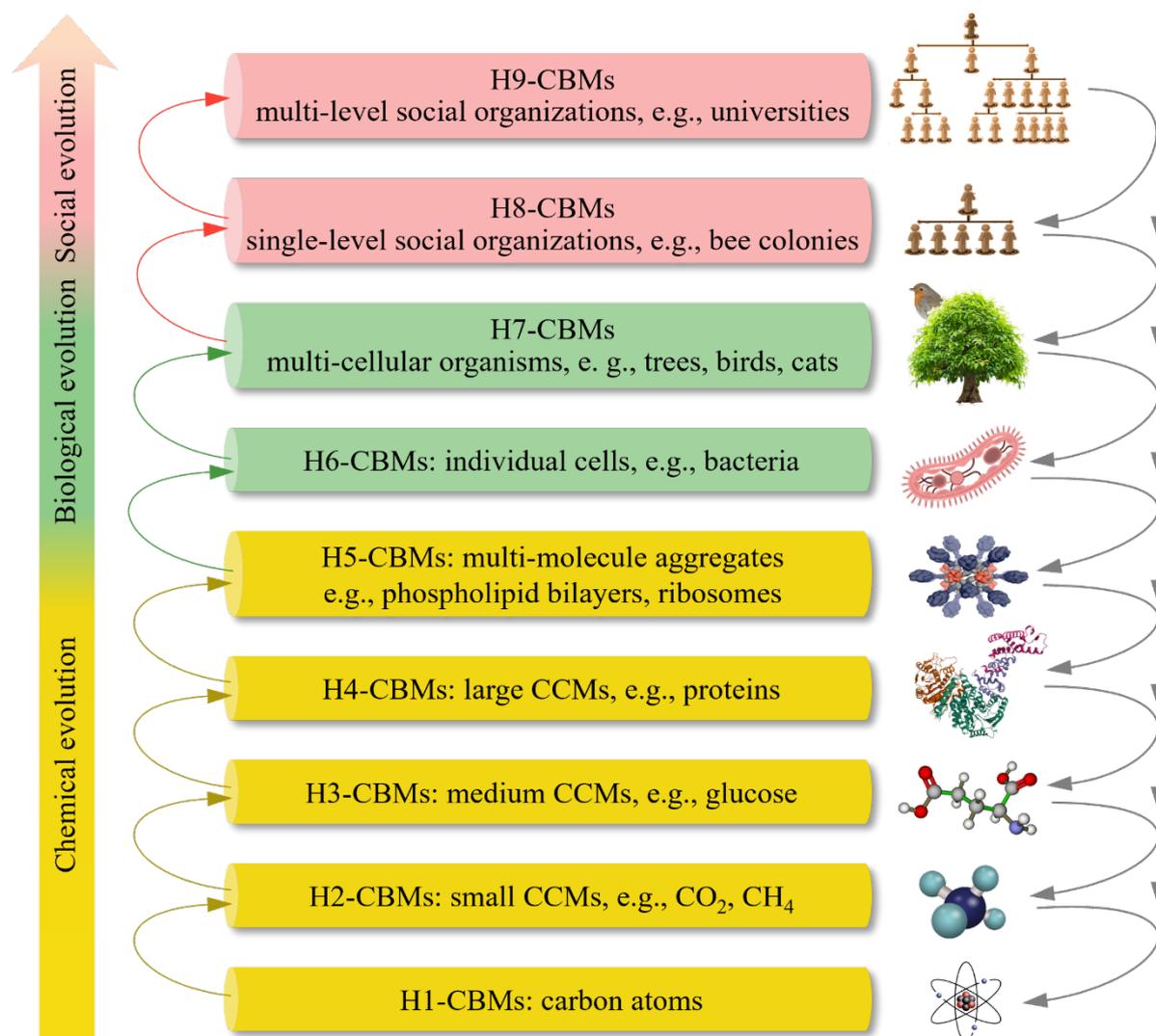
Distinct from most scientific theories that focus on domain-specific issues, CBET belongs to a rare type of broad-scoped theories addressing cross-domain questions. It is considerably broader in scope than Darwinian theory, though narrower than systems theory and cybernetics. These broad-

scoped cross-domain theories cannot be constructed through novel experiments, which are inherently limited by narrow targets. Instead, they can only be established through the integration of cross-domain knowledge. Accordingly, Darwinian theory was founded on the synthesis of diverse knowledge in the 19th century (e.g., Malthusian population theory, paleontology, artificial breeding)[2], and CBET is grounded in the integration of extensive, well-established cross-disciplinary knowledge accumulated through immense experimental and theoretical advances since Darwin's time.

## 2. Results

### 2.1. Hierarchies and Functions of CBMs

The core concept of 'organisms' in Darwinian theory is extended to 'carbon-based materials (CBMs)' in CBET. As illustrated in Figure 1, CBMs can be categorized into nine hierarchies (H1–H9), based on the criterion that higher hierarchies are constructed from lower ones via chemical, physical, or more complex integrative interactions, sometimes combined with certain non-CBM materials.



**Figure 1.** Nine hierarchies (H1–H9) of carbon-based materials (CBMs) from carbon atoms and carbon-containing molecules (CCMs) to social organizations. Arrows indicate the stepwise or cross-hierarchy formation or degradation of higher-hierarchy CBMs.

H1-CBMs refer to carbon atoms, which likely originated in stellar interiors.[9] H2-CBMs are small carbon-containing molecules (CCMs), like CH<sub>4</sub> and CO<sub>2</sub>. H3-CBMs are medium CCMs, like glucose and lysine. Polymerization of some H3-CBMs forms H4-CBMs, which refer to large CCMs, like proteins and nucleic acids—some of which can assemble into H5-CBMs, namely multi-molecule aggregates (MMAs), like phospholipid bilayers. The transition to life occurs at H6 (cells) and culminates at H7 (multicellular organisms such as pines and humans). Some H7 individuals form H8-CBMs, which represent single-level societies (e.g., ant colonies, small companies). Some H8-CBMs form H9-CBMs, which are multi-level societies (e.g., universities, armies, nations). Boundaries between hierarchies are not rigid, and transitional forms such as peptides (between H3 and H4) and viruses (between H4 and H5) can act as bridges facilitating hierarchical elevation of CBMs.

The following functions of CBMs are crucial to CBM evolution.

**(1) Macromolecular backbone function of carbon atoms.** Carbon atoms possess a unique ability to form long, stable chains and complex rings via strong, versatile C-C bonds. These bonds can link to diverse atoms (e.g., hydrogen, oxygen, nitrogen) and functional groups (e.g., hydroxyl, carbonyl, amino groups), yielding immense molecular diversity.[10] In contrast, silicon and boron can form weak and short covalent chains (e.g., Si-Si, B-B) prone to cleavage. This fundamental disparity explains why CBMs, rather than silicon- or boron-based ones, have naturally evolved into life.

**(2) Hierarchy elevation function.** Some CBMs can form higher-hierarchy CBMs through physical, chemical, biological, and/or social interactions. This is evidenced by transitions from CO<sub>2</sub> to amino acids, from amino acids to proteins, from ant individuals to ant colonies, and from small companies to large corporations.

**(3) Relative stability function.** Various CBMs are relatively stable. For instance, diverse H3-CBMs could persist for billions of years in meteorites;[11] some H4-CBMs were preserved in fossils for millions of years;[12] and humans typically live for decades.

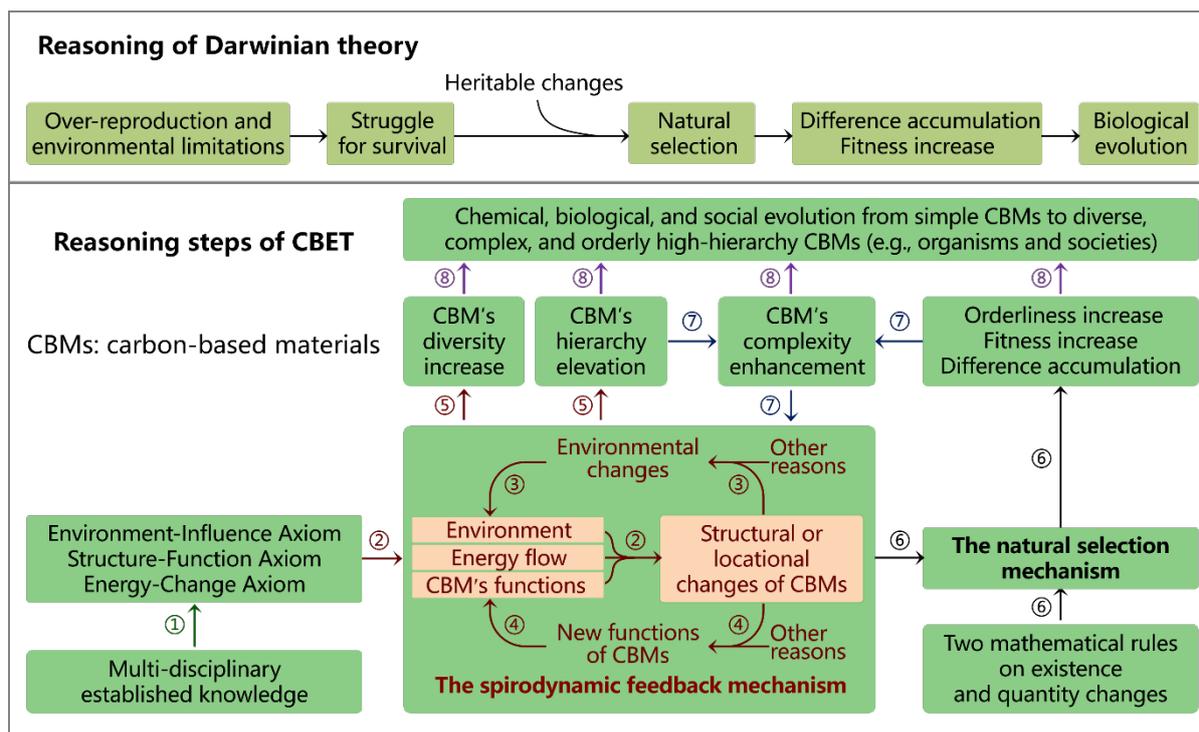
**(4) Changeability function.** The repeated formation and degradation of higher-hierarchy CBMs constitute Earth's carbon cycles,[13] and various CBMs (e.g., proteins and organisms) produced in these cycles exhibit variations relative to their progenitors.

**(5) Information function.** H6-CBMs and H7-CBMs can encode, read, translate, change, store, and transmit genetic information through the interactions of nucleic acids and proteins.[2] They also use diverse signaling pathways to respond to internal and external changes. Some high-hierarchy CBMs harness additional information forms—such as scents, sounds, behaviors, scripts, and electromagnetic waves.

**(6) Other functions.** The energy-storage and energy-release functions of various H3-CBMs (e.g., glucose) and H4-CBMs (e.g., lipids), the catalytic functions of various H4-CBMs (e.g., proteins), the reproduction of H6-CBMs, and the knowledge accumulation function of humans are all crucial to CBM evolution.

## 2.2. Reasoning Steps of CBET

CBET was derived through eight steps and five tiers of integrative reasoning (Figure 2). Mathematical formulation of these steps is given in Supplementary Information.



**Figure 2. The reasoning structure of the Carbon-Based Evolutionary Theory (CBET) and its relationship to Darwinian theory.** The derivation of CBET comprises eight reasoning steps (Steps 1–8), which are organized into five integrative tiers indicated by arrows with different colors. The first four tiers derive the three axioms, the spirodynamic feedback mechanism, the natural selection mechanism, and the reasons for complexity enhancement, respectively; the fifth tier represents their synergy. For comparison, Darwinian theory is shown to align primarily with Step 6 of CBET.

### Step 1. Reasoning of Three Axioms

The CBET framework begins with the derivation of three axioms from foundational knowledge across diverse disciplines, such as Newtonian mechanics from physics, the laws of thermodynamics and chemistry, and principles from the social sciences. This is achieved by extracting their core qualitative relationships to establish their applicability to all organic molecules, organisms, and societies. This derivation represents Tier 1 integrative reasoning within CBET. These axioms are explicit and have long guided research in physics, chemistry, biology, and social sciences.

**(1) The Environment–Influence Axiom.** Environment factors influence structural or locational changes in a material. These changes, in turn, can alter the environment of the material. For example, Earth’s habitable environment fosters CBM evolution,[14,15] which in turn profoundly transforms Earth’s environment.

**(2) The Structure–Function Axiom.** A material’s structure partly determines its functions, and structural changes can generate new functions. Concurrently, functions are the internal causes for maintaining or modifying structures. For example, a cell’s structure dictates its metabolic and reproductive abilities, which in turn are essential for sustaining and replicating that structure. This axiom suggests that the execution of a complex function (e.g., a car’s operation and a cell’s reproduction) — defined as one requiring multiple coordinated steps—typically necessitates a complex structure of specialized, organized components, because each step requires a specialized structural component.

**(3) The Energy–Change Axiom.** Energy flow drives structural changes (e.g., protein synthesis) or locational changes (e.g., bird flying) in a material under the modulation of functions of the material (internal causes) and the environment (external causes). This axiom highlights energy flow as the universal driver of structural and locational changes across all CBMs, from carbon atoms to

societies. It is derived from and supported by the two axioms above and principles from Newtonian mechanics and organic chemistry, as well as evidence from animal locomotion and social activities.

#### Steps 2–5. Reasoning of the spirodynamic Feedback Mechanism

**Step 2.** According to the Energy-Change Axiom, energy flow under the modulation of functions of CBMs and the environment drives structural or locational changes in CBMs.

**Step 3.** Structural or locational changes from Step 2 can cause environmental changes. Other reasons like earthquakes can also cause environmental changes. Environmental changes can feed back to Step 2 and thus initiate further structural or locational changes in CBMs. For instance, the atmospheric oxygenation by photosynthetic bacteria ~2.5 billion years ago selected against anaerobes in favor of aerobes.[2,16]

**Step 4.** Structural changes in CBMs and other reasons such as environmental shifts can generate novel functions. These new functions can feed back to Step 2 and thus initiate further structural changes in CBMs. An example is the formation of nucleotides, which enables their new function to polymerize into nucleic acids.

**Step 5.** The iterative feedback loops between changes in structures or locations (Step 2), functions (Step 3), and environments (Step 4) constitute the spirodynamic feedback mechanism. This represents Tier 2 integrative reasoning in CBET, which integrates the three axioms with the functions of CBMs and the foundational concept of feedback loops in systems theory and cybernetics.[17] This mechanism serves as the primary engine for amplifying CBM diversity (partially due to the changeability function of CBMs) and elevating CBM hierarchies (partially due to the hierarchy elevation function of CBMs).

#### Step 6. Reasoning of the natural Selection Mechanism

The following two rules are self-evident in fundamental mathematics.

**(1) The Quantity-Existence Rule.** A material exists if its cumulative formation exceeds its cumulative degradation. This applies to the synthesis/breakdown of molecules, birth/death of organisms, and establishment/dissolution of social organizations.

**(2) The Quantity-Change Rule.** The change in a material's existing quantity over a time interval [a,b] is determined by its initial quantity and the ratio of its total formation ( $\Gamma_{ab}$ ) to its total degradation ( $\Lambda_{ab}$ ) within that period. This ratio reflects a material's overall performance in formation and sustenance (OPFS). In the context of CBET, we define this OPFS ratio as the universal measure of fitness (Equation 1).

$$\frac{\Gamma_{ab}}{\Lambda_{ab}} = \text{OPFS}_{ab} = \text{Fitness}_{ab} \quad (1)$$

In modern biology, fitness is defined as the number of offspring an individual leaves in the next generation.[2] This measure fails to capture the fitness of molecules, social organizations, or worker bees, and it neglects generation time. The universal fitness calculation in Equation 1 overcomes these limitations. Additionally, we have developed another equation for calculating relative fitness in Supplementary Information.

Guided by the two mathematical rules, Changes that increase fitness, as well as the structures bearing such changes, tend to accumulate, while changes that decrease fitness, as well as the structures bearing such changes, tend to be eliminated. This process constitutes the natural selection mechanism and Tier 3 integrative reasoning within CBET. Natural selection filters changes resulting from the spirodynamic feedback mechanism and thus non-randomly shapes CBM evolution and enhances fitness across all hierarchies. As suggested by the Structure-Function Axiom, such fitness improvements typically entail greater structural orderliness and enhanced internal collaboration.

### Step 7. Reasoning of Complexity Enhancement and Its Feedback

The enhanced internal collaboration in Step 6 can support the hierarchical elevation in Step 5. They collectively increase the structural complexity of CBMs. This represents Tier 4 integrative reasoning in CBET, which integrates the effects of spirodynamic feedback and natural selection. The heightened structural complexity itself is a type of structural change and can thus constitute an input into the spirodynamic feedback and natural selection mechanisms. This creates a new feedback loop that can, in some cases, intensify the pressure of natural selection—a phenomenon illustrated by co-evolutionary arms races, such as those between predators and prey.[18] For instance, structural adaptations that grant gazelles greater speed exert stronger selection pressure on their predators (e.g., cheetahs) for corresponding speed enhancements. The success of these faster predators then exerts even stronger selective pressure for increased speed in the gazelle population.

### Step 8. Synergy of the Reasoning Steps

The seven reasoning steps above demonstrate how CBET integrates three axioms, two mathematical rules, CBM functions, and environmental factors to formulate two key mechanisms that respectively drive and shape the stepwise evolution from simple CBMs to complex, diverse, and orderly organisms and social organizations. This synergistic eighth step represents Tier 5 integrative reasoning in CBET and can be expressed using the CBET Equation (Equation 2), where  $\Delta E$  denotes net energy input,  $M_d$  the influence of the spirodynamic feedback mechanism,  $M_t$  the influence of the natural selection mechanism, and  $\Delta\Omega$  the synergistic changes in the diversity, complexity, and orderliness of the relevant CBMs.

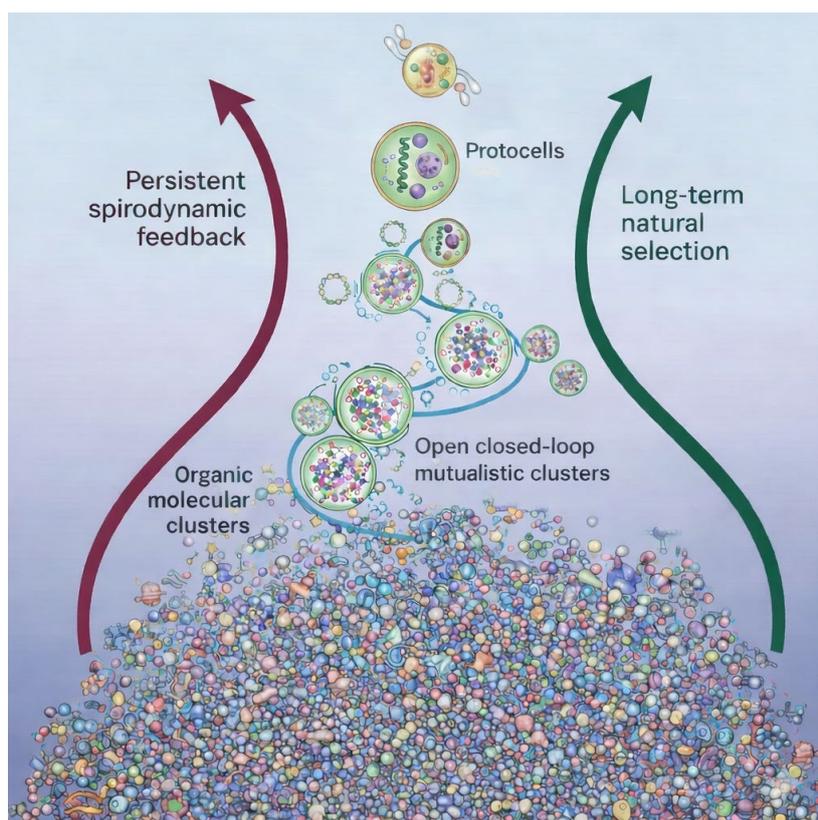
$$\Delta E = M_d \cdot M_t \cdot \Delta\Omega \quad (2)$$

This equation shows that energy can be converted into the diversity, complexity and orderliness of carbon-based matter. Yet the conversion is not entirely direct, instantaneous or quantitative. Instead, it requires two steps: generating changes through the spirodynamic feedback mechanism, and selecting changes through the natural selection mechanism.

In comparison, Darwinian theory primarily aligns with Step 6 of CBET and derives natural selection from over-reproduction, environmental limitations, struggle for survival, and heritable changes (Figure 2). It clarifies neither the mathematical rules of natural selection nor the mechanism underlying the hierarchy elevation and diversification of CBMs.

### 2.3. Application for Explaining Life's Origin

The above eight reasoning steps of CBET collectively form a schematic explanation for life's origin, which is the most intriguing event in the evolution of CBMs.[2] The integration of CBET with knowledge from astronomy, chemistry, biology, and other disciplines is needed to further clarify the possibility of life's origin and the scenario that chemical evolution proceeds toward life's origin (Figure 3).



**Figure 3.** The conceptual trajectory of chemical evolution toward life's origin under the synergistic action of the spirodynamic feedback and natural selection mechanisms within the CBET framework. Persistent spirodynamic feedback drives the long-term accumulation and diversification of organic molecules and their clusters in prebiotic environments. From this heterogeneous molecular reservoir, open closed-loop mutualistic clusters become increasingly prevalent, as they are theoretically advantageous under long-term natural selection. Their advantages are further amplified when such mutualistic clusters acquire reproductive capacity through structural modification, as reproduction can increase their prevalence. These reproductive clusters represent the earliest life structures (protocells).

**(1) Driving role of spirodynamic feedback towards life's origin.** It has been established in chemistry and widely utilized in industrial settings that, along with other materials, H1-CBMs can form H2-CBMs, some H2-CBMs can form H3-CBMs, and some H3-CBMs can form H4-CBMs (macromolecules).[3,5,6,15] These processes are driven by energy flows under the modulation of environmental factors and functions of relevant CBMs, which aligns with the spirodynamic feedback mechanism (Figure 2). In astronomy and geology, these processes could have persisted on Earth for hundreds of millions of years before life's origin,[5,6,15] and thus would have led to the accumulation of myriad organic molecules (H2-CBMs, H3-CBMs, and H4-CBMs). Crucially, the early atmosphere—with its dynamic fluidity, energy gradients, and abundance of carbon compounds—effectively constituted a vast, continuous prebiotic organic molecular reactor.[19–25] In physics, energy flows—such as those from wind, water flow, and wet-dry cycles—can drive the assembly of macromolecules into innumerable MMAs (H5-CBMs, such as phospholipid bilayers) and MMA clusters (the functions of relevant CBMs (e.g., their interaction through hydrogen bonds) also influence the formation of MMAs and MMA clusters). Thus, through persistent spirodynamic feedback, a vast and diverse reservoir of organic molecules and their clusters was built up on early Earth, providing the necessary prebiotic feedstock from which life could emerge.

**(2) Shaping role of natural selection towards life's origin.** Due to their relative complex structure, some organic molecules (H2-CBMs, H3-CBMs, H4-CBMs) or their clusters can catalyze the synthesis or degradation of proteins, nucleic acids, polysaccharides, and other biomacromolecules. This accelerates the formation-degradation cycles of organic molecules and their clusters. Natural

selection preferentially accumulated organic molecules and their clusters that can be readily formed but resistant to degradation through their formation-degradation cycles. Some organic molecular clusters can acquire substances (e.g., water, methane) and energy from the environment, and the core organic molecules within these clusters establish a closed-loop mutualistic relationship (e.g., A aids B, B aids C, and C aids A) with respect to the raw materials, energy, catalysts, and protective agents needed for their generation and maintenance. For instance, proteins and RNA can form diverse open closed-loop mutualistic clusters, as many proteins can catalyze RNA synthesis, and many RNA molecules (e.g., ribosomal RNAs) can catalyze protein synthesis.[2] DNA, lipids, and polysaccharides can participate in such clusters as DNA can stably store and provide information for the replicative synthesis of proteins, RNA, and DNA, polysaccharides can supply energy for the synthesis of proteins, RNA, and DNA, and lipids provide a suitable environment and protection for the synthesis of proteins, RNA, DNA, and polysaccharides. Some such open closed-loop mutualistic clusters possess inherent advantages against some other clusters to become relatively prevalent under long-term natural selection due to their openness and closed-loop mutualism. Furthermore, when such a cluster acquires reproductive capacity via structural modification, its natural selection advantage is further enhanced, because reproduction quantitatively increases the corresponding cluster. Information-encoding molecules (e.g., DNA and RNA) can support such a reproductive cluster to produce certain macromolecules according to certain sequences. Since all known life structures are open closed-loop mutualistic clusters of organic molecules with reproductive capacity[2], chemical evolution—i.e., the evolution of organic molecules—proceeds toward life's origin under the synergistic action of the spirodynamic feedback and natural selection mechanisms. Therefore, the likelihood of life emerging from prebiotic molecular clusters increased over planetary timescales on a habitable world. The mathematical modeling in Supplementary Information suggests that the first life structure could have emerged 760 million years after the formation of the Earth, and that 75 million abiogenesis events could have taken place over the subsequent 4 million years. Notably, the vast majority of living structures generated by these events likely perished due to natural disturbances such as lightning strikes, torrential rains, and volcanic eruptions.

**(3) Shaping role of natural selection after life's origin.** The capacity for reproduction confers living structures with a fundamental advantage under natural selection. Moreover, the persistent action of natural selection is expected to amplify this advantage, making reproductive living structures increasingly prevalent compared to non-reproductive organic clusters. Furthermore, once a particular life form establishes a dominant advantage under natural selection, it can, in principle and over evolutionary timescales, outcompete and exclude alternative life forms (e.g., those based on D-amino acids).[2]

#### 2.4. Application for Clarifying Misunderstandings

CBET can clarify the following common misunderstandings about evolution.

**(1) Misunderstanding about 'Survival of the fittest'.** Darwin adopted this phrase as shorthand for natural selection, but it is often interpreted literally to mean that only the fittest can survive.[1,4] A bacterial mutant with a detrimental mutation can increase in population size, even if its growth rate (e.g., 0.05% per day) is lower than that of its wild-type counterpart (e.g., 0.30% per day). This illustrates that 'survival of the fit enough' is more literally accurate than 'survival of the fittest.' Likewise, major evolutionary transitions—such as multicellularity, endothermy, and eusociality—could have been initiated by pioneers that were not fitter than their ancestors but were fit enough to establish new lineages.

**(2) Misunderstanding that all traits are advantageous.** The example above shows that neutral or detrimental traits can persist, provided the relevant CBM is fit enough. This is also evidenced by the vulnerability of human infants and the prevalence of neutral mutations in genomes.[2] Furthermore, traits may be advantageous in some contexts but detrimental in others. For instance, giraffes' height aids browsing and combat but hinders rising from ground.[26] Additionally, the fitness of a CBM reflects the combined contribution of all its traits, though specific key traits (e.g.,

antelope speed) can have a substantial effect on fitness. Therefore, natural selection shapes both all-around and specialized adaptation.

**(3) Misunderstanding that natural selection is a process of ruthless elimination.** As elucidated above, natural selection is also inclusive because it can tolerate advantageous, neutral, and even detrimental traits, provided the relevant CBM is fit enough, particularly in conducive environments when few competitors are available. This inclusiveness is also evidenced by the long-term increase in biodiversity throughout Earth's history, though catastrophes such as asteroid impacts occasionally trigger sharp declines in biodiversity.[2] Furthermore, the vast diversity of CBMs at H4 and higher hierarchies—driven by the spirodynamic feedback mechanism—facilitates the origin of life and higher-hierarchy CBMs and the adaptation of organisms and societies to diverse environments.

**(4) Misunderstanding that natural selection equals selfishness.** Selfish behavior is critical for acquiring energy, resources, favorable environments, and mating opportunities.[1,27] Yet CBET shows that selfishness and altruism coexist and balance throughout evolution. Diverse molecules often serve as catalysts, energy sources, or building blocks for the replication of other molecules;[4] diverse molecules in cells aid the formation or maintenance of other molecules; many immune cells in animals sacrifice for other cells; ant workers sacrifice for colony reproduction;[7] and humans in armies or police may die for societies. According to the Energy-Change Axiom, these altruistic behaviors are driven by energy flow that is modulated by the functions of the relevant CBMs and the environment.

**(5) Misunderstanding that only heritable changes matter.** It is frequently assumed that natural selection acts solely on heritable genetic changes, and that only these can lead to evolutionary change across generations.[1,2] In effect, non-heritable or acquired factors (e.g., vaccination, education), along with epigenetic changes (which may or may not be inherited), influence survival and reproduction.[28,29] Therefore, these changes also affect fitness and are under natural selection in shaping evolutionary outcomes. This suggests that both acquired and genetic factors matter in shaping evolutionary trajectories.

### *2.5. Application for Interpreting Societal Development*

CBET offers an innovative explanation for the origin of societies, framing them as a natural outcome of CBM evolution. It also clarifies that changes in CBMs—from organic molecules to complex social organizations—are governed by the same universal axioms, mathematical rules, and mechanisms, which involve hierarchically distinct functions, structures, environments, and energy flows. Critically, CBET elucidates that selfishness and altruism coexist in a dynamic balance throughout evolution, as exemplified by diverse molecules serving as raw materials, catalysts, or protective agents for other molecules, immune cells sacrificing for the organism, and animal and human individuals act for collective benefits. Furthermore, CBET reveals persistent natural balances between competition and collaboration, elimination and inclusiveness, and individual versus collective interests. It highlights the importance of self functions and environmental influence, direct and indirect effects of changes, all-around and specialized development, as well as inherited advantages and acquired endeavors. Therefore, from the evolutionary perspective, CBET establishes a foundational framework for interpreting social development and supports the core ethics essential for achieving harmonious societal development.

### *2.6. Validation of CBET*

The validity of CBET is grounded in rigorous integrative reasoning and supported by extensive empirical evidence, mathematical modeling, resilience to falsification, and cross-hierarchical explanatory power, as detailed in Methods.

### 3. Discussion

**Accessibility and falsifiability of CBET.** Like other cross-domain theories such as Darwinian theory, systems theory, and cybernetics, CBET is relatively accessible, since these four broad-scoped theories all apply to humans, a well-understood system. Its accessibility helps us identify any potential errors in the theory. Furthermore, CBET's core propositions are falsifiable because they are explicit and describe observable entities—from molecules to societies. Its falsifiability is demonstrated by the theory's own evolution. For instance, the concept of 'energy flow' in CBET has been revised from 'energy input,' because some changes in CBMs (e.g., the decay of carbon-14) do not depend on energy input.

**Significance in natural and social sciences.** Firstly, CBET redefines the natural selection mechanism that shapes evolution using mathematical rules, reveals the origin of natural selection options, and describes the mechanism more comprehensively (Table 1). It innovatively introduces the spirodynamic feedback mechanism that drives the stepwise evolution of CBMs from carbon atoms to life and societies. These two mechanisms potentially constitute the first conceptual framework that seamlessly bridges chemical, biological, and social evolution—a goal long desired in research.[2,4,8,29] Secondly, CBET clarifies the complex relationships among energy, structures, functions, information, orderliness, and complexity (Figure 2 and Equation 2). It explicitly explains the increasing orderliness observed in biological and social systems using the co-action of two mechanisms. This stands in contrast to previous elusive explanations that relied on thermodynamic concepts like entropy, which have been challenged because biological/social order does not merely result from thermodynamic processes.[30] Thirdly, CBET refines fitness calculation and integrates multiple facts (e.g., the prevalence of neutral mutations and epigenetic changes) that have not been integrated in a single evolutionary theory. It suggests that complex functions of certain CBMs, such as reproduction, nonrandom mutagenesis, and epigenetic changes, emerge from their complex structures.[28,29,31] Fourthly, CBET clarifies multiple common misunderstandings about evolution. Moreover, CBET establishes a foundational framework for understanding social development and supports multiple core ethics essential for achieving harmonious societal development. Comparison of CBET to other theories is detailed in Supplementary Information, and certain differences between Darwinian theory and CBET are shown in Table 1.

**Table 1. Selected differences between two theories of evolution in biology.**

	<b>Darwinian theory</b>	<b>The Carbon-Based Evolutionary Theory</b>
Scope	Biological evolution	Chemical, biological, and social evolution
Core concept	Organisms	Carbon-based materials (CBMs)
Mechanisms	Natural selection that shapes evolution	Spirodynamic feedback (drives evolution) and natural selection (shapes evolution)
Fitness calculation	The number of an individual's offspring in the next generation	The formation-to-degradation ratio of a CBM over a time interval
Life's origin	No explanation	Schematically accounting for life's origin
Inclusiveness of natural selection	Unable to seamlessly integrate neutral and detrimental mutations with natural selection	Seamlessly integrating the prevalence of neutral or detrimental mutations with natural selection
Changes under selection	Focuses on heritable genetic changes	Highlights the roles of genetic, epigenetic, and non-heritable changes

	Darwinian theory	The Carbon-Based Evolutionary Theory
Primary significance	Unveiling the natural selection mechanism and challenging creationism	Establishing a coherent framework theory that explicitly and schematically explains chemical, biological, and social evolution
Social significance	Its viewpoints can neither be applied in social science nor foster harmonious societal development	Establishing an evolutionary foundation for social sciences and fostering the core ethics for harmonious societal development

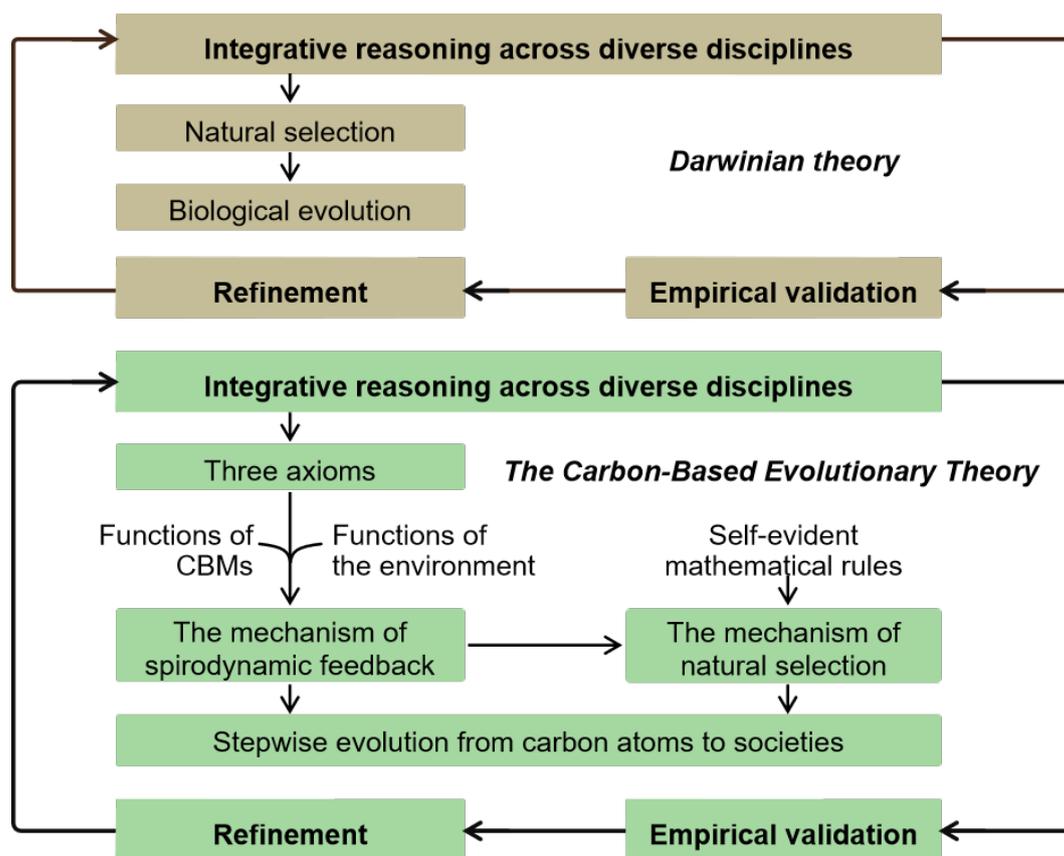
**Boundaries of CBET.** Darwinian theory and CBET are confined to explaining the evolution of organisms and CBMs, respectively. Furthermore, both Darwinian theory and CBET only provide a schematic and qualitative explanation for the plausibility of evolution, rather than a detailed, quantitative account of its inevitability. For example, while CBET innovatively identifies two mechanisms that drive and shape the evolution from MMA clusters to the origin of life, it clarifies few details about life's origin on its own. These boundaries of Darwinian theory and CBET have lowered the threshold for establishing the two frameworks and enhanced their credibility. For instance, CBET would be implausible if it attempted to describe protein synthesis and the emergence dynamics of companies in detail using the same quantitative equation.

**Outlook of CBET.** Looking ahead, the CBET framework will guide investigations, experiments, and computational modeling within their respective disciplines—to refine and extend existing evolutionary theories in three areas: (i) chemical evolution, detailing the roles of the spirodynamic feedback and natural selection mechanisms in the prebiotic ascent to life; (ii) biological evolution, integrating modern findings with the dual mechanisms to describe major biological transitions; and (iii) social evolution, employing the dual mechanisms to analyze societal dynamics and predict long-term social development trends. These applications will both enrich their fields and rigorously test and refine CBET itself.

## 4. Methods

### 4.1. Methodology of CBET

Darwinian theory was initially developed by Darwin and Wallace through the integration of the insights from diverse fields, such as Malthusian demography, Lyellian geology, artificial selection, and biogeography.[2] Later, this theory has been empirically validated and refined by more observations and scientific advancements (Figure 4). CBET extends this methodology through the integration of extensive, well-established knowledge from modern physics, chemistry, biology, and social sciences to derive its three axioms and two core mechanisms (Figure 4). This is followed by empirical validation and iterative refinements. As given in Section 1, neither theory can be based solely on novel experiments, which typically involve limited materials and limited time spans.



**Figure 4.** The methodology of Darwinian theory and the Carbon-Based Evolutionary Theory (CBET) starting from integrative reasoning. CBMs: carbon-based materials.

#### 4.2. Integrative Reasoning of CBET

**Selection of CBMs as CBET's core concept.** The core concept 'organism' is to biological evolution what 'CBM' is to CBET. Unlike more restricted or abstract concepts like 'molecule' 'gene' 'system' or 'entropy', 'CBM' is an explicit and precise concept that seamlessly encompasses entities from carbon atoms and organic molecules to organisms and societies.

**Integration of various key factors.** CBET integrates key factors that are consistently crucial to CBM evolution across hierarchies, including energy, structure, function, environment, feedback, mathematical rules, diverse hierarchies of CBMs, and diverse non-CBM materials (e.g., water). The deliberate selection of these concrete key factors allows CBET to provide a direct and explicit explanatory framework.

**Eight steps and five tiers of integrative reasoning.** CBET was derived through eight steps and five tiers of integrative reasoning, as outlined in Figure 2.

**Circumvention of circular reasoning.** CBET circumvents circular reasoning (i.e., tautology) by introducing the spirodynamic feedback mechanism to explain the generation of structural changes and emphasizing the importance of such changes in enhancing fitness—rather than relying solely on the natural selection mechanism or mathematical rules.[32]

#### 4.3. Empirical Validation of Spirodynamic Feedback

To empirically validate the spirodynamic feedback mechanism, we subjected it to a stringent test against 27 representative facts, randomly selected across a spectrum from molecular to social phenomena (Table 2).

All these 27 facts align with the core characteristics of the spirodynamic feedback mechanism, as detailed below.

- ✧ They require or rely on energy flow.
- ✧ They are influenced by environmental factors, which are different across hierarchies. For instance, the environmental factors are different between Facts 1 and 27.
- ✧ They rely on functions of the relevant CBMs, and the functions are partially determined by the structures of the relevant CBMs.
- ✧ They demonstrate that structural changes can generate new functions, which can initiate further structural changes, establishing a feedback loop that can lead to hierarchical elevation, as illustrated by Facts 1, 4, 7, 10, 13, 16, 19, 22, and 25.
- ✧ They show that structural or locational changes can alter the environment, which can in turn feedback to initiate further structural changes, as evidenced by Facts 1, 3, 5, 6, 8, 18, 20, and 27.

**Table 2.** The 27 representative facts used to validate the spirodynamic feedback mechanism.

Order	Description of the fact
1	Charcoal combustion which consumes oxygen and forms carbon dioxide
2	Diamond synthesis from graphite under certain conditions[33]
3	Water adsorption of activated carbon
4	CO <sub>2</sub> , NH <sub>3</sub> , and other molecules form amino acids via chemical reactions[2,5]
5	Methane explosion in coal mines
6	Evaporation of ethanol from an open bottle
7	The dehydration condensation of amino acids into peptides in tubes
8	The binding of gentamicin to the 30S ribosomal subunit of some bacteria
9	The degradation of glucose into carbon dioxide and water in cells
10	Some recombinant proteins self-assemble into virus-like particles
11	DNA synthesis catalyzed by a protein
12	Starch degradation in the stomach
13	Inputting certain DNA molecules into certain cells can create new viruses[34]
14	Inputting certain DNA molecules into certain cells can create new cells[35]
15	The formation of bilayer vesicles by amphiphilic lipid molecules
16	The development of a fertilized egg into a tadpole
17	<i>Escherichia coli</i> absorbs glucose via its membrane carrier proteins
18	The reproduction of bacteria within chicken intestines
19	A group of ant individuals form a eusocial ant colony
20	Some trees undergo spring budding and autumn leaf shedding
21	A car collision causes human casualties
22	The formation of a basketball team by a group of young people
23	Leafcutter ants harvest foliage to cultivate symbiotic fungi in their nests
24	The destruction of a beehive by a forest fire
25	Several institutions merged into Paris-Saclay University in 2018
26	University of the Arts Philadelphia was closed in 2024
27	The war between Russia and Ukraine in the 2020s

#### 4.4. Empirical Validation of Natural Selection

In biological evolution, extensive facts have been identified for the effect of natural selection across multiple taxa and ecosystems.[1,2] In chemical evolution, molecular populations undergo natural selection in those organic chemical reactions with multiple possible products, where the products that are easily formed and difficult to degrade tend to accumulate in greater quantities than those that are difficult to form and easily degraded. In social evolution, companies or schools undergo competition and selection, and those with the formation-to-degradation ratio  $>1$  demonstrate progressive accumulation.

#### 4.5. Evaluation of Conceptual Clarity and Logical Coherence

Following the empirical support outlined above, we further evaluated the CBET framework by assessing the conceptual clarity and logical coherence of its core components. This evaluation was conducted through a combination of AI-assisted analysis and structured feedback from human evaluators, including five university professors and 36 students randomly selected across diverse scientific disciplines. The primary aim was to identify potential ambiguities, internal contradictions, or robust counterevidence that might falsify the theory. A consensus emerged across all evaluators that CBET's core elements—including its hierarchical classification of CBMs, its three axioms, and its two mechanisms—are conceptually clear, rigorous in reasoning with the support of extensive empirical evidence. No robust counterevidence was identified by these evaluators to falsify these core viewpoints.

#### 4.6. Refinement of CBET

The CBET framework was iteratively refined based on empirical validation and critical feedback, to enhance its coherence, rigor, clarity, and explanatory power. Key refinements included redefining the hierarchies of CBMs, reformulating the three axioms and two mechanisms, streamlining the reasoning steps, updating the mathematical formulations, and redesigning the relevant figures. All elusive concepts (e.g., entropy) have been excluded from the final version. CBET is open to be further refined, if needed.

#### 4.7. Other Issues

Comparisons between CBET and other theories, along with the mathematical formulation and modeling of CBET, selected questions and answers, and a comprehensive glossary, are provided in Supplementary Information, which includes 15 additional references [36–50].

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Comparison of CBET to other theories, mathematical formulation of CBET, mathematical modeling of CBET, certain questions and answers about CBET, and the glossary of CBET.

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