Supplementary information of the article

The Carbon-Based Evolutionary Theory
Extending Darwinean Theory to Unify Chemical, Biological, and Social Evolution

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Content

PART 1 Novelties of the Carbon-Based Evolutionary Theory (CBET)

I. Novelties in Physics

In physics, CBET provides an explicit and holistic explanation for chemical, biological, and social evolution. This is achieved by integrating numerous comprehensible factors, such as including energy, structures, functions, information pathways, genetics, epigenetics, natural selection, carbon atoms, organic molecules, cells, organisms, and social organizations, into a unified framework. In contrast, previous studies primarily focused on specific aspects of chemical, biological, or social evolution [3].

CBET explicitly explains CBM evolution using three fundamental principles along with certain universal mathematical rules, while previous studies usually explained CBM evolution using a single principle, such as entropy dissipation into the surroundings in Schrödinger's negative entropy notion [22], self-organization in Prigogine's dissipative structure theory [23], the constructal law [24], the maximum entropy production hypothesis [25], or the free energy principle [26]. These single-principle explanations were based on a few factors, such as entropy, free energy, self-organization, dissipative structure, which are incomprehensible to common readers [27].

CBET clarifies the intricate relationships among the six basic concepts in sciences: materials, energy, structures, functions, information, and orderliness, through its seven reasoning steps (Fig. 2). These relationships have been frequently entangled with controversial notions associated with entropy [27].

II. Novelties in Biology

In biology, CBET reveals that the driving force of the origin and evolution of life is the synergy of energy, environmental factors, and functions of relevant materials. CBET provides more accurate explanations for the mathematical essence of natural selection and corrects multiple misconceptions about natural selection. Additionally, neutral mutations, epigenetic changes, and non-heritable traits, which cannot be integrated into previous evolutionary theories [2,3], can be well integrated into the framework of CBET. Some differences between Darwinian theory and CBET are listed in Table 1.

III. Novelties in Social Sciences

In social sciences, CBET uncovers the natural roots of the balance of multiple crucial and seemingly paradoxical social notions, such as self-functioning and environmental influence, all-round versus specialized development, competition versus inclusiveness, selfishness versus altruism, individual versus collective interests, and inheritable versus non-heritable traits. Accordingly, CBET advocates for the balanced and harmonious development of human society. In contrast, Darwinian theory overemphasizes selfishness, competition, and the elimination of the less advantaged, and has been misused to justify slavery, racism, and genocide [28].

IV. Comparison with Previous Theories

Throughout the history of science, theories with *partial* similarities to CBET exist. Below is a comparative analysis:

- **Oparin's Chemical Evolution Theory (1924)[4]**
  - *Similarity*: Both explains prebiotic transitions (H2→H5 in CBET).
  - *Key distinction*:
    * Oparin's theory is limited to chemical evolution and the description of the possibility rather than revealing the underlying mechanisms and mathematical rules.
    * CBET applies to chemical, biological, and social evolution, and reveals the underlying mechanisms and mathematical rules of natural selection as well as chemical, biological, and social evolution.
- **Modern Evolutionary Synthesis (1930s-nowadays)[1]**
  - *Similarity*: Both integrates genetics with natural selection.
  - *Key distinction*:
    * Modern Evolutionary Synthesis is confined to **biological evolution** and devoid of a coherent framework to integrate various evolutionary phenomena. It can neither interpret the mechanism behind the origins of life and multicellular organisms nor rationally calculate the fitness of worker bees.
    * CBET applies to chemical, biological, and social evolution, reveals the mechanisms underlying the hierarchical escalation of biosystems, integrates various evolutionary phenomena in a coherent framework, and can rationally calculate the fitness of all molecules, organisms (e.g., trees and worker bees), and social organizations.
- **Herbert Spencer's Social Darwinism (19th century)[3,8,28]**
  - *Similarity*: Both extends evolution to society.
  - *Key distinction*:
    * Spencer emphasized "survival of the fittest" in social competition and justified colonialism.
    * CBET interprets the mathematical rule of "the survival of the fit" and the balance between competition versus inclusiveness and the balance between selfishness versus collaboration and altruism.
- **John Holland's Complex System Theory (CST)[29]**
  - *Similarity*: Both emphasize the emergence of new functions, adaptation to the environment, and feedback of complex systems.
  - *Key distinction*:
    * CST uses **abstract models** and focuses on the emergence of new functions, active adaptation to the environment, and modeling the current complex systems. It has not revealed the underlying mechanisms of chemical, biological, and social evolution with concrete and explicit concepts.
    * CBET interprets complexity with concrete and explicit concepts (e.g., energy, structures, and functions) and focuses on revealing the mechanisms behind the evolution.

- **Ilya Prigogine's Dissipative Structures (1977 Nobel Prize)[24]**
  - *Similarity*: Explains complexity emergence in open systems.
  - *Key distinction*:
    - Prigogine focused on **physicochemical systems** and interpreted complexity with abstract and elusive concepts.
    - Prigogine highlighted self-organization and neglected the role of natural selection.
    - CBET explains the mechanism behind the natural increases in the orderliness of molecules, organisms, and social organizations with concrete and explicit concepts. CBET highlights natural selection and the interplay between materials and the environment, rather than only self-organization.
- **Karl Friston's Free Energy Principle (FEP) [26,30]**
  - *Similarity*: Both highlight feedback loops, energy, non-heritable traits, and the interplay of organisms and the environment.
  - *Key distinction*:
    - FEP uses abstract concepts and does not explicitly explain the evolution of CBMs.
    - FEP focuses on interpreting how a complex system achieves and maintains its complex functions, rather than addressing the origins of the complex system itself.
    - CBET provides explicit explanation of the mechanisms behind the evolution of CBMs using concrete concepts.
- **David Sloan Wilson's Multilevel Selection (MLS) [31]**
  - *Similarity*: Both highlight hierarchies, altruism, and selection at multiple levels.
  - *Key distinction*:
    - MLS lists populations and species without close internal collaboration as hierarchies.
    - MLS focuses on altruistic behavior in biological evolution and explains them using the claim that natural selection exists at multiple levels. It has not revealed the mechanisms underlying natural selection and chemical, biological, and social evolution.
    - In CBET, only entities with close internal collaboration are listed as hierarchies. CBET develops a coherent theory interpreting the mechanisms behind natural selection and chemical, biological, and social evolution, and consequently explains the pervasive altruistic behavior and other important phenomena in CBM evolution. CBET clarifies the mathematical rules of natural selection and an accurate method for calculating fitness, which explicitly clarifies that the fitness of worker bees is not zero.
- **Other evolutionary studies highlighting the hierarchies of CBMs [32]**
  - *Similarity*: highlights the structural hierarchies of biosystems
  - *Key distinction*:
    - Some previous studies have categorized molecules, cells, organs, and ecosystems into different hierarchies. In contrast, in CBET, organs are defined as components of individual organisms, whereas ecosystems are regarded as a kind of environment.
    - Previous studies have not developed a coherent theory that unifies chemical, biological, and social evolution using the concept of CBMs at different hierarchies.
    - Previous studies have not revealed the driving forces and mechanisms behind the hierarchical escalation of CBMs.

V. Conclusion

While some historical theories share partial similarities with CBET, *none* articulates the underlying mechanisms and mathematical rules of natural selection, as well as chemical, biological, and social evolution, through *concrete, empirical concepts* under a *coherent theoretical framework*. CBET distinguishes itself by integrating concrete concepts, mathematical rules, and interdisciplinary empirical evidence to illuminate the mechanisms driving the stepwise chemical, biological, and social evolution. This systematic approach bridges gaps left by prior theories, offering a novel and holistic perspective on the world and ourselves.

PART 2 Mathematical Formalization of the Carbon-Based Evolutionary Theory (CBET)

I. Fundamental Principles

The three fundamental principles in CBET, which were derived through inductive synthesis of abundant empirical evidence in physics, chemistry, biology, and social sciences, can be expressed through the following equations.

$$\Psi_m = \mathcal{F}_m(\mathbf{S}_m) \tag{1}$$

$$\partial \mathbf{S}_m = \mathcal{F}_m(\partial \Psi_m) \tag{2}$$

$$\Psi_e = \mathcal{F}_e(\mathbf{S}_e) \tag{3}$$

$$\partial \mathbf{S}_e = \mathcal{F}_e(\partial \Psi_e) \tag{4}$$

$$\partial \mathbf{S}_m = \mathcal{G}_m\left(\Phi, \mathcal{A}(\Psi_m, \Psi_e)\right) \tag{5}$$

$$\partial \mathbf{S}_e = \mathcal{G}_e\left(\Phi, \mathcal{A}(\Psi_m, \Psi_e)\right) \tag{6}$$

- Ψ: physical/chemical/biological/social functions
- m: the target material (typically an open system exchanging energy and matter with its environment)
- $\mathbf{S}$: physical/chemical/biological/social structure
- $\mathcal{F}$: the deterministic relationship between Ψ and $\mathbf{S}$
- ∂: change (e.g., $\partial \mathbf{S}_m$ denotes structural changes in the target material)
- e: the environment
- Φ: energy flow
- $\mathcal{A}$: the synergistic effect of Ψ_m and Ψ_e that modulates Φ's impact on structural changes
- $\mathcal{G}$: the generative relationship between structural changes and the combined effects of energy flow, material functions, and environmental functions

Equation 1 establishes that a material's functions are determined by its structure, representing a core tenet of the Structure-Function Principle.

Equation 2 demonstrates how structural modifications in the target material can alter its functions, potentially yielding new functions - another key aspect of the Structure-Function Principle.

Equations 3 and 4 extend the relationships above to the environment, which can itself be considered as a material system.

Equation 5 reveals that energy flow drives structural changes in the target material, with this process being modulated by both the material's functions and environmental functions. This equation embodies:

- The Driving-Force Principle (energy-mediated changes)
- The Environment-Influence Principle (the influence of environmental factors, acting as the external cause)
- The Structure-Function Principle (the influence of material's functions, acting as the internal cause)

Equation 6 shows that energy flow, which is modulated by material and environmental functions to drive changes in the target material, simultaneously drives environmental structural changes. This equation is supported at least in physics by the Law of Conservation of Energy and the Law of Conservation of Mass. It incorporates viewpoints of both the Driving-Force and Environment-Influence Principles (i.e., some changes of materials can alter the environment).

II. Hierarchical Escalation of CBMs

Certain forms of energy (e.g., radiation, thermal energy) — when modulated by the functions of charcoal (which consists primarily of carbon atoms) and the environment (e.g., oxygen availability) — drive the structural transformation of charcoal into CO_2. This process simultaneously alters the environmental composition (e.g., increasing atmospheric CO_2 concentration). The resulting CO_2 acquires novel functions absent in charcoal, such as participating in amino acid synthesis under suitable energy and environmental conditions. Along with the six equations above, this fact exemplifies the following feedback mechanism:

$$\mathcal{G}_m\left(\Phi, \mathcal{A}(\Psi_m, \Psi_e)\right) = \partial \mathbf{S}_m = \mathcal{F}_m(\partial \Psi_m) \tag{7}$$

$$\mathcal{G}_e\left(\Phi, \mathcal{A}(\Psi_m, \Psi_e)\right) = \partial \mathbf{S}_e = \mathcal{F}_e(\partial \Psi_e) \tag{8}$$

Consequently:

$$\mathcal{G}_m\left(\Phi, \mathcal{A}(\partial\Psi_m, \partial\Psi_e)\right) = \partial(\partial \mathbf{S}_m) \tag{9}$$

Certain structural changes in carbon-based materials (CBMs) constitute hierarchical transitions of CBMs. Thus, on habitable planets like Earth, Equation 9 suggests the possibility of:

$$\mathcal{G}_m\left(\Phi, \mathcal{A}(\partial\Psi_m, \partial\Psi_e)\right) = \partial(\partial \mathcal{H}_m) \tag{10}$$

where $\partial\mathcal{H}_m$ represents material hierarchical changes, and $\partial(\partial\mathcal{H}_m)$ denotes subsequent rounds of hierarchical changes, including hierarchical escalation and hierarchical decline.

Equation 10 demonstrates the theoretical possibility of serial hierarchical escalation if supported by energy flow, the functions of the target material (e.g., CBMs), and the functions of the environment. In reality, as stated in the main text, CBMs possess the functions to support the serial hierarchical escalation, and Earth is a rare habitable planet that supports such escalation of CBMs, with abundant liquid water, CBMs, and diverse energy flows—including sunlight, radiation, chemical energy release, and geothermal energy. Consequently, the origins of life and social organizations become both theoretically and empirically plausible.

Consistent with Darwinian theory (which is itself non-quantitative), the ten equations above can only serve as qualitative and universal formulations (applicable to molecules, biological systems, and social organizations). Logically, they cannot simultaneously be quantitative and universal. This is because the relationships described by these equations exhibit fundamentally diverse quantitative manifestations across different molecules, biological entities, and social systems. For instance, if these equations were to quantitatively model the dynamic process of carbon combustion into carbon dioxide, such quantitative formulations would most likely prove inapplicable to describing the development of business organizations.

III. Natural Selection

1. Reasoning of the Quantity-Limitation Rule

The total quality of a higher-hierarchy CBM (HHCBM) in an environment is limited by its functions and the energies, materials, and other conditions in the environment.

$$N_{\max} = f(\Phi, \Psi_m, \Psi_e) \tag{11}$$

- Φ: Energy flow
- Ψ_m: Functions of HHCBMs
- Ψ_e: Functions of the environment
- Because the relationships described by this equation vary quantitatively across different functions, energies, hierarchies, and types of HHCBMs, this equation is qualitative rather than quantitative.

2. Reasoning of the Quantity-Existence Rule and the Quantity-Change Rule

There exits such a self-evident equation in basic mathematics:

$$N_{existing} = \Gamma_{cumulative} - \Lambda_{cumulative} \tag{12}$$

- $N_{existing}$: currently existing quantity
- $\Gamma_{\text{cumulative}}$: cumulative formation quantity
- $\Lambda_{\text{cumulative}}$: cumulative degradation quantity
- According to this qualitative equation, an HHCBM exists if its cumulative formation exceeds its cumulative degradation, regardless of whether it is fitter than its ancestors or other HHCBMs. This validates the Quantity-Existence Rule. This rule supports the concept of "Survival of the fit" and challenges the concept of "Survival of the fittest" and the concept of "Survival of the fitter".
- According to this qualitative equation, the existing quantity of an HHCBM increases if its formation-to-degradation ratio is >1, and the existing quantity of an HHCBM decreases if its formation-to-degradation ratio is <1, regardless of whether it is fitter than its ancestors or other HHCBMs. This validates the Quantity-Change Rule.

- According to this qualitative equation, a change increasing $\frac{d\Gamma}{d\Lambda}$ (the formation/degradation ratio) is advantageous to increasing the existing quantity of the HHCBM and is thus prone to be accumulated along with the HHCBM.

- According to this qualitative equation, a change reducing $\frac{d\Gamma}{d\Lambda}$ is harmful to increasing the existing quantity of the HHCBM and is thus prone to be eliminated along with the HHCBM.

- The above two effects resulting from mathematical rules are termed natural selection, which, like a railway adjusting the movement of a train, is a pivotal mechanism to shape the evolution of CBMs, but not the only force to drive the evolution. Without the energy from sunlight, the existence of organisms on Earth is impossible, let alone their evolution. The driving force of evolution is explained by the Driving-Force Principle, or Equation 5.

- For a company, this formula does not represent the relationship between the company's economic income and expenditure and its survival. Instead, it indicates the relationship between the number of establishments and closures of a specific type of company and the existing quantity of that type of company.

- For a country, this formula does not represent the relationship between its net economic income and its survival. Instead, it indicates the relationship between the number of new formations and dissolutions of a specific type of country (e.g., slave-holding countries) and the existing number of that type of country .

3. Calculation of fitness

In modern evolutionary biology, fitness equals the number of offspring surviving to reproductive age an individual leaves in the next generation [2], which encounters the dilemma that worker bees, whose fitness is calculated to be zero, have sustained their prevalence across geological eras. Furthermore, this definition cannot be employed to describe the quantity changes in molecules and social organizations. In CBET, this definition is extended by the the following equation:

$$\mathrm{Fitness}_{ab} = \frac{d\Gamma_{ab}/\mathrm{t}_{ab}}{d\Lambda_{ab}/\mathrm{t}_{ab}} = \frac{d\Gamma_{ab}}{d\Lambda_{ab}} \tag{13}$$

where:

- $\mathrm{Fitness}_{ab}$: Fitness of an HHCBM during the period t_{ab} from time a to time b (b>a)

- $d\Gamma_{ab}$: The formation quantity of the HHCBM during the period from time a to time b (b>a)

- $d\Lambda_{ab}$: The degradation quantity of the HHCBM during the period from time a to time b (b>a)

- To minimize sampling biases, the observation period should be long enough to ensure that$d\Lambda_{ab}$ reaches a sufficiently large value (e.g., ¿10 for an endangered species).

- According to this equation, $\mathrm{Fitness}_{ab}$ >1 means the increase in the existing quantity; $Fitness_{ab}$ <1 means the decrease in the existing quantity; $Fitness_{ab} = 1$ means that the existing quantity remains unchanged.

- This equation demonstrates that worker bees possess sufficient fitness to sustain their prevalence across geological eras. This qualitative equation can also describe the quantitative changes in various materials, such as molecules, social organizations, stones, and houses.

PART 3 Rationality and Empirical Evidence of CBET

I. Rational Objectives of CBET

- The purpose of CBET is to provide a novel, credible, direct, comprehensible, and holistic explanation for the entire evolution of CBMs, covering chemical, biological, and social evolution. It also aims to correct several misconceptions about natural selection.
- Because CBM evolution involves countless changes in molecules, organisms, and social organizations, and many changes occurred millions or even billions of years ago, no theory can precisely reconstruct its detailed trajectory. Thus, it is rational for CBET to aim to provide only a constitution-like schematic rather than detailed explanation for CBM evolution. Similarly, Darwin's theory offers a schematic rather than detailed explanation for biological evolution [1], yet its great importance remains undiminished.
- Usually, it is significantly simpler to construct a schematic explanation (e.g., the concept that humans evolved from primates) than to develop a detailed explanation (e.g., specifying the exact processes, timelines, and locations of human evolution from primates).

II. Rational Methods of CBET

- **Rationality for CBET's selection of CBM as its core concept**: Like the core concept of *virus* in the research of virus evolution, the concept of *CBM* is more precisely and directly scoped in the research of CBM evolution than other concepts, such as systems, materials, microscopic particles, dissipative structures, genes, or entropy.
- **Rationality for CBET's selection of various key factors**: CBET employs various key factors, such as hierarchy, energy, structures, functions, environmental factors, driving forces, mechanisms, changes, feedback, natural selection, competition, collaboration, water, genes, epigenetics, neutral mutations, Earth's environment, and carbon atomic structure. These factors are concrete and known to be crucial for CBM evolution and directly associated with CBM evolution. All abstract or elusive concepts are excluded from the theory. The selection of these key factors is important for the theory to be able to provide a direct and explicit explanation for CBM evolution.
- **Rationality for CBET's methodology**: CBET was developed through holistic reasoning from the synthesis of existing knowledge and universal mathematical rules to deduce the underlying mechanisms of natural selection and CBM evolution, starting from carbon atoms. These mechanisms were then rendered explicit and free of counter-evidence through iterative empirical evaluation and refinement (Fig. S1). This research paradigm was not suitable for Darwin in developing his theory because the science in his era was far less advanced than today's science, which has accumulated abundant knowledge in physics, chemistry, astronomy, biology, and social sciences. The explanation derived from CBET starts with carbon atoms, analogous to accounting for a man's success from his birth or a river from its source.

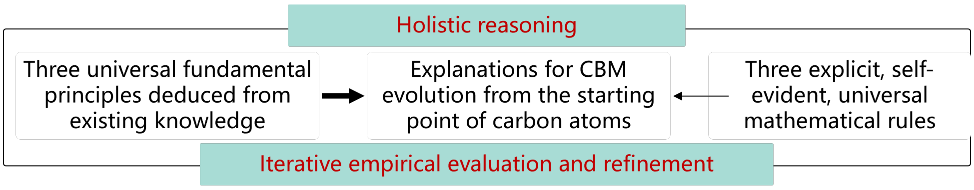

Fig. S1. The research methodology of CBET

- **Circumventing circular reasoning (tautology)**: The defining characteristic of circular reasoning is "using the conclusion as its own premise," creating logical equivalence between the foundational assumptions and final inferences. CBET is grounded in three fundamental principles derived through inductive synthesis of countless facts and clarifies the origins of the options of natural selection, fundamentally circumventing tautological reasoning. This stands in marked difference to Darwin's theory, which does not address the origins of the options available for natural selection—specifically, why organisms are capable of survival and mutation on Earth—a gap that has long drawn criticism for its potential to lapse into tautology [33].

III. Rational Expression of CBET

- **Comprehensibility**: All CBET viewpoints, including its three fundamental principles, seven reasoning steps, four feedback loops, and its perspectives on natural selection, are comprehensible and devoid of elusive concepts. We conducted an online test, which showed that 33 of the 35 undergraduates tested demonstrated an understanding of the CBET viewpoints within 30 minutes.
- **Falsifiability**: All CBET viewpoints, such as the one that environmental factor influence many changes of molecules, organisms, and social organizations, are falsifiable as they pertain to observable materials.
- **Neither counter-evidence nor logical contradictions** have been identified through our research.
- **Inclusiveness**: Certain sentences of CBET use the words 'some', 'many', or 'can', rather than 'all' or 'must', so that they allow exceptions, see Section V below.
- **Robust empirical evidence**: see Section IV below.
- **Widespread applications**: see Section V below.

IV. Robust Empirical Evidence of CBET

1. Empirical Evidence Supporting the Fundamental Principles

We systematically evaluated the fundamental principles in CBET using the following 27 randomly selected representative facts (3 facts per CBM hierarchy).

- **From H1-CBMs**
  - **Fact 1** (Charcoal Combustion): Charcoal combustion consumes atmospheric oxygen while releasing carbon dioxide. The process requires an initial energy flow to ignite and relies on the chemical energy stored in charcoal to sustain the reaction.

  - **Fact 2** (Graphite to Diamond): Diamond synthesis from graphite under high-pressure, high-temperature conditions illustrates allotropic transitions driven by extreme environmental parameters. The process requires energy flow to overcome the energy barrier between the two carbon forms [34].
  - **Fact 3** (Water Adsorption by Activated Carbon): Activated carbon's porous structure mediates water adsorption through intermolecular forces, showcasing environment-dependent surface interactions. The process is driven by a tendency toward lower system energy and involves energy transfer.

- **From H2-CBMs**
  - **Fact 4** (CO_2 to Amino Acids): With energy flow (e.g., lightning) and suitable environmental conditions, carbon dioxide and other molecules undergo chemical reactions through their functional groups to form amino acids.
  - **Fact 5** (Methane Combustion): Methane's dual role as an energy source and explosion hazard highlights environment-dependent energy release dynamics.
  - **Fact 6** (Ethanol Volatilization): The phase transition of ethanol exemplifies how molecular properties respond to ambient energy conditions.

- **From H3-CBMs**
  - **Fact 7** (Amino Acids to Proteins): Protein synthesis through dehydration condensation reveals how directed energy flow drives biomolecular assembly.
  - **Fact 8** (Remdesivir Mechanism): Target-specific antiviral action demonstrates precise bioenergetic interactions in enzymatic environments.
  - **Fact 9** (Glucose Catabolism): Stepwise energy extraction from glucose exemplifies metabolic pathway regulation through catalytic environments.

- **From H4-CBMs**
  - **Fact 10** (Proteins to Multi-molecule Aggregates (MMAs)): Recombinant proteins self-assemble into virus-like particles under energy flow and proper environmental conditions, as used in hepatitis B vaccines.
  - **Fact 11** (DNA Replication): Template-directed polynucleotide synthesis showcases molecular fidelity maintenance through enzymatic environments.
  - **Fact 12** (Starch Hydrolysis): Hierarchical carbohydrate breakdown illustrates sequential environmental adaptation in digestive systems.

- **From H5-CBMs**
  - **Fact 13** (MMAs to Cells): The successful experiment on the abiotic production of viruses and functional cells using MMAs suggests the possibility of transformation from MMAs to cells [35,36].
  - **Fact 14** (Ribosome Function): Ribosomes read the genetic information carried by mRNA and assemble amino acids into polypeptide chains according to the codon sequence. This process requires energy to link amino acids via peptide bonds to form proteins.
  - **Fact 15** (mRNA Vaccine Delivery): Amphiphilic lipid molecules form bilayer vesicles that electrostatically encapsulate negatively charged mRNA [37], enhancing stability and cellular delivery.

- **From H6-CBMs**
  - **Fact 17** (Cells to Individuals): The development of a fertilized egg into a tadpole requires energy derived from nutrient reserves, a suitable environment (such as optimal temperature and water conditions), and the intact functionality of the fertilized egg itself to drive the complex processes of cell division, differentiation, and morphogenesis.
  - **Fact 18** (Bacterial Nutrient Uptake): *Escherichia coli* actively transports glucose molecules into cells via membrane carrier proteins for energy metabolism. The process requires energy input.
- **From H7-CBMs**
  - **Fact 19** (Individuals to Social Organizations): A group of ants works in unison to carry a large crumb of meat back to their nest, with each ant gripping and pulling in coordinated motion.
  - **Fact 20** (Seasonal Tree Phenology): Trees undergo spring budding, summer foliation, autumn leaf shedding, and winter dormancy via interactions between energy, environment, and intrinsic biological programs.
  - **Fact 21** (Traffic Fatalities): Vehicle collisions cause human casualties through kinetic energy transfer, environmental factors, and biological vulnerability.
- **From H8-CBMs**
  - **Fact 22** (Tribes to Tribe Alliances): Due to natural and social pressures (environment) and the collaborative functions of relevant tribes, some tribes form alliances.
  - **Fact 23** (Leafcutter Ant Fungiculture): Leafcutter ants harvest foliage to cultivate symbiotic fungi in their nests, using chewed leaf pulp as substrate and consuming the fungal hyphae.
  - **Fact 24** (Beehive Destruction by Wildfire): A forest fire completely destroys a beehive.
- **From H9-CBMs**
  - **Fact 25** (Country Formation): Due to natural and social pressures (environment) and the collaborative functions of relevant tribe alliances, some tribe alliances united to form countries, while others declined in the competition among human societies. The process required energy input.
  - **Fact 26** (Corporate Growth): NVIDIA became a corporate giant due to its own functions and the influence of its social environment, which is associated with political, economic, technological, and marketing conditions. The process required energy input.
  - **Fact 27** (Russo-Ukrainian War): The conflict arises from the political, economic, cultural, and military functions of both countries under the influence of the international geopolitical context (environment). The war requires energy to carry out and sustain.

The 27 facts above systematically uphold CBET's core viewpoints, because all the changes/processes embodied in the facts:

- require energy flow, which can come from the environment, the target material, or interactions between them.
- are influenced by the environment.
- rely on the functions of the target material, which derive from its structure.

- involve changed structures that can acquire new functions not possessed by the original structures; these new functions enable participation in new structural changes or processes, thus constituting the serial hierarchical escalation demonstrated by Facts 1, 4, 7, 10, 13, 16, 19, 22, and 25.

More than 35 randomly selected undergraduate students and five randomly selected professors or associated professors were invited to answer the following questions.

- **Question 1**: Do any structural changes in molecules, organisms, or social organizations not driven by or rely on energy flow? You may think that some structural changes of a country are driven by its culture, not by energy flow, but the structural changes fundamentally rely on energy flow.
  The students and professors all answered this question with "no".

- **Question 2**: Are any structural changes in molecules, organisms, or social organizations not affected by the environment? You may list a special case that the beta decay process of carbon-14 is not affected by the environment. However, the process is affected by the environment as high-energy particles on the Sun's surface (such as protons, alpha particles, and high-energy photons) can potentially disrupt the atomic structure of carbon-14 and thus affect the beta decay process.
  The students and professors all answered this question with "no".

- **Question 3**: Can you list some functions of molecules, organisms, or social organizations determined by their structures?
  The students and professors all answered this question with "Yes".

- **Question 4**: Can you list some examples showing that functions of a molecule, organism, or social organization can change due to the structural changes of the molecule, organism, or social organization?
  The students and professors all answered this question with "Yes".

The AI tools of ChatGPT, DeepSeek, and Doubao were also employed to answer the four questions above. They gave the same answers as stated above.
The above answers given by the students, scholars, and AI tools to the four questions further demonsrtrated that the fundamental principles in CBET are supported by robust empirical evidence.

2. Empirical Evidence Supporting Hierarchical Escalation of CBMs

- Formation of H1-CBMs. According to current cosmology, H1-CBMs (carbon atoms) were formed within the interiors of giant or supergiant stars [9]. These atoms were scattered into space as dust during the explosive deaths of these stars in the form of powerful and luminous supernovae. The dust from these supernovae events eventually coalesced to form the Sun, Earth, and other celestial bodies within the solar system approximately 4.6 billion years ago [2,10].

- Formation of H2-CBMs. It is known that some H1-CBMs have the function to transform into H2-CBMs through chemical reactions. In history, before the formation of Earth, many H2-CBMs, such as CO_2, CH_4 and HCN, could have been accumulated through inorganic or organic chemical reactions on Earh, and they were the initial materials for CBM evolution on Earth [38]. In chemistry, this formation process results from the synergistic interaction of the three fundamental principles associated with energy flow, environment, structures, and functions.

- Formation of H3-CBMs. It is known that some H2-CBMs have the function to transform into H3-CBMs through chemical reactions. In history, Earth possesses abundant energy sources, including sunlight, lightning, geothermal energy, volcanic activity, fires, water currents, wind, and the decomposition of organic matter [10]. The energy released from these sources is adjusted by the extensive water, which amounts to approximately 1.35×10^{18} tons, as well as the atmosphere, which is over 1,000 km thick, on Earth [10]. The adjustment helps to maintain a moderate, widespread, and persistent distribution of energy on Earth and renders Earth a rare habitable planet [10]. Under the second law of thermodynamics, many H2-CBMs and other substances (e.g., water) on Earth spontaneously absorb heat from these heat sources [4,39]. Chemically, the absorbed heat energy and some functions of H2-CBMs constitute the driving force to transform many H2-CBMs into diverse distinct H3-CBMs through heat-absorbing organic synthesis reactions. The prebiotic chemical synthesis of various H3-CBMs, such as amino acids, nucleotides, and monosaccharaides, has been experimentally validated in laboratories [2,4,5], and supported by the fact that myriad distinct H3-CBMs have been identified from meteorites [40]. Some functions of certain H2-CBMs, such as the reactivity of CO_2 with H_2O and the reactivity of CH_4 with NH_3, are critical for the formation of H3-CBMs. In chemistry, the formation process above results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions.

- Formation of H4-CBMs. It is known that diverse H3-CBMs (e.g., nucleotides, amino acids, and glucose) have the function to transform into H4-CBMs through chemical reactions. Many H3-CBMs generated through the above processes can further spontaneously absorb heat on Earth under the second law of thermodynamics from abundant heat sources on Earth. Chemically, the absorbed heat energy and some functions of H3-CBMs, such as the one that some H3-CBMs have two or more active function groups, constitute the driving force to transform many H3-CBMs into myriad distinct H4-CBMs through heat-absorbing organic chemical reactions. Studies have shown that high pressure, certain inorganic molecules like boric acids, and certain H3-CBMs, such as N-phosphoryl amino acids, can facilitate the abiotic synthesis of some H4-CBMs, like proteins, nucleic acids, lipids, and myriad heteropolymers—hybrid macromolecules incorporating residues of multiple types (e.g., chains bearing both amino acids and nucleotides) [2,4,5,41]. Among all atoms, only carbon atoms can serve as the backbone to bond with other atoms, such as hydrogen, oxygen, nitrogen, sulfur, phosphorus, halogens, metals, and various functional groups, to form long, complex, and water-soluble large molecules, which are essential for the construction of organisms [11]. Consequently, it is assumed that only CBMs have the potential to naturally evolve from simple structures into life [11]. It has been established that the natural synthesis of small H4-CBMs (e.g., short-chain polymers such as oligopeptides, oligonucleotides, and glycopeptides) on prebiotic Earth was more feasible and frequent than that of large H4-CBMs [4,5,41]. Due to their structural complexity, some small H4-CBMs can acquire novel functions (e.g., certain catalytic activities) absent in H2-CBMs and H3-CBMs. Consequently, some small H4-CBMs might have acted as catalysts to accelerate the polymerization of larger H4-CBMs, forming a positive evolutionary feedback loop. In chemistry, the formation process above results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions. Notably, in chemistry, some H2-CBMs (e.g., C_2H_4 and C_2H_2) also have the function to directly transform into H4-CBMs through chemical reactions.

- Formation of H5-CBMs. In physics and chemistry, it is known that some H4-CBMs have the function to transform into H5-CBMs (MMAs), such as virus-like particles or water-in-oil emulsion, through physical and chemical reactions. The energy provided by the wind, rain, lightning, and solar evaporation and some functions of H4-CBMs, such as the interaction among certain proteins through hydrogen bonds, drive the formation of myriad MMAs. Due to the vast structures of MMAs and their complex structures, some MMAs could have certain metabolic functions, such as catalyzing the random formation of H4-CBMs, catalyzing the special formation of certain H4-CBMs according to certain sequences (which represent certain information), and catalyzing the degradation of certain H3-CBMs or H4-CBMs, etc. various metabolic MMAs, such as polymerase-chain-reaction (PCR) systems for DNA amplification, have been widely applied in biomedical labs. In physics and chemistry, the formation process above results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions.

- Formation of H6-CBMs. It is known that some H5-CBMs have the function to transform into H6-CBMs through the reproduction process of H6-CBMs (e.g., bacteria, archaea, and protozoa). The formation process, in nature, results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions. Although the precise steps by which the Last Universal Common Ancestor (LUCA) of all living things originated remain unknown, the abiotic origin of life is theoretically and empirically possible due to Equation 10, the functions of CBMs, and the habitable environment of Earth, as elucidated in Part 1 of this file. The possibility is reinforced by the fact that experiments on the abiotic synthesis of viruses and cells have been successful [35,36]. Previously, it was hypothesized that life originated in a warm pond (by Darwin), hydrothermal vents, or volcanic lakes [3]. Here we propose the Atmosphere-Origin Hypothesis, which explains why it was much more likely for life to emerge in Earth's early atmosphere than in hydrothermal vents or volcanic lakes.
  - The Atmosphere-Origin Hypothesis is supported by the fact that laboratory experiments have demonstrated that amino acids, peptides, sugar phosphates, and uridine ribonucleoside could be naturally synthesized in the Hadean atmosphere [4,42-46].
  - The Atmosphere-Origin Hypothesis is grounded in the established recognition that the Earth's early atmosphere (the Hadean atmosphere) was distinct from today's, featuring high temperatures, high pressures, high water concentration, high volcanic ash concentration, and abundant reactive gases like CO_2, H_2, and NH_3, as well as variable winds and frequent heavy rains [38,42]. The Hadean atmosphere was like a floating volcanic lake and dark near its base due to the presence of nearly all of Earth's water (in vapor) and abundant volcanic ash, with no liquid water on the hot Earth's surface. Geological evidence of intense Hadean volcanism suggests the plausibility of long-term maintenance of ash-rich atmospheric conditions [38,42].
  - The Hadean atmosphere shared advantages with hydrothermal vents and volcanic lakes: abundant energy flow, water, and mineral catalysis (via suspended volcanic ash that enhances reaction yields).
  - The Hadean atmosphere had the following six unique and crucial merits unavailable to hydrothermal vents and volcanic lakes, and consequently, the probability of life originating in the prebiotic atmosphere could be millions of times higher than in prebiotic hydrothermal vents or volcanic lakes.
    * Unparalleled energy diversity (solar radiation, electrical discharges, and thermal gradients);
    * Frequent dynamic phase cycling of organic-containing aerosol droplets (evaporation-condensation, analogous to dry-wet cycling) [42-46];
    * Far greater planetary-scale spaces than hydrothermal vents and volcanic lakes for chemical evolution, boosting reaction volumes and diversity;
    * Far longer time for chemical evolution, as hydrothermal vents and volcanic lakes likely existed hundreds of millions of years later than the atmosphere [38,42];

    * Efficient global mixing of reactants via wind, facilitating compartmentalization of organic molecules and MMAs;
    * The Hadean atmosphere had distinct features at different heights and altitudes, thus containing vast areas for organic chemical synthesis alongside other vast areas for the accumulation or assembly of organic-containing aerosol droplets or MMAs [44].
    * Notably, the Atmosphere-Origin Hypothesis is not a component of CBET, while this hypothesis supports the claim of CBET that life could originate on Earth through chemical evolution.
  - In suitable environments, H6-CBMs can survive because their reproductive function can facilitate their cumulative formation in exceeding their cumulative degradation.
  - In suitable environments, H6-CBMs can mutate because there are no robust mechanisms to completely block their mutation. Consequently, myriad H6-CBMs could emerge on Earth in billions of years.

- Formation of H7-CBMs. In biology, it is known that some H6-CBMs (i.e., reproductive cells) have the function to transform into H7-CBMs through the reproduction and development of H7-CBMs.The process, in nature, results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions.
  Some variants of H6-CBMs evolved into eukaryotic multicellular organisms (H7-CBMs) during the middle Proterozoic eon [2]. Energy supply under the laws of physics and chemistry is critical to the formation and maintenance of H7-CBMs. For instance, energy-absorbing organic synthesis reactions and many energy-consuming physical movements are essential for fertilized eggs and related materials to develop into adult elephants and other H7-CBMs. Glacial cold periods with less energy on Earth can lead to mass extinction of H7-CBMs. The synergy of energy and some functions of the relevant H6-CBMs (e.g., the fertilized eggs of elephants or trees) and the environment can act as the driving force for the formation of adult elephants, trees, and other multicellular H7-CBMs in suitable environments. The driving force is embodied in the spring and summer, when many plants sprout and grow vigorously. It is also embodied in the tropical rain-forest, which is rich in the diversity of animals and plants.

- Formation of H8-CBMs. It is known that some H7-CBMs (multicellular animal or human individuals) have the function to transform into H8-CBMs (social groups with only one hierarchy in management). Multicellular animals possibly emerged on Earth 800 million years ago. Possibly 100 million years ago, some insects established their social groups (H8-CBMs). Sociality is widespread in *Hymenoptera* (ants, bees, and wasps), *Blattodea* (termites), and *Hemiptera* (aphids). A typical animal social collective has a queen and a few reproductive males, who take on the roles of the sole reproducers, and other individuals act as soldiers and workers who collaborate to create a living situation favorable for the brood. Some small companies can also be taken as H8-CBMs. Energy supply is critical to the formation and maintenance of H8-CBMs. For instance, the chemical energy stored in honey collected by honeybees is crucial for honeybee colonies, supporting their survival, flight, heat production, and reproduction. Meanwhile, some functions of the relevant animals, such as their complexity in gene regulation, chemical communications, and internal collaboration determine their approaches of energy consumption, which constitute the power for establishing social groups. For example, during the swarming of honeybees, the old queen bee leaves the hive with a group of worker bees to establish a new colony. This swarm will settle in a new location, and the old queen will begin laying eggs to start the new hive. In the original hive, the first new queen to emerge usually kills or expels other queen larvae to become the sole queen. Once the queen starts laying eggs, the colony stabilizes, with workers continuing to forage, nurse larvae, and maintain the nest. Energy and some functions of humans, such as high intelligence, language and written communication, knowledge accumulation, and collaboration capabilities, also offer humans a driving force for forming some H6-CBMs, such as small companies or sport teams. In nature, the transformation of H7-CBMs into H8-CBMs results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions.

- Formation of H9-CBMs. It is known that some H8-CBMs (e.g., tribes) have the function to transform into H9-CBMs (e.g., tribal alliances) through social collaboration. H9-CBMs are human social groups that have multiple hierarchies in management. Supply of energy associated with food, hydropower, animal power, human power, coal, electricity, nuclear energy, and/or solar energy is essential for the formation of H9-CBMs. Some functions of certain human social groups at low hierarchies, such as the advanced technologies and management systems of some companies with a strong willing to expand their groups, also participate in the driving force for establishing human social groups at higher hierarchies. The formation of H9-CBMs is influenced by the natural and social environment, and the activities of H9-CBMs influence the environment. In nature, the transformation of H7-CBMs into H8-CBMs results from the synergistic interaction of the three fundamental principles associated with energy, environment, structures, and functions.

3. Empirical Evidence for Natural Selection

- Biological systems provide extensive empirical support for natural selection processes across multiple taxa and ecosystems [1,2].
- In chemical evolution, molecular populations undergo competition and selection in chemical reactions and storage processes of organic molecules, where those compounds with formation-to-degradation ratios (γ/λ) >1 demonstrate progressive accumulation, consistent with the natural selection dynamics.
- In social evolution, companies or schools undergo competition and selection where those their formation-to-degradation ratios (γ/λ) >1 demonstrate progressive accumulation, consistent with the natural selection dynamics.

4. Empirical Evidence for the Mathematical Rules

- The three rules are self-evident and universal. The Quantity-Limitation Principle can be deduced by the Environment-Influence Principle. The other two rules can be deduced by rudimentary mathematics, which are applicable to all materials, such as molecules, stones, icebergs, organisms, social organizations, and stars.
- When an asteroid impact causes extinction, the **cumulative formation** (Γ_{total}) of the affected species throughout its evolutionary history becomes equal to its **cumulative degradation** (Λ_{total}) at the extinction moment. This satisfies the Quantity-Existence rule.

5. Empirical Evidence of Additional Viewpoints

The main text provides sufficient empirical evidence to support CBET's viewpoints regarding:

- The importance of both competition and inclusiveness across hierarchies;
- The coexistence of selfish and collaborative or altruistic behavior across hierarchies;
- The complementary roles of heritable and non-heritable factors in biological evolution.

V. Widespread Applications of CBET

- CBET offers an explicit, holistic, and schematic answer to the fundamental question of how simple CBMs have evolved into complex organisms and societies, which has been desired for centuries in evolutionary studies [3,8,48,49].
- Qualitatively, CBET elucidates that the origin of life, which cannot be explained merely by natural selection, thermodynamics, or self-organization, resulted from the synergy of energy, functions of relevant materials, and environmental factors, as well as certain universal mathematical rules.
- Qualitatively, CBET elucidates that the origin of multicellular organisms, which cannot be explained merely by natural selection, thermodynamics, or self-organization, resulted from the synergy of energy, functions of relevant materials (e.g., certain unicellular organisms), and environmental factors, as well as certain universal mathematical rules.
- Qualitatively, CBET suggests that self-replicating macromolecules, which have been sought for long for the studies of the origin of life [46], are rare in nature because self-replication of macromolecules is a complex function, which involves information encoding, information reading, and precise catalysis. This complex function usually requires a structure more complex than the structure of a single macromolecule. CBET assumes from probability that the origin of life resulted from the collaboration of diverse "common" molecules, rather than from those "hero-like" macromolecules with the special function of self-replication.
- Quantitatively, CBET elucidates the natural selection rule of the "survival of the fit" rather than "survival of the fittest" in mathematics.
- CBET elucidates the prevalence of altruistic behavior in CBM evolution and the importance of epigenetic and non-heritable changes in CBM evolution.
- CBET elucidates that organisms can obtain some complex functions, such as prevalent non-random mutations and epigenetic changes, which stem from their complex genomic structures [21,50].
- CBET can qualitatively predict, from the perspectives of energy, functions of CBMs, and the environment, various changes in diverse CBMs, such as diamond production, glucose synthesis, tree growth, and social organization development. For instance, according to CBET, the structures of human brains enable the function of knowledge accumulation. This function, combined with natural selection in social organizations, drives the continuous development of new technologies. Consequently, AI machines are likely to replace most jobs, resulting in profound shifts in the social environment. These changes in the social environment will, in turn, significantly reshape social organizations, according to the three fundamental principles in CBET.

VI. Questions and Answers

Question 1

Just as Maxwell's equations unified electromagnetism, CBET unifies chemical, biological, and social evolution. Have you conducted any *experiments* to validate this theory?

Answer

I have researched viral evolution, and my brother (co-author of this article) has studied plant evolution. We did not cite our research to support CBET because all viewpoints of this theory are established on the knowledge well-established by extensive experiments on molecules, organisms, and social systems reported by countless researchers during the past two centuries. We have synthesized these *experimental findings* for more than three decades to derive, validate, and refine a unified theory that explains the mechanisms underlying chemical, biological, and social evolution.

Question 2

Unlike in Darwin's era, scientists over the past two centuries have conducted extensive experiments, enabling us to synthesize such large-scale theories. I believe all core tenets of CBET, such as environmental influences on material changes, energy as a fundamental driver of change, and the emergence of new functions from structural changes, are explicit and established on the knowledge well-established by extensive experimental and empirical evidence. *Thus no further experiments are needed to validate these viewpoints.* However, a critical question arises: How can such a theory achieve significant scientific innovation, given that CBET's viewpoints are established on existing well-established knowledge?

Answer

CBET could achieve significant innovation through its novel and systematic synthesis of extensive experimental and empirical evidence from a *bird's eye perspective* and the starting point of carbon atoms, to address a *fundamental unsolved question.* Moreover, CBET focuses on providing a schematic rather than detailed explanation for the entire evolution of carbon-based molecules (CBMs) using multiple concrete rather than abstract concepts. This approach is analogous to a scenario where countless scientists have built a high tower, enabling us to use an excellent camera to take the *first empirical aerial photograph* that reveals the panoramic landscape (rather than fine details) of a previously enigmatic domain.

Question 3

CBET classifies countries as a form of carbon-based materials. Does this imply that CBET oversimplifies the behavior of countries and neglects the roles of political and cultural factors?

Answer

CBET is applicable across all hierarchical levels because its key concepts—*CBMs, energy, changes, structures, functions, and environments*—apply universally to all hierarchies and can grow increasingly complex as hierarchies escalate. A country can emerge through an evolutionary trajectory where carbon atoms → small carbon-containing molecules → large carbon-containing molecules → multi-molecular aggregates → cells → multicellular organisms → humans → tribes → tribal alliances → countries. A country's behavior and evolution are shaped by both natural and social environments, relying on energy as well as the physical, chemical, biological, and social functions of the country and its internal entities (e.g., populations, schools, corporations, and armies). Its social functions include political, cultural, psychological, legislative, religious, and military dimensions. Restructuring a nation can generate new functions, enabling adaptation to environmental changes. Moreover, countries undergo natural selection governed by the same mathematical rules as molecules and organisms. For example, slave-holding countries went extinct because they were less advantageous than capitalist countries in natural selection, resulting in their cumulative formation equaling their cumulative degradation. These examples demonstrate that CBET neither oversimplifies country's behavior nor ignores political or cultural factors.

Question 4

The three fundamental principles of CBET offer only a *qualitative* description of the relevant relationships. Can the relevant relationships be described *quantitatively*?

Answer

No, and such quantification is and *theoretically unjustified.* It is also *unnecessary* for CBET's framework. The three principles provide a qualitative description of the relationships among environmental factors, energy dynamics, material changes, structures, and functions. However, these relationships vary profoundly among different hierarchies, changes, materials, and environments, making a unified quantitative framework impractical and theoretically unjustified.

Question 5

Is CBET a theory of *philosophy*?

Answer

Although CBET explores a holistic answer to a very big question in science, it is fundamentally a *scientific theory* rather than a *philosophical study*, for the following three reasons.

- CBET employs multiple explicit and concrete concepts, such as materials, CBMs, structure, functions, environment factors, energy, changes, carbon cycles, feedback loops, mathematical rules, and natural selection, to deduce and describe the theory, and thus holds robust empirical foundations. CBET is also grounded in experimental evidence and interdisciplinary data, such as the findings from **chemistry** (e.g., Miller-Urey experiment), **biology** (e.g., neutral mutations, epigenetics, and environmental influences on organisms), and **social sciences** (e.g., environmental influences on companies). It avoids normative claims or metaphysical speculation.
- CBET employs quantitative rules to describe the essence of natural selection (See Part 2 above).
- CBET is falsifiable. Counter-evidence can falsify CBET's principles, if exists, which contrasts with philosophical theories that often lack empirical falsifiability.

Question 6

How can *AI tools* be used to support this work?

Answer

AI tools have significantly assisted in refining the English expression of this article. For example, they suggested revising "total formation" to the more precise "cumulative formation." Meanwhile, we find ourselves in a race against rapidly advancing AI tools in the development of this theory. It is highly plausible that AI could independently formulate a similar theory in the near future—even without referencing this article, whose preprint was first published in 2020 (available at https://www.preprints.org/manuscript/202010.0004/v1). We further believe that AI tools will, in the coming years, validate both the novelty and credibility of this theory, which offers a novel holistic framework for understanding the world and human societies.

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