 doi:10.20944/preprints202010.0004.v5

A comprehensive evolutionary theory deduced from thermodynamics

Ji-Ming Chen*

China Animal Health and Epidemiology Center, Qingdao, 266032, China

*** Corresponding author.**
Email: jmchen678@qq.com;
Telephone: +86-13854212160.

Abstract

Studies on evolution have made significant progress in multiple disciplines, but evolutionary theories remain scattered and controversial. Here we deduce that, thermodynamically, many carbon-based entities (CBEs) on the Earth tend to absorb energy from widespread relatively temperate heat streams on the Earth flowing from the solar, geothermal, and other energy sources, to form higher-hierarchy CBEs (HHCBEs). This has been the driving force of evolution leading to accumulation and regeneration of HHCBEs for billions of years. We further deduce three progressive mechanisms of evolution from the driving force. We hence establish the CBE evolutionary theory (CBEET) which suggests that evolution driven hierarchy-wise by thermodynamics favors fitness and diversity. The CBEET provides novel explanations for origin of life (abiogenesis), macroevolution, natural selection, sympatric speciation, and animal group evolution in a comprehensive and comprehensible way. It elucidates that altruism, collaboration, and obeying rules with increasing freedom are important throughout the CBE evolution. It refutes thoroughly the notion that negative entropy leads to order in biology which is distinct from order in thermodynamics. It integrates with research advances in multiple disciplines and links up laws of physics, evolution in biology, and harmonious development of human society.

Keywords

carbon-based entity; driving force; energy; evolution; fitness; mechanism; natural selection; speciation; thermodynamics; theory

1. Introduction

Charles Darwin's evolutionary theory built on natural selection is a breakthrough in science. This theory was updated with the Modern Synthesis last century, which changed the definition of natural selection from "survival of the fittest" to "gradual replacement with those carrying adaptive mutations" [1-3]. Thereafter, the Modern Synthesis has met challenges from research advances in molecular biology and epigenetics, and has not integrated with these challenges [1-7]. Moreover, the Modern Synthesis is unable to interpret the mechanisms for origin of life and macroevolution [1-3].

Both Charles Darwin's theory and the Modern Synthesis were extrapolated from microevolution (evolution within species) [1-14]. This logic is apt to generate controversial and scattered views, like using fishes' eyes to reveal the structure of a river, as different fishes could have different views, and no fishes could reveal the panorama of the river.

Here we deduced a comprehensive evolutionary theory, which can integrate with research advances in multiple disciplines and interpret the mechanisms for origin of life and macroevolution. This theory relies on extrapolation from microevolution in determining the theory's details, and deduction from thermodynamics in determining the theory's framework. This theory is termed the CBE evolutionary theory (CBEET), where CBE denotes carbon-based entity. CBEs include some small molecules (e.g. methane and ethanol), middle organic molecules (e.g. amino acids and nucleotides), large organic molecules (e.g. proteins and nucleic acids), and organisms (e.g. bacteria, animals, and plants). CBEs have hierarchies, and large organic molecules are higher-hierarchy CBEs (HHCBEs) compared with middle organic molecules, but they are lower-hierarchy CBEs (LHCBEs) compared with organisms. The differences between the CBEET and previous theories are outlined in **Figure 1** and listed in **Table 1**.

2. Methods

2.1 Definitions

Autocatalysis: the phenomenon that the product of a reaction has the activity to catalyze the reaction to produce the product itself.

Multiple other concepts including altruism, CBE, HHCBE, LHCBE, the extrapolation logic, the deduction logic, the backstepping logic, microevolution, macroevolution, natural selection, positive selection, negative selection, punctuated equilibrium, chemical evolution, animal group evolution, and cultural evolution are defined at relevant sites in the main text.

2.2 Fundamentals of thermodynamics [17,18]

The first law of thermodynamics: increase of internal energy of a closed system is equal to the work the outside gives to the system plus the heat the outside gives to the system.

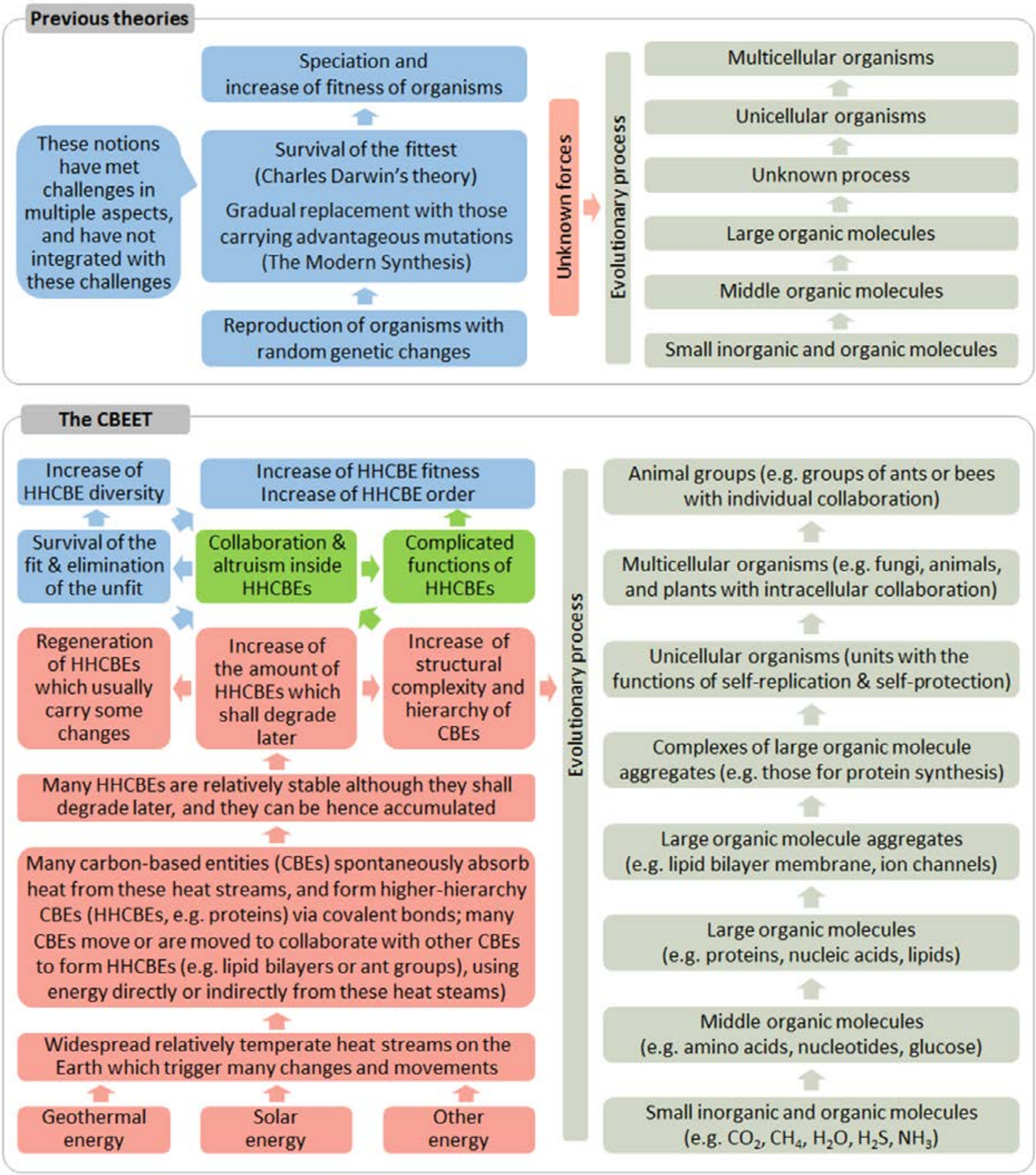

Figure 1. Major views of previous evolutionary theories versus the CBEET. The red, green, and blue arrows represent the driving force mechanism, the structural mechanism, and the natural selection mechanism, respectively.

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Table 1. Differences between the evolutionary theory CBEET and previous theories.

Topics	Previous theories	CBEET views
Logic	Extrapolation from microevolution, like using fishes' eyes to reveal the structure of a river	Extrapolation from microevolution (like using fishes' eyes to reveal details of a river) and deduction from thermodynamic laws (like using satellites to reveal the panorama of a river)
The driving force of evolution	Natural selection, genetic drift, mutation, or competition (none of them provide energy)	The tendency of carbon-based entities (CBEs) to absorb energy from heat streams on the Earth to form higher-hierarchy CBEs (HHCBEs)
Progressive mechanisms of evolution	Natural selection, sexual selection, and epigenetic changes lead to increase of fitness of organisms; no rational mechanisms have been proposed to interpret macroevolution	The driving force increases the structural complexity and hierarchy of CBEs; CBEs with increased structural complexity and hierarchy can obtain spontaneously some complicated functions; natural selection leads to increase of diversity and fitness of HHCBEs
Natural selection	Defined as "survival of the fittest" or "gradual replacement with those carrying advantageous mutations"; stressing positive selection in one aspect; claiming mutations occur randomly and only inheritable changes are under natural selection	Defined as "survival of fit HHCBEs and elimination of unfit HHCBEs"; highlighting the overall fitness constituted by all traits of HHCBEs; highlighting selection from various aspects; accepting that some mutations occur not randomly, and inheritable and uninheritable changes (e.g. vaccination) are all under natural selection
Chemical evolution	Neither the driving force nor the mechanisms have been proposed to interpret how large organic molecules evolved into lives; stressing autocatalysis and RNA	The driving force and mechanisms of chemical evolution are revealed; lives originated hierarchy-wise from small molecules with several intermediate hierarchies; stressing collaboration and altruism of various molecules
Biological evolution	Interpreting sympatric speciation with diverging selection targeting different niches in the same area	Proposing a novel sympatric speciation mechanism which targets the same niche through different combinations of traits
Animal group evolution	Not having established the concept of animal group evolution; difficult to explain altruism and social norms; having negative influence on human society	Establishing animal group evolution as a phase of the evolution; clarifying that altruism, collaboration, and obeying rules with increasing freedom are important throughout the evolution of CBEs; having positive influence on human society
Order in biology and entropy	Organisms have order and low entropy due to negative entropy (input of low-entropy matter and output of high-entropy matter)	Organisms are of high entropy; the notion of "negative entropy" is wrong; order in biology is contrary to order in physics; order should not be always hooked with low entropy
General features	Not relying on energy, scattered, prejudiced, elusive, unable to integrate with recent discoveries, separated from physics and social sciences	Relying on energy, inclusive and integrated, comprehensive, comprehensible, able to integrate with recent discoveries in molecular biology and epigenetics, bridging laws of thermodynamics and social sciences

The second law of thermodynamics: heat can spontaneously flow from a hotter body to a colder body, and cannot spontaneously flow from a colder body to a hotter body; the entropy of an isolated system never decreases over time.

The third law of thermodynamics: the entropy of a system approaches a constant value as its temperature approaches absolute zero, and the entropies of perfect crystals at absolute zero temperature are zero.

The Boltzmann formula of entropy: $S=K\times Ln\Omega$, where S, K, and Ω denote entropy, a constant, and microstates (i.e. possible microscopic configurations), respectively.

The Clausius inequality of entropy: $dS \geq \delta Q/T$, where dS, δQ, and T denote changes of the entropy of a closed system, heat absorbed by the system from the outside, and absolute temperature, respectively.

2.3 Deduction and Validation

Deduction of the CBEET was detailed below. The major views of the CBEET are validated through one or two ways: whether the views can explain some phenomena which have not been well explained; whether the views reflect the reality better.

3. Deduction of the driving force of evolution

The earth's surface has widespread relatively temperate heat streams flowing from the solar, geothermal, and other energy sources. The earth, as a rare habitable planet in astronomy, is in a suitable orbit and receives temperate sunlight, which leads to temperate heat streams on the Earth for billions of years [14]. Meanwhile, many sites on the Earth, particularly at hydrothermal vents, have emitted geothermal energy for long periods [15,16]. The huge amount of water on the Earth and the atmosphere of the Earth regulate these energy flows through evaporation, diffusion, and rainfall, making them more temperate, last longer, and distributed more widely.

The widespread relatively temperate heat streams on the Earth trigger many changes and movements. According to the second law of thermodynamics (i.e. heat can spontaneously flow from a hotter location to a colder location) [17,18], stones can spontaneously absorb heat from these heat streams and increase their temperatures, and many CBEs can spontaneously absorb heat from these heat streams to form HHCBEs through covalent bonds, partially because carbon atoms are apt to form covalent bonds after absorbing heat [19]. Meanwhile, many CBEs are mobile, they can hence meet and collaborate with other CBEs to form HHCBEs not through covalent bonds. For example, lipid molecules can form bilayer membranes and ants can form ant groups in this way, where energy required for the movement of these CBEs is directly or indirectly from the widespread relatively temperate heat streams on the Earth.

Although all HHCBEs shall degrade sooner or later, many HHCBEs are relatively stable and can be accumulated. HHCBEs have hence been formed, degraded, regenerated, and accumulated at a myriad of places for billions of years, due to the widespread relatively temperate heat streams on the Earth, which constitutes the evolution of CBEs (**Figure 1**). Therefore, the tendency of CBEs on the Earth to absorb energy to form HHCBEs, is the driving force of evolution.

Initially, the driving force of evolution was from solar energy and geothermal energy. Later, with the increase of organisms on the Earth, biological energy became a source of the driving force of evolution. This is of paramount significance for animals which can actively obtain energy and materials from other organisms. Energy from coal, petrol, water flow, and even nuclear power has been utilized by humans for the development of human society.

The above driving force can explain why non-living organic molecules evolved to lives, why unicellular organisms evolved to multicellular organisms, and why ectotherm animals evolved to warm-blooded animals, because all these three macroevolution events were the processes where CBEs absorbed energy and formed HHCBEs. They cannot be well explained with previous theories including natural selection, because none of the processes added fitness to CBEs [3-5,10,20,21].

During the whole history of the Earth, the amount and the diversity of HHCBEs including organisms on the Earth are generally increasing [22]. However, meteorite impacts, huge volcano eruptions, long glacial periods, and other catastrophes can destroy the temperate heat streams on the Earth and structures of many organisms [23-25]. Consequently, the amount and the diversity of organisms could decline greatly for these catastrophes, sometimes leading to mass extinctions [23-25].

4. Deduction of the progressive mechanisms of evolution

Three progressive mechanisms of evolution were deduced from the driving force of evolution. The first is termed the driving force mechanism shown with the red arrows in **Figure 1**, where the driving force of evolution directly raises the amount of HHCBEs and increases the structural complexity and hierarchy of CBEs. The second is termed the structural mechanism shown with the green arrows in **Figure 1**, where CBEs with increased structural complexity and hierarchy spontaneously obtain some complicated functions, due to collaboration and altruism of the components inside HHCBEs (altruism is the action supporting the existence and production of other entities). For example, when green fluorescence protein is formed by amino acids, it obtains spontaneously the function of emitting green fluorescence, due to collaboration of its amino acid components which all "sacrifice" their freedom to "work" for the protein. The third mechanism is termed natural selection shown with the blue arrows in **Figure 1**, which leads to increase of the diversity and the fitness of CBEs, as detailed below.

As shown in **Figure 1**, the driving force of evolution leads to formation and accumulation of HHCBEs. The formed HHCBEs shall degrade into LHCBEs sooner or later, due to outer factors (e.g. fire burning) or inner factors (e.g. natural aging) [1,2]. Therefore, lots of CBEs on the Earth are in the cycle of formation and degradation of HHCBEs, leading to regeneration of HHCBEs. Regenerated HHCBEs usually carry some changes which influence the overall fitness of HHCBEs. Some regenerated

HHCBEs are formed faster and/or degrade more slowly than some other HHCBEs, resulting from the overall fitness of HHCBEs.

Natural selection is defined in the CBEET as survival of fit HHCBEs and elimination of unfit HHCBEs as per their overall fitness. The overall fitness of HHCBEs is determined not only by collaboration and altruism of components of HHCBEs, but also by the environment. For example, great fitness in a hot rainforest can be a terrible burden in a cold desert. Moreover, when the environment is comfortable, the fitness threshold of natural selection is low, which allows survival of HHCBEs carrying various changes [26]. In contrast, the fitness threshold of natural selection increases greatly when a catastrophe occurs, which can lead to mass extinction of organisms including those quite fit previously [23-25].

The CBEET definition of natural selection maintains the core feature of the concept of natural selection in Charles Darwin's evolutionary theory and in the Modern Synthesis [3-5]: fitness of organisms increases over time because natural elimination of the unfit, making unfit HHCBEs survive less time and/or reproduce fewer progenies.

The CBEET definition of natural selection is also different from previous definitions in multiple aspects. First, the CBEET definition covers non-living CBEs and can be extended to origin of life. Second, as shown in **Figure 1**, complicated functions, fitness, and order of HHCBEs are all based on collaboration and altruism of components of HHCBEs, and the collaboration and altruism are under natural selection and influenced by changes of HHCBEs. Moreover, all these processes can be deduced from laws of thermodynamics. Therefore, unlike that natural selection in previous theories is supported by itself and hence suspected of tautology [27], natural selection in the CBEET is supported by structures of HHCBEs and laws of thermodynamics. Third, the CBEET definition (survival of fit HHCBEs) is less harsh and more inclusive than "survival of the fittest" in Charles Darwin's theory and "gradual replacement with those carrying advantageous mutations" in the Modern Synthesis [1-4], and the CBEET definition reflects the reality correctly because research advances in molecular biology suggest that most genomic changes are likely neutral without increase in fitness [3-5,10,12,28]. Fourth, the CBEET definition of natural selection highlights the overall fitness because the reality is that the existence of an HHCBE is determined by its overall fitness, although a certain trait may play a leading role in the overall fitness of an HHCBE. Therefore, the CBEET allows an organism to have disadvantageous traits, if its overall fitness is adequate. For example, antelopes are less strong than buffaloes to fight against carnivores, but they run fast and have other advantages, making them have adequate fitness in general. This suggests a novel mechanism of sympatric speciation, because multiple combinations of traits can all have adequate fitness in occupying the same ecological niche in the same area. Previously, only the mechanism for sympatric speciation targeting different ecological niches in the same area through diverging selection pressure has been proposed [3]. Fifth, genetic mutations, epigenetic changes, and uninheritable changes all influence the overall fitness of HHCEBs, and they are thus all under natural selection. For example, vaccination which is uninheritable makes many animals survive viral infections and pass the relevant natural selection. Sixth, previous definitions usually assume that mutations under natural selection occur randomly. Now it has been known that many organisms have the complicated function which makes many mutations occur not randomly, as evidenced in the evolution of microbial genomes and mammalian immunoglobulin genes [9,29].

Organisms accumulated much fitness through long geological periods. Therefore, organisms are under both positive selection (supporting those changes which add fitness) and negative selection (inhibiting those changes which reduce fitness) [30]. Because natural selection "selects" organisms as per their overall fitness which is influenced by all genomic sites and all traits, all genomic sites and all traits are under both positive selection and negative selection [30,31]. Accordingly, natural selection functions extensively in evolution. Moreover, a conserved trait or genomic site without change during a long geological period does not mean that the trait or site is not under natural selection, but likely under strong negative selection [30].

Natural selection in the CBEET targets all hierarchies of CBEs. For example, giraffe groups, giraffe individuals, and cells, large organic molecules including genes in giraffes are all under natural selection along with giraffe groups. If a giraffe group is favored by natural selection, the LHCBEs involved in the formation of the giraffe group, including genes of the giraffe group, are also favored by natural selection.

Natural selection, mutation, genetic drift, and competition were claimed to be the driving force of evolution [3-5,20,28,31]. These "driving forces" are not directly related to energy, and they are largely mechanisms or processes of evolution. The role of energy in biological evolution was highlighted previously [32,33], but energy was not associated with the driving force of evolution. Here the driving force of evolution from thermodynamics provides energy for the evolution of CBEs. Moreover, all the three progressive mechanisms of evolution are derived from the driving force of evolution (**Figure 1**). Therefore, the driving force of evolution plays the first leading role in evolution, although natural selection functions extensively in evolution and remains a leading role in evolution.

4. Deduction of the process of evolution

The driving force of evolution from thermodynamics leads to formation and accumulation of HHCBEs hierarchy by hierarchy. For example, amino acids, nucleotides and other middle organic molecules could not bypass the intermediate hierarchy of large organic molecules to form unicellular organisms, and large organic molecules could not bypass the intermediate hierarchy of unicellular hierarchy to form multicellular organisms. Accordingly, as per the backstepping logic (i.e. if hierarchy A exists, the hierarchies lower than hierarchy A should have existed in advance), there should be the following seven major steps constituting the whole evolution of CBEs on the Earth (**Figure 1**).

Step 7, many animal individuals of the same species collaborate with each other and form animal groups, which include groups of bees, ants, humans, and many other animals. Animal groups have novel functions which cannot be fulfilled by animal individuals. For example, some ant groups plant fungi for food, which cannot be fulfilled by ant individuals [34]. Some animal groups are eusocial, where some individuals reduce their own lifetime reproductive potential to raise the offspring of others. Many other animal groups are presocial, where the parents take care of their own progenies [46]. Although presocial species are much more common than eusocial species, eusocial species have disproportionately large populations [35].

Step 6, many cells collaborate with each other and form multicellular organisms, which include fungi, plants, and animals. Multicellular organisms have novel functions which cannot be fulfilled by any cells (e.g. birds can fly faraway which cannot be fulfilled by any cells).

Step 5, many complexes of large organic molecule aggregates collaborate with each other and form the first batch of unicellular organisms, which are the units having the complicated functions of self-replication via catalysis (for efficiently generating HHCBEs) and self-protection (for efficiently maintaining HHCBEs). The first batch of unicellular organisms emerged at a tiny possibility, and this tiny possibility was realized through the effect of vast spaces and vast time.

Step 4, many large organic molecule aggregates collaborate with each other and form complexes of large organic molecule aggregates which, like organelles in the unicellular organisms, have some complicated functions (e.g. synthesis of proteins).

Step 3, many large organic molecules collaborate with each other and form large organic molecule aggregates (e.g. lipid bilayer membranes and channels allowing ions to pass lipid bilayer membranes) [36]. From this step to the seventh step, energy is not always required to form chemical bonds, but is required for the movement of CBEs to meet and collaborate with other CBEs.

Step 2, many middle organic molecules (e.g. amino acids, nucleotides, glucose) collaborate with each other and form proteins, nucleic acids, polysaccharides, and other large organic molecules. Before origin of life, few mechanisms were available to direct the synthesis of large organic molecules according to certain orders, and so proteins, nucleic acids, lipids, polysaccharides were produced with few repetitions, and thus the products were of a myriad of diversity. These highly diversified large organic molecules could provide abundant candidates for forming HHCBEs in **Steps 3–7**. This was beneficial for complexes of large organic molecule aggregates to form unicellular cells at a tiny possibility.

Step 1, many small molecules (e.g. CO_2, CH_4, H_2O, H_2S) collaborate with each other and form middle organic molecules (e.g. amino acids, nucleotides, glucose). This step has also occurred on other planets, and lots of middle organic molecules were sent to the Earth by meteorites [37].

Steps 1–5 constitute chemical evolution which is also termed abiogenesis or origin of life. **Steps 5–7** constitute biological evolution excluding abiogenesis. **Step 7** constitutes animal group evolution including the development of human society.

Steps 1–5 suggest that, before origin of lives, there were five successive and overlapping worlds: the world of small molecules, the world of middle organic molecules, the world of large organic molecules, the world of large organic molecule aggregates, and the world of complexes of large organic molecule aggregates. Compared with previous theories which emphasize the special role of RNA and some organic molecules with the function of autocatalysis [38,39], the CBEET highlights collaboration and altruism of various molecules.

Obeying rules is embodied throughout the evolution of CBEs. For example, molecules should obey some rules in cells, and cells should obey some rules in multicellular organisms. Individuals in animal groups should obey some rules, including that lion kings should take their responsibility to fight against invaders, and worker bees should work diligently all days for their groups, and drivers should obey traffic rules. Obeying rules is the basis of collaboration and altruism of inside HHCBEs which, in turn, determine the overall fitness of HHCBEs. Additionally, freedom of components inside HHCBEs increases with the CBE evolution, because as for the seven steps given above, components inside HHCBEs are restricted within molecules (**Steps 1 and 2**), within molecular aggregates or complexes (**Steps 3 and 4**), within cells (**Step 5**), within multicellular organisms (**Step 6**), or within certain areas (**Step 7**).

5. Significance for human society

The CBEET aids the harmonious development of human society. First, previous evolutionary theories stress selfishness, competition, and elimination of those less fit in certain traits [1-5,24]. Particularly, social Darwinism which was established on the wrong view of "survival of the fittest" in the fierce competition [1-4], has been employed to justify authoritarianism, eugenics, racism, imperialism, fascism, and Nazism [40]. In contrast, the CBEET not only emphasizes selfish (self-reproduction and self-protection), fitness, and competition, but also emphasizes co-existence of many differences and changes if the relevant HHCBEs have adequate fitness. This suggests that we should respect diversity in races, culture, and management systems. Second, previous evolutionary theories stress genetic differences, while the CBEET not only emphasizes genetic differences, but also emphasizes the effects of endeavor to increase fitness, even if the effects are uninheritable. Third, previous evolutionary theories stress advantages of a single trait, while the CBEET emphasizes overall fitness. This is important for humans in making correct decisions. Moreover, the CBEET demonstrates that collaboration, altruism, and obeying rules with increasing freedom are all fundamental throughout the evolution of CBEs including development of human society.

6. Significance in physics

The CBEET refuted the notion that negative entropy leads to order in biology. Evolution leads to increase of order in biology, which seems contrary to the second law of thermodynamics leading to increase of entropy in isolated systems, because entropy represents chaos in thermodynamics [17,18,41]. Scientists assumed that organisms are systems with low entropy because they have much order, and organisms keep low entropy through absorbing low-entropy matter and discharging high-entropy matter, and hence the controversial notion of "negative entropy" was established [41]. We believe that this notion is wrong as per the definitions of entropy [17,18], and order in biology is distinct from order in thermodynamics. For example, the order in biology of a dog declines, and the order in thermodynamics of the same dog increases, when the dog is dying in the snow with heat being lost from the body, as per the Clausius inequality of entropy [17,18]. Live dogs are warm and moving systems with many microstates, and they have hence high entropy, compared with perfect crystals at absolute zero temperature which have the lowest entropy and the highest order in thermodynamics, as per the Boltzmann formula of entropy and the third law of thermodynamics [17,18]. Moreover, during the period that fertilized eggs grow into mature dogs, the order in biology of these dog change little while their entropies have increased billions of times, as per the additive property of entropy [17,18]. In effect, order in biology is established through billions of years' evolution, rather than a short-time metabolic effect of negative entropy. Contrary to the notion of negative entropy, Ludwig Boltzmann who created the Boltzmann formula of entropy pointed that animate beings struggle for entropy, which becomes available through the transition of energy from the hot sun to the cold earth [42]. Interestingly, this view was inherited and detailed by the CBEET.

Acknowledgements: This study has not been supported by any funds so far. The author thanks many friends of his for providing precious comments on this study.
Author contributions: This study is completed by Jiming Chen.
Competing interests: The author declares no conflict of interest.

References

1. Chen JM. A new evolutionary theory deduced mathematically from entropy amplification. Chin Sci Bul. 2000;45(1):91–96. https://doi.org/10.1007/BF02884912
2. Chen JM, Chen JW. Root of science: the driving force and mechanisms of the extensive evolution. Beijing, China: Science Press, 2000.
3. Futuyma DJ, Kirkpatrick M. Evolution. 4th ed. Sunderland, UK: Sinauer Press, 2017.
4. Huneman P, Walsh DM. Challenging the Modern Synthesis: adaptation, development, and inheritance. Oxford, UK: Oxford University Press, 2017.

5. Preiner M, Asche S, Becker S, et al. The future of origin of life research: bridging decades-old divisions. Life (Basel). 2020;10(3):20. http://doi.org/10.3390/life10030020
6. Pagel M. Natural selection 150 years on. Nature. 2009;457:808–811. https://doi.org/10.1038/nature07889
7. d'Ischia M, Manini P, Moracci M, et al. Astrochemistry and astrobiology: materials science in wonderland? Int J Mol Sci. 2019;20(17):4079. http://doi.org/10.3390/ijms20174079
8. Orgel L. In the beginning. Nature. 2006;439(7079):915–915. https://doi.org/10.1038/439915a
9. Fitzgerald DM, Rosenberg SM. What is mutation? A chapter in the series: How microbes “jeopardize” the modern synthesis. PLoS Genet. 2019;15(4): e1007995. https://doi.org/10.1371/journal.pgen.1007995
10. Koonin EV. Darwinian evolution in the light of genomics. Nucleic Acids Res. 2009;37(4):1011–1034. http://doi.org/10.1093/nar/gkp089
11. Dickins TE, Rahman Q. The extended evolutionary synthesis and the role of soft inheritance in evolution. Proc Biol Sci. 2012;279(1740): 2913–2921. http://doi.org/10.1098/rspb.2012.0273
12. Casillas S, Barbadilla A. Molecular population genetics. Genetics. 2017;205(3):1003–1035. https://doi.org/10.1534/genetics.116.196493
13. Walker SI. Origins of life: a problem for physics, a key issues review. Rep Prog Phys. 2017;80(9):092601. https://doi.org/10.1088/1361-6633/aa7804
14. Seager S. Exoplanet habitability. Science. 2013;340(577):577–581. http://doi.org/10.1126/science.1232226
15. Dodd MS, Papineau D, Grenne T, et al. Evidence for early life in earth's oldest hydrothermal vent precipitates. Nature. 2017;543(7643): 60–64. http://doi.org/10.1038/nature21377. PMID 28252057.
16. Proskurowski G, Lilley MD, Seewald JS, et al. Abiogenic hydrocarbon production at lost city hydrothermal field. Science. 2008;319(5863):604–607. http://doi.org/10.1126/science.1151194.
17. DeVoe H. Thermodynamics and chemistry. 2nd Edition. Version 10. http://www2.chem.umd.edu/thermobook/v10-screen.pdf. Accessed on Sep. 20, 2020.
18. Borgnakke C, Sonntag RE. Fundamentals of Thermodynamics. 8th edition. Hoboken, USA: John Wiley & Sons, 2013.
19. Carbon. https://en.wikipedia.org/wiki/Carbon. Accessed on Sep. 20, 2020.
20. Benton MJ. The Red Queen and the Court Jester: species diversity and the role of biotic and abiotic factors through time. Science. 2009;323(5915):728–732. http://doi.org/10.1126/science.1157719
21. Lynch M. The frailty of adaptive hypotheses for the origins of organismal complexity. Proc Natl Acad Sci U S A. 2007;104(Suppl 1):8597–8604. http://doi.org/10.1073/pnas.0702207104

22. Rohde RA, Muller RA. Cycles in fossil diversity. Nature. 2005;434(7030):208–210. http://doi.org/10.1038/nature03339
23. Percival LME, Ruhl M, Hesselbo SP, et al. Mercury evidence for pulsed volcanism during the end-Triassic mass extinction. Proc Natl Acad Sci U S A. 2017;114(30):7929–7934. http://doi.org/10.1073/pnas.1705378114
24. Fields BD, Melott AL, Ellis J, et al. Supernova triggers for end-Devonian extinctions. Proc Natl Acad Sci U S A. 2020;117(35):21008–21010. http://doi.org/10.1073/pnas.2013774117
25. Bader J, Jungclaus J, Krivova N, et al. Global temperature modes shed light on the Holocene temperature conundrum. Nat Commun. 2020;11:4726. https://doi.org/10.1038/s41467-020-18478-6
26. McGee MD, Borstein SR, Meier JI, et al. The ecological and genomic basis of explosive adaptive radiation. Nature. 2020. https://doi.org/10.1038/s41586-020-2652-7
27. Hunt T. Reconsidering the logical structure of the theory of natural selection. Commun Integr Biol. 2014;7(6):e972848. https://doi.org/10.4161/19420889.2014.972848
28. Nei M. Mutation-driven evolution. Oxford, UK: Oxford University Press, 2013.
29. Olivieri DN, Mirete-Bachiller S, Gambón-Deza F. Insights into the evolution of IG genes in Amphibians and Reptiles. Dev Comp Immunol. 2020: 103868. https://doi.org/10.1016/j.dci.2020.103868. Epub ahead of print.
30. Chen J, Sun Y. Variation in the analysis of positively selected sites using nonsynonymous/synonymous rate ratios: an example using influenza virus. PLoS One. 2011;6(5):e19996. http://doi.org/10.1371/journal.pone.0019996.
31. Hershberg R, Petrov DA. Selection on codon bias. Annu Rev Genet. 2008;42(1):287–299. http://doi.org/10.1146/annurev.genet.42.110807.091442
32. Martin WF, Sousa FL, Lane N. Energy at life's origin. Science. 2014;344:1092–1093. https://doi.org/10.1126/science.1251653
33. Sousa FL, Thiergart T, Landan G, et al. Early bioenergetic evolution. Philos Trans R Soc Lond B Biol Sci. 2013;368(1622):20130088. http://doi.org/10.1098/rstb.2013.0088
34. Styrsky JD, Eubanks MD. Ecological consequences of interactions between ants and honeydew-producing insects. Proc Biol Sci. 2007;274(1607):151–164. http://doi.org/10.1098/rspb.2006.3701
35. Nowak M, Tarnita C, Wilson E. The evolution of eusociality. Nature. 2010;466:1057–1062. https://doi.org/10.1038/nature09205
36. Levy E, Erba E, Robinson C, et al. Assembly reflects evolution of protein complexes. Nature. 2008;453:1262–1265. https://doi.org/10.1038/nature06942
37. Follmann H, Brownson C. Darwin's warm little pond revisited: from molecules to the origin of life. Naturwissenschaften. 2009;96(11):1265–1292. http://doi.org/10.1007/s00114-009-0602-1.
38. Kauffman SA. Approaches to the origin of life on the Earth. Life (Basel). 2011;1(1):34–48. http://doi.org/10.3390/life1010034.

39. Robertson MP, Joyce GF. The origins of the RNA world. Cold Spring Harb Perspect Biol. 2012;4(5): a003608. http://doi.org/10.1101/cshperspect.a003608.
40. Rudman LA, Saud LH. Justifying Social Inequalities: The role of social Darwinism. Pers Soc Psychol B. 2020;46(7):1139–1155. https://doi.org/10.1177/0146167219896924.
41. Schrödinger E. What is life – the physical aspect of the living cell. Cambridge, UK: Cambridge University Press, 1944.
42. Boltzmann L. The second law of thermodynamics. In *Theoretical physics and philosophical problems* (pp. 13-32). Dordrecht, Netherlands: Springer, 1974.