RESEARCH ARTICLE

Systematically Challenging Three Prevailing Notions About Entropy and Life

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Abstract

This article systematically challenges three notions prevailing in diverse disciplines: 1) Entropy is a measure of disorder; 2) life relies on negative entropy; 3) and many systems tend to become increasingly disordered due to the second law of thermodynamics, using the original, fundamental, and uncontroversial (OFU) nature of entropy: entropy, whose unit is joule/kelvin, is a physical concept analogous to energy and is heat energy mathematically divided by the relevant thermodynamic temperature. The challenge is supported by numerous compelling facts in physics, chemistry, and biology. The challenge, if widely accepted, could facilitate the eradication of the entrenched misleading effects of these misconceptions in diverse disciplines and facilitate relevant research and education on complexity, entropy, disorder, order, evolution, life, and thermodynamics.

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1. Introduction

Multiple notions associated with entropy, such as the idea of animals struggling for plants' entropy proposed by Ludwig Boltzmann in the 1880s [1], the concept of animals relying on negative entropy proposed by Erwin Schrödinger in the 1940s [2], the maximum entropy production hypothesis[3], and minimum energy dissipation principle [4], have been frequently applied to interpret complexity, disorder, and order in life sciences and other disciplines [4][5][6][7][8][9][10][11][12][13][14][15][16]. It is desirable to investigate whether these notions are correct to ensure the validity of their applications.

2. Methods

The original, fundamental, and uncontroversial (OFU) nature of entropy is clarified and employed below as the criterion to judge whether an entropy-associated notion is correct, according to the basic logic in science: any notions derived from a valid concept (e.g., entropy) should not contradict the OFU nature of the concept.

3. Results

3.1. The OFU nature and features of entropy

In 1854, Rudolf Clausius created the concept of entropy (S) and the Clausius formula of entropy,

$$\Delta S = \Delta Q/T \qquad (1)$$

to mathematically describe the second law of thermodynamics and explain the efficiency of heat-to-work conversion in Carnot cycles [17]. The law states that heat can spontaneously flow from a hot object to a cold object and cannot spontaneously flow reversely. The law involves heat energy (Q), the kinetic energy of the unordered vibration of molecules in an object [18][19][20], and thermodynamic temperature (T). T is higher than zero for all objects worldwide, according to the third law of thermodynamics [18][19][20][21][22]. The Clausius formula denotes that, at a time point, the increase in the entropy of an object (S) is equal to the heat absorbed by the object (Q) divided by the thermodynamic temperature of the object (T) [18][19][20][21][22], and the entropy of an object increases when it absorbs heat from its surroundings (Q>0) and declines when it dissipates heat into its surroundings (Q<0). This formula suggests that the entropy of an isolated system always increases until its components reach the same temperature, which accurately describes in mathematics the second law of thermodynamics (Box 1). The Clausius formula defines the OFU nature of entropy: entropy is a physical concept analogous to energy and is heat energy mathematically divided by the relevant thermodynamic temperature. This OFU nature of entropy, which is widely applied in current thermodynamics [18][19][20][21][22][23], aligns with Rudolf Clausius's statement: “…I have designedly coined the word ‘entropy’ to be similar to ‘energy’, for these two quantities are so analogous in their physical significance...” [22].

Box 1. Changes of the entropy of an isolated system

In an isolated system containing only hot A and cold B, heat spontaneously flows from A to B, and for any time point before A and B reach the same temperature, A is hotter than B ($T_A > T_B > 0$), the heat released by A is equal to the heat absorbed by B ($Q_B = -Q_A > 0$).

The change of entropy ($\Delta S = \Delta Q/T$) of B, A, and the isolated system (i-system) are:

$\Delta S_B = \Delta Q_B/T_B > 0$ because B absorbs heat ($\Delta Q_B > 0$) and $T_B > 0$

$\Delta S_A = \Delta Q_A/T_A < 0$ because A dissipates heat ($Q_A = -Q_B < 0$) and $T_A > 0$

$\Delta S_{i\text{-system}} > 0$ because $\Delta S_{i\text{-system}} = \Delta S_A + \Delta S_B = \Delta Q_A/T_A + \Delta Q_B/T_B = -\Delta Q_B/T_A + \Delta Q_B/T_B = \Delta Q_B\,(1/T_B - 1/T_A)$, $\Delta Q_B > 0$, and $T_A > T_B$

The above inequality $\Delta S_{i\text{-system}} > 0$ accurately describes in mathematics the second law of thermodynamics[17][18][21].

Entropy has the following two features.

1. Entropy is a derived quantity with the unit joule/kelvin (J/K)[18][19][20], where "kelvin" is the unit of thermodynamic temperature and "joule" is the unit of energy. As 1 joule = 1 kg×m/(s^2), entropy can be considered a quantity derived from four basic quantities in physics: mass, length, time, and thermodynamic temperature.
2. Entropy is an additive quantity in physics. For instance, the entropy of the isolated system composed of objects A and B in Box 1 is equal to the entropy of object A plus the entropy of object B [18][19][20].

About in 1900, Max Planck created another formula for entropy:

$$S = k \ln W \qquad (2)$$

Max Planck termed this formula the Boltzmann formula because it originated from Boltzmann's view that the second law of thermodynamics can be explained with statistical probability [1][24]. In this formula, ln represents the natural logarithm, k denotes the Boltzmann constant (1.38065×10^{-23} J/K), and *W* is from the German “Wahrscheinlichkeit”, which means probability, and represents a probability associated with heat transfer [24][25][26]. Since disorder does not correlate with heat transfer, this formula does not support the idea that entropy is a measure of disorder. Later, *W* was translated into English words such as complexions, permutations, or thermodynamic probability [26]. *W* is now frequently translated as multiplicity (the count of microstates) [26], which is elusive because it is unknown whether this word is associated with the microstates of molecules, atoms, and/or elementary particles such as electrons and quarks. Nevertheless, *W* represents a probability associated with heat transfer. In contrast, disorder (chaos, untidiness, or abnormalities) does not consistently change with the probability associated with heat transfer.

To combine the above two formulas, it can be deduced that, at a time point:

$$\Delta S = \Delta Q/T = S_2 - S_1 = k\ln W_2 - k\ln W_1 = k(\ln W_2 - \ln W_1) = k(\Delta \ln W) \qquad (3)$$

$$\Delta \ln W = \Delta Q/(kT) \qquad (4)$$

Equation (4) shows that *W*, like S, is also a quantity associated with heat energy (Q) and thermodynamic temperature (T).

3.2. Five types of changes caused by entropy increases

Entropy increases due to heat absorption or heat transfer can lead to at least five types of changes, as exemplified below.

1. A stone, metal, or ideal gas becomes hotter.
2. Ice melts into water.
3. The energy in an isolated system is distributed more evenly, as shown in Box 1, where no chemical reactions occur.
4. A solar battery gains electrical energy.
5. Carbon dioxide, along with water, forms glucose through heat-absorbing organic synthesis (photosynthesis) in plant leaves [27][28].

In the first two types of changes, the increased heat or entropy of the objects remains as heat energy, which can be dissipated if the surroundings become colder. In contrast, some of the increased heat or entropy of the objects in the last two types of changes is stored as electrical energy or chemical energy, which can be stored in the objects even if the surroundings become colder [27]. The last two types of changes also demonstrate that energy can be more unevenly distributed in a system due to an increase in its entropy, which contradicts the tendency shown by the third type of change (the energy of a system distributes more evenly due to an increase in its entropy), where no chemical reactions occur.

3.3. Animals struggle for plants' entropy

Ludwig Boltzmann stated in 1886 that animals struggle for plants' entropy that is transformed from solar energy[1] [Box]. This notion is correct according to the OFU nature of entropy. When plants absorb heat from sunlight, their entropy increases, and the increased entropy, or the absorbed energy, is stored as chemical energy in carbohydrate molecules through photosynthesis (see Section 3.2) [27][28]. Animals can utilize the entropy or energy stored in the carbohydrate molecules in plants, which serve as animals' food, and released through the metabolic degradation of animals' food, for movement, maintaining body temperatures, and other purposes. Animals do not struggle for the heat energy abundant on Earth that they cannot directly utilize.

Box 2. A part of the lecture of Boltzmann on entropy and life1

… The general struggle for existence of animate beings is therefore not a struggle for raw materials—-these, for organisms, are air, water and soil, all abundantly available—nor for energy, which exists in plenty in any body in the form of heat (albeit unfortunately not transformable), but a struggle for entropy, which becomes available through the transition of energy from the hot sun to the cold earth. In order to exploit this transition as much as possible, plants spread their immense surface of leaves and force the sun's energy, before it falls to the earth's temperature, to perform in ways yet unexplored certain chemical syntheses of which no one in our laboratories has so far the least idea. The products of this chemical kitchen constitute the object of struggle of the animal world…

3.4. Can entropy be a measure of disorder

The notion that entropy is a measure of disorder (higher entropy means greater disorder) has been widely stated in numerous dictionaries [29], encyclopedias [21][22][30][31], textbooks [18][20], and research articles [4][5][31][32][33][34][35][36][37], although this notion has faced a few challenges [6][19][38][39][40]. This notion has been applied frequently to research on disorder or order in the biomedical and social sciences [13][14][15][16][17][18][19][20].

Even though entropy is in some ways related to the concepts of relative order and relative disorder, we challenge the notion that entropy is a measure of disorder using the following facts.

1. Entropy and disorder are concepts with distinct meanings. Entropy, in its OFU nature, is analogous to energy with the unit of J/K [18][19][20]. In contrast, disorder is not analogous to energy, and its unit is not J/K. According to various Oxford dictionaries [41], the Collins English Dictionary [42], and entropy-associated research articles [4][31][32][33][34], disorder refers to chaos, untidiness, or abnormalities, and typically arises from a decline in a system's order.
2. Order or disorder has distinct meanings in physics and other disciplines. For instance, sometimes the formation of an orderly arrangement in a static state (e.g., crystallization) requires energy dissipation and a decrease in the entropy of the relevant system. This is in contrast to orderly motion in physics (e.g., the directed flow of electrons caused by direct current), which typically requires energy input and an increase in the entropy of the system.
3. An entropy decline in a system cannot always lead to an increase in its order. According to the OFU nature of entropy, when a stone, ideal gas, or rat dissipates heat into its surroundings, it becomes colder, its entropy declines, and the velocity of its unordered molecular vibration declines. However, its molecular vibration remains fully unordered without an increase in the order of its molecular movement or its molecular arrangement.
4. Heat absorption by plants from warm sunlight, which increases plants' entropy, usually does not augment the disorder in plants, so entropy cannot represent disorder in plants.
5. Heat dissipation from human bodies on cold days can reduce their entropy and cause disorder in their bodies, so entropy cannot represent disorder in humans.
6. Humans who die acutely due to myocardial infarction dissipate heat into their surroundings, and their body temperatures decrease during the process of death, resulting in a decline in their entropy, which does not lead to an increase in the order of their bodies, so entropy cannot represent disorder in humans.
7. Drinking water can restore order in a thirsty man, which simultaneously increases the man's entropy because entropy is an additive quantity [18][19][20]. This fact also suggests that entropy cannot represent disorder in humans.

The above facts suggest that the notion that entropy is a measure of disorder could arise from the ignorance of the OFU nature of entropy and multiple reasoning confusions: the confusion of the velocity of fully unordered molecular vibration with the extent of disorder of the vibration or the relevant system; the confusion of static, cold, and orderly arrangement (e.g., crystals at low temperatures) with moving, warm, and orderly motion (e.g., the movement of many molecules in mammals); and the confusion of those systems with physical changes with those systems with chemical changes caused by entropy increases (see Section 3.2).

The misconception that entropy is a measure of disorder could originate in the 1880s, when Hermann von Helmholtz used the word “disorder” to describe entropy [24]. It also could result from confusion of the concept of W in the Boltzmann formula and disorder. As equation (4) shows that W, like S, is also a quantity associated with heat energy and thermodynamic temperature, W does not directly correlate with disorder, which refers to chaos, untidiness, or abnormalities and does not consistently change with heat energy and thermodynamic temperature.

Some argue that "disorder" in thermodynamics means how close a system is to thermodynamic equilibrium or a measure of energy's diffusion or dispersal [30]. This argument contradicts the meaning of disorder (chaos, untidiness, or abnormalities) and the OFU nature of entropy (entropy is analogous to energy with the unit of J/K and is heat energy mathematically divided by the relevant thermodynamic temperature).

3.5. Is Schrödinger's negative entropy notion correct

Nobel laureate Erwin Schrödinger stated in 1944 that life relies on negative entropy in his famous tiny book, *What is life* [2][7](Box 3). Schrödinger's negative entropy notion contradicts Boltzmann's statement that animals struggle for plants' entropy (see Section 3.3). Schrödinger's notion is based on the change of the quantity W in the Bolt zmann formula with disorder (D) without giving robust reasons [Box 3], and the notion that entropy represents disorder, which has been challenged in Section 3.4. Nevertheless, this notion has garnered widespread acceptance for nearly 80 years, with only a few criticisms [7][43][44]. For instance, Google Scholar showed that Schrödinger's book, *What is life*, had been positively cited over 11,000 times, mainly due to the inclusion of the negative entropy notion. In 2023, this book was cited nearly 600 times, as exemplified by six references [8][9][10][11][12][45], with few doubts about this notion.

Box 3. Two parts of the book *What is life*. The underlined sentences constituted the three viewpoints of Schrödinger's notion.

[Part 1] … a living organism continually increases its entropy, or, as you may say, produces positive entropy and thus tends to approach the dangerous state of maximum entropy, which is of death. It can only keep aloof from it, i.e. alive, by continually drawing from its surroundings negative entropy — which is something very positive as we shall immediately see. What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive…

[Part 2] … If D is a measure of disorder, its reciprocal, 1/D, can be regarded as a direct measure of order. Since the logarithm of 1/D is just minus the logarithm of D, we can write Boltzmann's equation thus:

–(entropy) = k log (1/D)

Hence the awkward expression 'negative entropy' can be replaced by a better one: entropy, taken with the negative sign, is itself a measure of order. Thus the device by which an organism maintains itself stationary at a fairly high level of orderliness (= fairly low level of entropy) really consists in continually sucking orderliness from its surroundings. This conclusion is less paradoxical than it appears at first sight. Rather could it be blamed for triviality. Indeed in the case of higher animals we know the kind of orderliness they feed upon well enough, viz. the extremely well-ordered state of matter in more or less complicated organic compounds, which serve them as foodstuffs. After utilizing it they return it in a very much degraded form — not entirely degraded, however, for plants can still make use of it (These, of course, have their most powerful supply of negative entropy in the sunlight)…

Coinciding with the popularity of this notion, English Wikipedia and other academic websites deliberately added "negative" with brackets in Boltzmann's statement before "entropy" [13][46] [Box 2]. However, it is unlikely that Boltzmann neglected the word "negative" because: 1) the concept of negative entropy was coined after his death; 2) "negative entropy" is distinct from "entropy"; and 3) Boltzmann's statement is correct, as given in Section 3.3.

Schrödinger's notion contained three viewpoints, which are all challenged below.

Its first viewpoint, that entropy represents disorder and is thus detrimental to animals, has been challenged in Section 3.3.

Its second viewpoint is that animals rely on food to reduce their entropy and generate order to offset the spontaneous increase in their entropy or disorder. This viewpoint assumes that animal food contains less entropy than animal excreta, so animals can obtain order due to entropy decline (i.e., negative entropy) because the entropy they dissipate into the surroundings is greater than the entropy they obtain from low-entropy food. This viewpoint is questionable because the order of life is encoded and provided by genes inherited from parents and accumulates through long-term natural selection [47]. The order of life is neither provided by food nor suddenly emerges due to entropy decline or negative entropy. Furthermore, food provides animals with energy and, thus, entropy to support their lives (see Section 3.3) (Fig. 1). The assumption that animal food contains less entropy than animal excreta is questionable because food metabolism dissipates heat, and hence animal food contains more entropy than animal excreta. Additionally, during the developmental process from a fertilized egg into a prenatal baby of a human, its entropy increases by millions of times because entropy is an additive property, and the increased entropy is from the food consumed by the baby's mother.

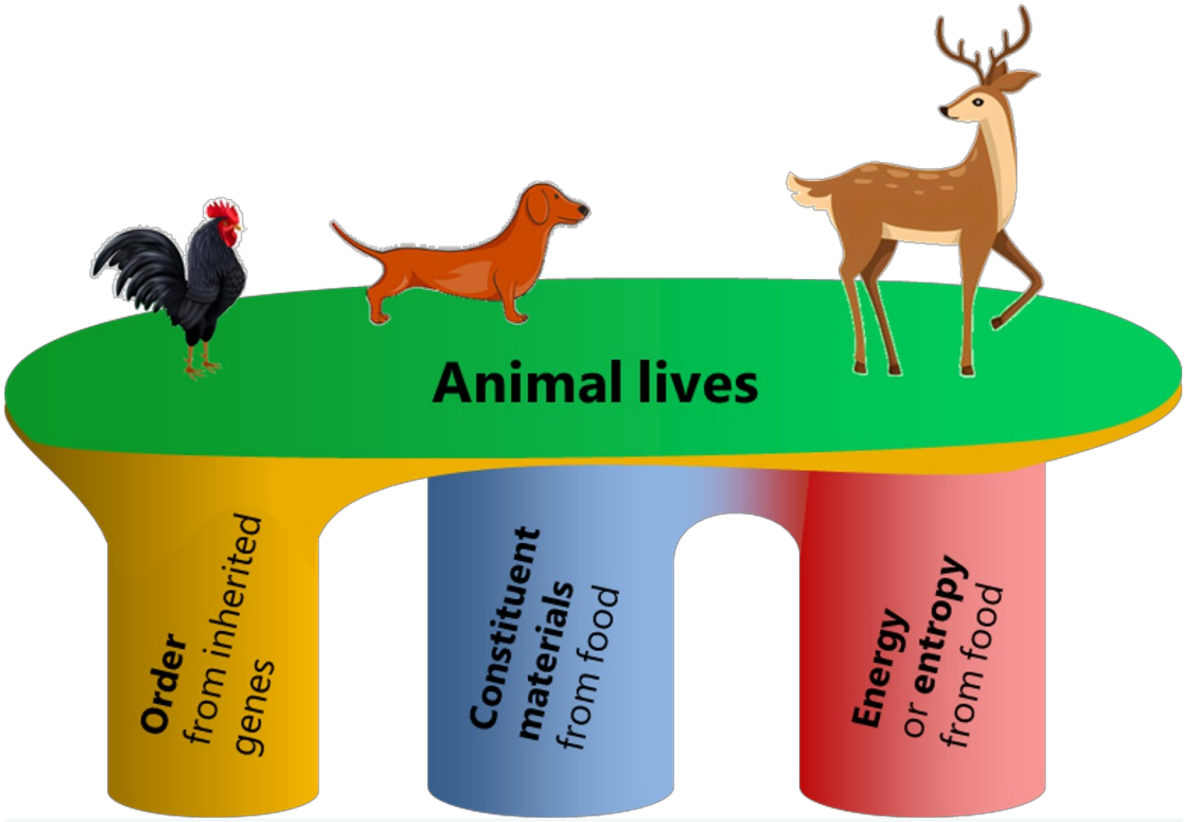

Figure 1. Three pillars of animal lives and their origins.

The third viewpoint of Schrödinger's notion is that sunlight provides negative entropy to plants. This viewpoint is incorrect because, according to the OFU nature of entropy, the entropy of plants, stones, ices, and any other objects increases rather than reduces when they absorb heat from sunlight. Some of the energy or entropy absorbed by plants is stored as chemical energy in carbohydrate molecules through heat-absorbing photosynthesis [25]. Furthermore, in biology, sunlight or any type of energy cannot directly provide order to plants, and the order in plants is also encoded and provided by inherited genes and accumulates through long-term natural selection rather than from the environment, food, and entropy decline [47].

In recent decades, negative entropy has also been employed to represent information[48], which is also controversial[49].

3.6. A prevailing misuse of the second law of thermodynamics

The second law of thermodynamics can be mathematically expressed as the entropy of an isolated system increasing over time until all parts of the system reach the same temperature (see Section 3.1). Since entropy is widely accepted to be a measure of disorder, it is widely assumed by researchers from various fields, such as physics, chemistry, biology, medicine, and social sciences, that many natural or social systems tend to become increasingly disordered due to entropy, or the second law of thermodynamics [4][5][8][9][10][11][12][18][20][29][30][31][32][33][34][45]. As elucidated in Section 3.4, entropy cannot be a measure of disorder, so the above assumption is incorrect.

Furthermore, it could be a fact that many systems tend to become increasingly disordered. This possible fact results from certain statistical probabilities because many systems are more likely to stay in a disordered state than in an orderly state. However, these statistical probabilities are barely associated with heat transfer. Therefore, the possible fact is not due to entropy or the second law of thermodynamics, a law that only states heat transfer direction.

The reasoning errors of the three notions challenged above are summarized in Fig. 2.

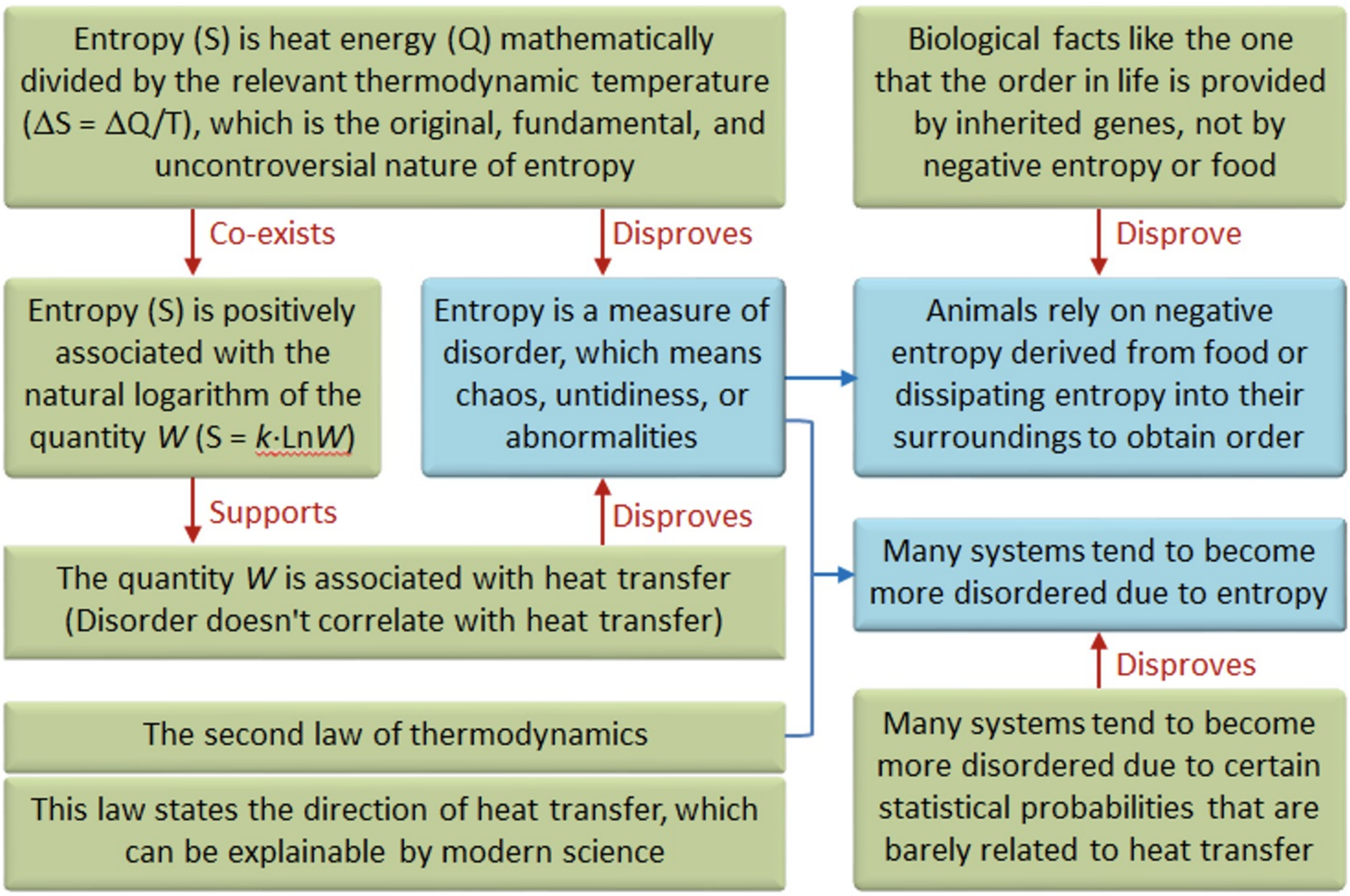

Figure 2. The flawed reasoning steps, which are shown with blue arrows, for the three misconceptions, which are shown in blue boxes. The flawed reasoning is debunked by the correct reasoning shown with red arrows.

4. Discussion

As elucidated above, although the three notions challenged in this article have encountered a few challenges, primarily from a single aspect, they have been widely accepted and frequently applied in life sciences and other disciplines for decades, misleading countless common people and many researchers through numerous mediums such as textbooks, research papers, and online social communications. Consequently, these notions have become a significant stumbling block and have caused severe pollution in science in recent decades.

This article systematically challenges the three notions. The systematic challenge has the potential to eradicate the entrenched misleading effects of the notions in life sciences and beyond. Furthermore, it could reshape the understanding of entropy, energy, disorder, order, life, thermodynamics, and rigorous reasoning among researchers and the general public. It could rectify and facilitate the relevant scientific research on complexity, order, and evolution [6][14][35][36][37]. For instance, the systematic challenge suggests that the second law of thermodynamics neither correlates with the changes of disorder nor contradicts evolution, a natural process characterized by an increase in order.

5. Conclusions

This article systematically challenges three notions prevailing in diverse disciplines: 1) Entropy is a measure of disorder; 2) life relies on negative entropy; 3) and many systems tend to become increasingly disordered due to the second law of thermodynamics, using the OFU nature of entropy and numerous compelling facts in physics, chemistry, and biology. The challenge, if widely accepted, could facilitate the eradication of the entrenched misleading effects of the misconceptions in diverse disciplines.

Statements and Declarations

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contribution

Conceptualization: J.-M. C.; Investigation: J.-M. C., J.-W. C., R. Z.; Writing—original draft preparation: J.-M. C; writing—review and editing: J.-M. C., J.-W. C., R. Z. All authors have read and agreed to the published version of the manuscript.

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