Entropy, the Second Law, and Life

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1. Introduction

I would like to start this article with a quotation by Albert Einstein on thermodynamics:

"It is the only physical theory of universal content, which I am convinced, that within the framework of applicability of its basic concepts will never be overthrown."

Most people who use this quotation, emphasize the last part, namely, that Thermodynamics will "*never be overthrown*." Of course I agree with that part. However, my emphasis, in this article is on the *"framework of applicability."* My main point is that entropy and the Second Law were used far beyond their *"framework of applicability."* One such application is to living systems, which I will discuss in this article. The second is the application of Entropy and the Second Law to the entire universe. This is discussed in details in references [1,2].

The application of entropy and the Second Law to a living system is based on two erroneous assumptions:

1. Entropy is a measure of disorder (or disorganization)
2. Life is understood as a process towards organization and creation of order

From these two assumptions it follows, almost naturally that life-processes seem to be "a struggle against the Second Law of Thermodynamics."

In this article we shall distinguish between two different questions:

The first one, the possibility of *defining* entropy; and the second, the applicability of the Second Law to living systems. We shall start with the general question on whether one can or cannot describe a living system by a few thermodynamic variables such as temperature, pressure and composition. This discussion will lead us to conclude that one cannot specify the "thermodynamic state" of a living system. It follows that entropy is undefinable for any living system. Next, we shall discuss the question of the applicability of the Second Law to living systems. The answer to this question is a definite, No!

1.1 Can entropy be defined for any living system?

This question is part of a more general question: Can physics, as we know it today, be used to discuss and explain all aspects of life? In particular, those aspects of life we call *mental processes* such as thinking, feeling, consciousness, and the like. This question has been discussed by numerous scientists, in particular by Schrödinger [3], Penrose [4,5] and many others. Interestingly, some of these scientists raised serious doubts about the general question stated above, yet they did not shy away from applying entropy and the Second Law to living systems.

Everyone knows that life phenomena are the most complex, intricate, interesting, wonderful, and whatever one wishes to ascribe to it. During the 20th century science had achieved a great amount of knowledge and understanding about the many aspects of life, from biochemical processes, genetics, molecular biology, to brain functions, and many more. There are however many more aspects of life that we do not understand. There are also aspects of life that we might never understand.

Indeed, during the past century remarkable advances in understanding the molecular basis of life have been achieved. A whole new branch of biology was created: Molecular Biology. The mechanism of heredity was deciphered, the so-called "genetic code" was discovered, the code which is responsible for translating the message "written" in the DNA into synthesizing proteins which are the so-called molecular robots in our cells.

There are many specific processes which have been studied by thermodynamics. Examples: Chemical reactions, including metabolism where energy stored in some chemical bonds are used to synthesize many molecules which are vital to life. Photosynthesis, where energy from the sun rays is used to convert carbon dioxide (CO_2) and water (H_2O) to high energy sugars. In all of these cases the reactions could be studied *in vitro*, i.e. in a laboratory setting, or in test tubes, isolated from the entire complicated environment in the cell (*in vivo*).

Clearly, thermodynamics was, and still is, the main tool in understanding the energetics of these reactions.

There are other processes such as muscle contraction (i.e. converting chemical energy into mechanical work) or "firing" of electrical signals along the nerves' axons which were studied thoroughly by thermodynamics and statistical mechanics.

In all of these specific processes one can isolate the process and study it in well-defined environments and apply all the tools of thermodynamics successfully. However, with all these remarkable achievements which fill up countless textbooks on molecular biology, biochemistry, energy transduction, neural networks and more, there is still one phenomenon that was, and still is, inaccessible to study with the tools of thermodynamics in particular, and in physics, in general. This is life itself.

In fact, we still do not know how to define "life" or life related phenomena such as consciousness, awareness, the mechanism underlying our thinking, our feelings, and our ability to make decisions or create arts. Notwithstanding the difficulty of defining "life," it is clear that a living system is far from equilibrium. As such the concept of entropy cannot be applied—simply because entropy is a *state function.* This means that entropy is definable for a well-defined *thermodynamic system* at equilibrium.

We can easily describe the "state" of person sitting in a room. But this is not a thermodynamic description which requires just a few thermodynamic parameters. However, even if we could describe the *physical state* of the body, there is still the question of how to describe the *state of the mind* of the person? The last question brings us to the classical question about the nature of the mind.

One can safely say that the question about whether the "mind" is a *material* or a *spiritual* thing has been discussed ever since mankind became conscious of themselves and started pondering about the nature of their own consciousness.

Today, we distinguish between materialism (everything is matter including the mind), and non-materialism. The latter is also known as "dualism," i.e. there are two different entities; mind and matter. The most famous proponent of dualism was the 17th century French scientist and philosopher René Descartes who referred to his "*res cogitans*" – the "thinking thing" to non-material things which are not subject to the Laws of Physics.

Most people believe that there is an entity, at least for humans which is different from matter, and which is not subjected to the Laws of Physics. More recently, in particular after having developing a successful theory of neural networks, physicists are starting to believe that all our thoughts and feelings are related to some electrical activities in the brain.

The clearest presentation of the materialistic view of life may be found in Crick's book [6] "The Astonishing Hypothesis." Crick based his main argument on recent advances in our understanding as to how our brain functions. Indeed, many of our mental activities may be understood in terms of simple models of neural networks. Phenomena such as memory (storage, and retrieving), and process of learning (with or without a teacher) may be understood by a very simple model of a system of neurons connected by axons along which electrical signals are transmitted. From these models Crick drew his "*Astonishing Hypothesis*," which is summarized in his book's introduction:

"The Astonishing Hypothesis is that 'You,' your joys and your sorrows, your memories and your ambitions, your sense of personal identity and free will, are in fact no more than the behavior of a vast assembly of nerve cells and their associated molecules. As Lewis Carroll's Alice might have phrased it: "You're nothing but a pack of neurons." This hypothesis is so alien to the ideas of most people alive today that it can truly be called astonishing."

It should be emphasized however, that although recent advances in neural network theory are truly remarkable, they are still based on a very simple model. Not every mental activity can be explained by this model. One can claim that the uniqueness of each of us is determined by the collection of all the perceptions we have received through our senses in our lifetime, and which are recorded as patterns of connections among the neurons. However, it is far from clear that this hypothesis is well-established. It is possible that many of our mental activities, such as the creation of arts or proving a mathematical theorem, will not be explainable by neural network models.

In Daniel Dennett's recent book [7] "*From Bacteria to Bach and Back*," he argues against dualism:

"The problem with dualism, ever since Descartes, is that nobody has ever been able to offer a convincing account of how these postulated interactive transactions between mind and body could occur without violating the laws of physics."

The fact that "*nobody has been able to offer…"* is not, and cannot be, an argument against any view, and in particular not against *dualism*. Simply because we cannot explain all mental activities at present, does not mean that such understanding could not be achieved in the future. It is possible that within some future extensions of physical theories all mental activities could be discussed. However, at this point in time it is appropriate to be cautious and refer to this possibility as a "hypothesis." In my view, Crick's "Astonishing Hypothesis" is very much a *hypothesis*, and it will remain a hypothesis for a long time. If and when this hypothesis will be proven to be correct, then it will be an enormously astonishing achievement, particularly to all those who subscribe to the concept of dualism.

To conclude, we do not know whether or not living systems can be described as purely material objects on which all the physical laws are applicable. But even if such a description becomes feasible, one could not claim that living systems are well-defined thermodynamic systems, i.e. macro-systems describable by a few thermodynamic variables. Therefore, entropy may not be applied to such systems. This conclusion very clearly follows from any definition of entropy See Ben-Naim [1,2,8-10].

2 Can the Second Law of thermodynamics be applied to any living system?

As we have discussed earlier [1,2,8,9] there are essentially two different but equivalent formulations of the Second law: the entropy and the Probability formulation. We shall briefly discuss each of these separately.

2.1 The entropy formulation for isolated systems

We start with an isolated system characterized by a fixed energy, volume and number of particles. We also neglect any effect of external fields on the particle of the system.

Sometimes you might come across a formulation of the Second Law as: ***Entropy for isolated systems can never decrease***. This is almost correct but one should emphasize that both initial and final states must be *equilibrium states.*

The entropy formulation of the Second Law applies only to *isolated systems*. We shall formulate it for a one-component system having *N* particles. If there are *k* components, then *N* is reinterpreted as a vector comprising the numbers $(N_1, N_2, \dots, N_k)$ where N_i is the number of particles of species *i*.

The entropy of an unconstrained isolated system $(\boldsymbol{E}, \boldsymbol{V}, \boldsymbol{N})$***, at equilibrium is larger than the entropy of any possible constrained equilibrium states of the same system.***

Note that this formulation uses only *macroscopic quantities*. Also, it applies only to equilibrium states. The entropy formulation means that if we remove any of the constraints in any possible constrained equilibrium system, the entropy will either increase or remain unchanged.

Therefore, an equivalent formulation of the Second Law is:

Removing any constraint from a constrained equilibrium state of an isolated system will result in an increase (or unchanged) entropy.

Before we discuss the probability formulation of the Second Law, it is advisable to summarize a few relationships between differences in a thermodynamic potential and the ratio of probability.

We present here these three equations:

$$\frac{\Pr(final)}{\Pr(initial)} = \exp\left[[S(final) - S(initial)]/_{k_{\mathrm{B}}} \right]$$

$$\frac{\Pr(final)}{\Pr(initial)} = \exp\left[-[A(final) - A(initial)]/k_{\mathrm{B}}T\right]$$

$$\frac{\Pr(final)}{\Pr(initial)} = \exp\left[-[G(final) - G(initial)]/k_{\mathrm{B}}T\right] \qquad \textbf{(1)}$$

Here S is the entropy, A is the Helmholtz energy and G is the Gibbs energy. The first equation is valid for an (E, V, N) system, the second is valid for a (T, V, N) system, and the third for a (T, P, N) system. The first equation reduces to Boltzmann's formulation when all the microscopic states have equal probabilities, in which case the probability ratio is equal to the ratio: $W(final)/W(initial)$. Note that sometimes, W itself is equated to the probability (Pr), and not the ratio. This is not true since the probability is a number between zero and one, whereas W could be any number [2].

Note that the probability ratio is the same in all the Equations (1). It is therefore clear from these equations that the probability formulation of the Second Law which will be stated below, is far more general than any of the thermodynamic formulations in terms of either entropy, the Helmholtz energy or Gibbs energy. One important advantage of the probability formulation is that the Second Law does not apply to any system which has a "free will." This conclusion debunks claims by many authors, e.g. Atkins [11,12], that entropy or the Second Law "controls" or "drives" our thoughts, feelings and creation of arts. The fact is that no one has ever shown that either entropy or the Second Law has anything to do with "thinking, feelings or creation of arts."

2.2 The Probability formulation of the Second Law

The original idea of the probability formulation of the Second Law can be traced back to Boltzmann [13,14]:

"… the system… when left to itself, it rapidly proceeds to the disordered, most probable state."

Boltzmann uses the term disorder to *describe* what happens "when (the system) is left to itself, it rapidly proceeds to disordered most probable state." Here we focus on the "most probable" aspect of this quotation. Before we make a statement of the probability formulation of the Second Law, which is simply a matter of common sense, we first discuss a simple example by which we can understand the relationship between the *state* of the system, the *probability of the state* and the corresponding SMI.

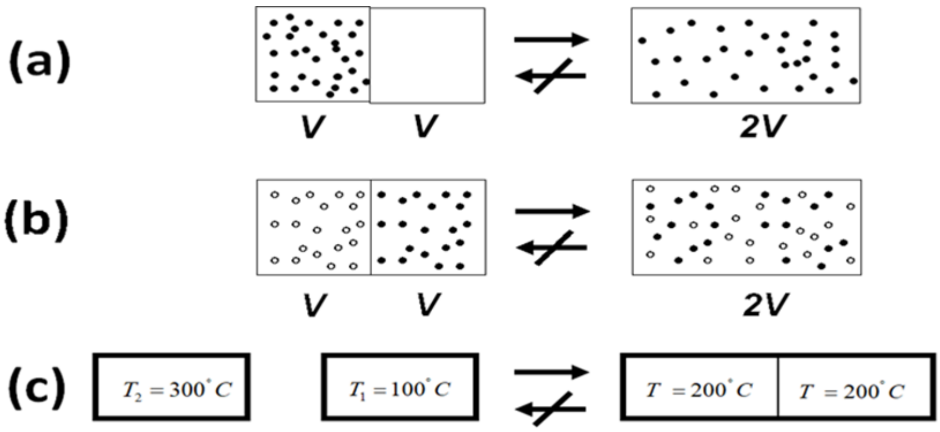

Figure 1. Three typical irreversible processes: (a) Expansion of a gas, (b) Mixing of ideal gases, (c) Heat transfer from a hot to a cold body.

Consider the three processes shown in Figure 1. These are typical processes which are textbook examples of irreversible processes. Why do we always see these processes going in one direction? Clearly, the random motion of the particles cannot determine a unique direction. The fact that we observe such a one-way or one-directional processes led many to associate the so-called Arrow of Time with the Second Law, more specifically with the "tendency of entropy to increase." See also references [2,10,15].

Unfortunately, all the processes we observe here are one-directional, or irreversible only in *practice*, and not in an absolute sense. (More on this in Ben-Naim [2, 10, 15]). We *see* that the gas *always* expands from V to $2V$. We *see* that the two gases *always* mix and *never* un-mix, we observe that heat *always* flows from the hot to the cold body. All these "*always*" are only *in practice* and are not *absolute*. If we live long enough some $10^{10^{20}}$ years we should be able to observe the reversal of all these processes.

Thus, we can conclude that the apparent irreversibility of all the processes we deemed to be "irreversible," is only an illusion. The reader might think that the death of a living system is irreversible in the absolute sense. The truth is that we do not know whether or not life processes are reversible or irreversible. Whatever the truth is, as far as we know living systems are not subjected to the Second Law of Thermodynamics.

It follows that there is no need to ask: "What is the cause of one-way processes?" or "What drives the processes in one direction?" We do not need to ask such questions simply because the processes are not irreversible, and do not occur in one direction only. All these processes are irreversible only *in practice*, or equivalently, they are irreversible only with *high probability*.

If one still insists on asking: "Why do these processes occur in "one direction" with high probability?" The answer is quite simple: The probability of the final state is much higher than the probability of the initial state.

Clearly, the probability is not a physical cause. It does not *drive* the processes; it is our way of rationalizing why we *always* see these processes occurring in one direction only.

These thoughts lead us to reformulate the Second Law in terms of probability. This formulation is not free from some deep pitfalls. I believe this formulation is more general, more easily comprehended, and devoid of mystery compared with any formulation involving entropy.

Look again at the three equations (1). On the right hand side of each of these equations we have a difference in a thermodynamic quantity. On the left hand side, we have the probability ratio.

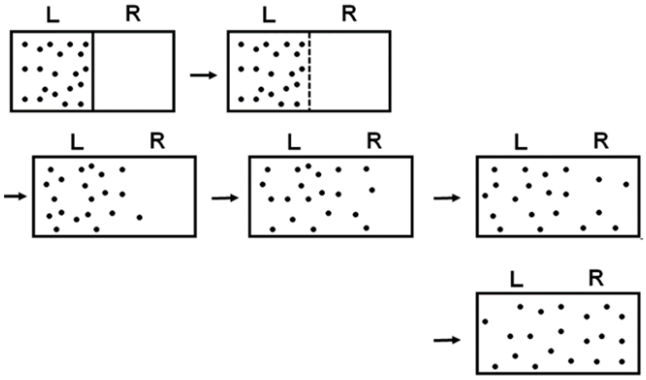

Figure 2. The initial, the final, and a few intermediate states in the expansion process.

We first state the probability formulation of the Second Law for the particular process of expansion, Figure 2. (For more details see references [1, 2]). We start with a system of N particles in one compartment, where N is of the order of one Avogadro number, about 10^{23} particles. We remove the partition and follow the evolution of the system. At any point in time we define the *distribution* of *particles* by the pair of numbers $(n, N-n)$. Of course, we do not count the *exact* number of particles in each compartment n, but we can measure the density of particles in each compartment, $\rho_L = n_L/V$ and $\rho_R = n_R/V$, where n_L and n_R are the numbers of particles in the left (L) and right (R) compartments, respectively $(n_L + n_R = N)$. From the measurement of ρ_L and ρ_R we can also calculate the pair of *mole fractions*$x_L = n_L/(n_L + n_R) = \rho_L/(\rho_L + \rho_R)$ and $x_R = n_R/(n_L + n_R) = \rho_R/(\rho_L + \rho_R)$, with $x_L + x_R = 1$. The pair of numbers (x_L, x_R) is referred to as the *configuration* of the system. Note that the pair (x_L, x_R) is also a probability distribution.

After the removal of the partition between the two compartments, we can ask what the probability of finding the system with a particular configuration (x_L, x_R) is? We denote this probability by $\Pr(x_L, x_R)$. Since both x_L and Pr are probabilities, we shall refer to(x_L, x_R) as the *probability distribution* and to $\Pr(x_L, x_R)$ as the *probability of the distribution*; $\Pr(x_L, x_R)$ is the probability of finding the probability distribution (x_L, x_R). We can now state the Second Law for this particular system as follows:

Upon the removal of the partition between the two compartments, the probability distribution, or the *configuration* will evolve from the initial one $(x_L, x_R) = (1,0)$, (i.e. all particles in the left compartment) to the final new equilibrium distribution (1/2,1/2), which is characterized by a uniform locational distribution. This means that the densities ρ_L and ρ_R are equal (except for negligible deviations), or equivalently the mole fractions x_L and x_R are equal to ½ . We shall *never* observe any significant deviation from this new equilibrium state, not in our lifetime, and not in the universe's lifetime which is estimated to be about 15 billion years.

Note that *before* we removed the partition the probability of finding the configuration (1, 0) is *one*. This is an equilibrium state and all the particles are, by definition, of the initial state in the L compartment.

Note also that the *probability* of finding the configuration (x_L, x_R), denoted by $\Pr(x_L, x_R)$, is the probability of the configuration attained *after* the removal of the partition when x_L can, in principle, attain any value between zero and one. Therefore, the probability of obtaining the configuration (1, 0) is negligibly small. On the other hand, the probability of obtaining the configuration in the neighborhood of $\left(\frac{1}{2}, \frac{1}{2}\right)$ is, for all practical purposes nearly one. This means that *after* the removal of the partition, and reaching an equilibrium state, the ratio of the probabilities of the initial configuration (1, 0) and the final configuration, i.e. in the neighborhood of $\left(\frac{1}{2}, \frac{1}{2}\right)$, is almost infinity (of the order of 2^N) with $N \approx 10^{23}$, this is an unimaginably large number). Thus, we can say that for 10^{23} the probability ratio is:

$$\frac{\Pr(final\ configuration)}{\Pr(initial\ configuration)} \approx infinity \qquad (2)$$

This is the essence of the probability formulation of the Second Law for this particular experiment. This law states that starting with an equilibrium state where all particles are in L, and removing the constraint (the partition), the system will evolve to a new equilibrium configuration which has a probability overwhelmingly larger than the initial configuration.

Note carefully that if *N* is small, then the evolution of the configuration will not be monotonic, and the ratio of the probabilities in the equation above is not near infinity. For some simulations the reader is referred to reference [2, 10, 15]. For very large N, the evolution of the configuration is also not strictly monotonic, and the ratio of the probabilities is not strictly, infinity. However, in *practice,* whenever *N* is large we shall *never* observe any deviations from monotonic change of the configuration from the initial value (1, 0) to the final configuration $\left(\frac{1}{2},\frac{1}{2}\right)$. Once the final equilibrium state is reached [i.e. that the configuration is within experimental error $\left(\frac{1}{2},\frac{1}{2}\right)$], it will stay there *forever*.

The distinction between the strictly *mathematical* monotonic change and the *practical* change is important. The process is mathematically *always* reversible, i.e. the initial state will be visited. However, in practice the process is irreversible; we shall *never* see the reversal to the initial state.

Let us repeat the probability formulation of the Second Law for this particular example.

We start with an initial *constrained equilibrium state*. We remove the constraint, and the system's configuration will evolve with probability (nearly) one, to a new equilibrium state, and we shall *never* observe reversal to the initial state. "Never" here, means never in our lifetime, nor in the lifetime of the universe.

This formulation is valid for large N. It is also valid for any *initial constrained equilibrium state*. As we have seen the entropy formulation, the Helmholtz energy formulation, and the Gibbs energy formulation pertain to specific thermodynamic systems; isolated (E, V, N), isothermal (E, V, N), and isothermal isobaric (T, P, N), respectively. In this sense, the probability formulation is very general as it applies to any thermodynamic system.

3. Misapplication to living systems

Regarding the Entropy formulation, once we found out that entropy is definable only to equilibrium states, it is easy to conclude that entropy should be excluded from any discussion of living systems. Here I mean living system as a whole, not some specific processes in living systems. Therefore, I was shocked when I read Schrödinger's book [3], which is discussed below, in which the concept of "negative entropy," appears in connection with living systems. Entropy, by definition is a positive quantity. What Schrödinger meant by "negative entropy" is probably either "negative change in entropy," or "entropy" with a minus sign ($-S$).

The *change* in entropy can be negative or positive but entropy itself is by definition positive, it can never be negative. When I read in Schrödinger's book where he claims that living systems avoid death by feeding on negative entropy, I was not sure whether that was an error or a joke. Living systems are not only far from equilibrium, but they cannot be described or be specified by the thermodynamic variables. Therefore, everything that Schrödinger wrote on entropy and the Second Law in connection with life was totally meaningless, no matter who said it, be it a student or a Nobel laureate.

Regarding the application of the Second Law, consider the following simple process: Imagine yourself sitting for a short period of time in an isolated box or a room, totally isolated from the rest of the world. Do not worry, you can try this experiment at home and no harm shall come to you; the experiment in this isolated system will take a few seconds only. While you are seated in a well-insulated room, do something; raise your hand or read a book. That is all. In fact, you do not have *to do* anything, you can just sit back, relax, and *think* about something.

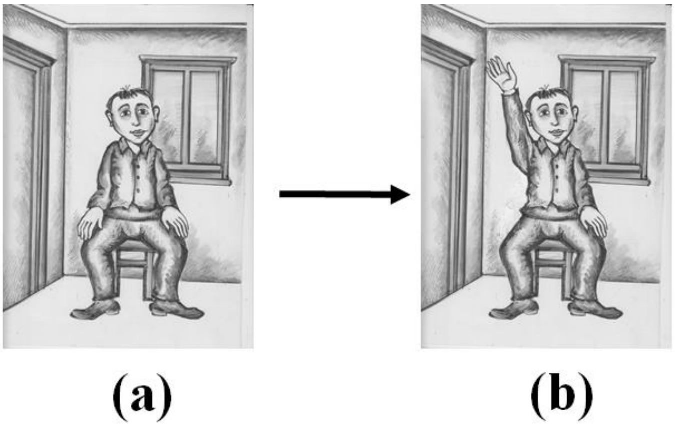

Figure 3. A process in an isolated system: (a) The initial and (b) the final state.

Clearly, a process was carried out in an *isolated system*, and it was spontaneous, Figure 3. You did whatever you wanted with no one telling you what to do, nor was any force exerted on you from the outside. Remember the room was totally isolated. What is the entropy change in this process? Most people, who believe that in any process occurring in an isolated system, the entropy must increase, would answer that $S(b) - S(a) > 0$. If this were true, then suppose that we reverse the process, i.e., we go from state (b), back to state (a). Again, a process has occurred in an isolated system. Would we conclude that $S(a) - S(b) > 0$?

In my opinion, both answers are wrong. The system in Figure 3 is not a well-defined thermodynamic system. Therefore, one cannot define the entropy for either state (a) or state (b), hence, one cannot say anything on the (undefinable) difference $S(a) - S(b)$.

What about applying the probability-formulation of the Second Law?

If one believes that a spontaneous process had occurred in an isolated system, then oneshould conclude that in the process$(a) \rightarrow (b)$, the probability ratio $\Pr(b)/\Pr(a)$, must be much larger than one. However, using the same argument for the reversed process $(b) \rightarrow (a),$ one should conclude that the ratio $\Pr(b)/\Pr(a)$ must be much smaller than one.

Obviously, these conclusions cannot be true. Indeed, a process did occur in an isolated system. However, neither the entropy difference, nor the probability ratio may be calculated for such processes involving a living system. The conclusion regarding the probability ratio is tantamount to assuming that any action we do is governed by the probability law, i.e. that systems will proceed from a relatively low to relatively high probable state. This is equivalent to denying that there exists free will.

As we have seen in reference [2], none of the definitions of entropy may be applied to any living system. Therefore, the question on the change in entropy in this process is meaningless.

4. The history of application of Entropy and the Second Law to living systems

Perhaps the oldest association of Second Law with life is due to Boltzmann. On May 29, 1886, Ludwig Boltzmann presented a talk at the Festive Session of the Imperial Academy of Sciences in Vienna where he discussed "***The Second Law of Thermodynamics"*** with special emphasis on its application in relation to Charles Darwin's 1859 theory of evolution [16].

The most-quoted passage from this lecture is that life is a **struggle for entropy**:

"*The general struggle for existence of animate beings is not struggle for raw materials, these, for organisms, are air, water and soil, all abundantly available, nor for energy, which exists in plenty in anybody in the form of heat Q, but of* ***a struggle for entropy****, which becomes available through the transition of energy from the hot sun to the cold earth."*

As we have discussed above, Boltzmann believed that a system proceeds from a low to a high probability, also he stated that systems proceed from ordered to disordered states. Since living systems are considered to proceed from disorganized to more organized he has used essentially the argent in the abstract to conclude that life is a "**struggle for entropy"**

However, the most influential physicist who propagated the erroneous ideas about entropy and life was Erwin Schrödinger. In his book "What is Life?" published in (1944) [3], he discussed in greater detail the role of entropy in living systems. We will provide some quotations from this book in the next section.

4.1 Schrödinger's book: What is life?

On the question: "What is life? one cannot avoid starting with the most famous book written by Schrödinger [3].

This book is based on lectures delivered by Schrödinger in Dublin in 1943. This book was most influential for a long time and probably laid the cornerstone for the creation of the whole field of molecular biology. It also has encouraged many physicists to apply the methods of physics to biology. In this section we shall present only a few comments about some of Schrödinger's statement regarding entropy, more details may be found in reference [2].

In Chapter 1 of his book, Schrödinger correctly pointed out that "the physicist's most dreaded weapon, mathematical deduction, would hardly be utilized. The reason for this was not that the subject was simple enough to be explained without mathematics, but rather it was too much involved to be fully accessible to mathematics. As I noted above, it is not clear at all which kind of mathematics or physics one would need to describe life.

Then Schrödinger outlines the plan of his lectures as follows:

"The large and important and very much discussed question is: How can the events in space and time which take place within the spatial boundary of a living organism be accounted for by physics and chemistry?"

His preliminary answer to this question:

"*The preliminary answer which this little book will endeavor to expound and establish can be summarized as follows: The obvious inability of present-day physics and chemistry to account for such events is no reason at all for doubting that they can be accounted for by those sciences*."

Schrödinger attempts to explain the source of difficulty of applying the methods of physics and chemistry to living systems. The fundamental difference between a living system and any piece of matter that physicists and chemists have ever handled is in the structure, or the arrangement of atoms and molecules in the organism differs fundamentally from that of a system dealt with physics and chemistry. It seems to me that Schrödinger, at least in this stage of the book believed that once physicists enter into biology and apply their powerful arsenal of physical methods and theories, they shall be able to answer the question posed in the book.

On page 10 Schrödinger provides some hints about his intention to use the Second Law:

"*The reason for this is, that what we call thought (1) is itself an orderly thing, and (2) can only be applied to material, i.e. to perception or experiences, which have a certain degree of orderliness… Therefore, the physical interactions between our system and others must, as a* *rule, themselves possess a certain degree of physical orderliness, that is to say, they too must obey strict physical laws to a certain degree of accuracy."*

My impression is that Schrödinger used the terms "*orderly thing," "orderliness," "physical organization," "well ordered organization,"* and similar terms in anticipation of his usage of entropy and the Second Law of thermodynamics in later chapters.

Chapter 6, of his book is titled: "Order, disorder and entropy." He starts with the common and erroneous statement of the Second Law in terms of the "order" and "disorder."

"*It has been explained in Chapter 1 that the laws of physics, as we know them, are statistical laws. They have a lot to do with the natural tendency of things to go over into disorder."*

There is of course, no such "natural tendency," except in the minds of those who have a distorted view of the Second Law.

Then, he makes another typical statement about life:

Life seems to be orderly and lawful behavior of matter, not based exclusively on its tendency to go over from order to disorder, but bases partly on existing order that is kept up.

The idea that life somehow withstands the "natural tendency to go from order to disorder" is quite frequently found in the literature;" "life withstands the ravages of entropy," "life disobeyed the Second Law" and so on. Unfortunately, all these statements are *meaningless*; there exists no tendency of going from order to disorder in the first place. The tendency of entropy to increase applies to some specific processes in isolated systems, and not to a living system which is an open system, far from equilibrium.

It is only on page 74 that he explicitly relates the Second Law with the behavior of living systems.

"*The general principle involved is the famous Second Law of Thermodynamics (entropy principle) and its equally famous statistical foundation."*

His main claim is that "living matter evades the decay to equilibrium."

"*It is avoiding the rapid decay into the inert state of 'equilibrium' that an organism appears to be enigmatic; so much so, that from the earliest times of human thought some special non-physical or supernatural force (vis viva, entelechy) was claimed to be operative in the organism, and in some quarters is still claimed."*

Then he asks:

"*How does the living organism avoid decay? The obvious answer is: By eating, drinking, breathing and (in the case of plants) assimilating. The technical term is* ***metabolism.***"

I believe that the book's highlight is reflected on page 76:

“*What then is that precious something contained in our food which keeps us from death? That is easily answered. Every process, event, happening – call it what you will; in a word, everything that is going on in Nature means an increase of the entropy of the part of the world where it is going on. Thus, 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 death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment 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 organism succeeds in freeing itself from all the entropy it cannot help producing while alive.”*

First, I certainly do not agree that everything that goes on in Nature means an “increase of the entropy,” second, that living things “produce positive entropy,” and finally that the only way it can keep alive is by drawing *negative entropy* from its environment. I, of course realize that such assertions have been made by numerous scientists. Unfortunately, none of these can be justified in terms of the entropy and the Second Law.

Such statements, in my opinion are meaningless. Entropy, by definition, is a positive quantity. There is no negative entropy, as there is no negative volume, negative mass or negative time. Did Schrödinger have a bad slip of the tongue in this statement? It seems to me that Schrödinger did believe in what he said. It is unfortunate however, that many others, scientists as well as non-scientists fell into the pitfall created by Schrödinger’s negative entropy.

On page 78 Schrödinger concludes that “organization is maintained by extracting order from the environment.”

“Living organism… delays the decay into thermodynamic equilibrium (death), by feeding upon negative entropy, attracting a stream of negative entropy upon itself… and to maintain itself on a stationary and fairly low entropy level.”

Since there is no way of measuring or calculating the “entropy level” of a living system, all these impressive statements are outright meaningless. They certainly do not answer the question posed in the title of Schrödinger’s book.

In concluding, Schrödinger’s book was no doubt a very influential one especially in encouraging many physicists to look into biology. Most people praised the book, but some expressed their doubts about its content.

Perhaps, the most famous skeptic of Schrödinger’s contribution to understanding of life, was Linus Pauling. In Hager’s (1995) biography of Linus Pauling, he wrote about Pauling’s view about Schrödinger’s book [17].

"Pauling thought the book was hogwash. No one had ever demonstrated the existence of anything like "negative entropy… Schrödinger's discussion of thermodynamics is vague and superficial… Schrödinger made no contribution to our understanding of life."
I fully agree!

Likewise, Perutz had a similar criticism of Schrodinger's book, in 1987) [18]:
"When I was invited to review the influence of What is Life? I accepted with the intention of doing honor to Schrodinger's memory. To my disappointment, a close study of his book and of the related literature has shown me that what was true in his book was not original, and most of what was original was known not to be true even when it was written."

In conclusion, in my view both comments by Pauling and Perutz were quite mild. Regarding the involvement of entropy and the Second Law, I feel that Schrödinger has miserably gone astray. In general, I was disappointed with his book. My main reason is not because Schrödinger did not offer an answer to the question posed in the title of the book, but because whatever partial answers he offered are at best unconvincing and perhaps even meaningless.
I should also add one personal comment about the very idea of invoking entropy and the Second Law in connection with life phenomena. Personally, I believe that if ever a "*complete theory of life*" will be available, it will involve neither entropy nor the Second Law of thermodynamics. In light of this belief, I think that Schrödinger's book has unintentionally encouraged people in making a lot of meaningless statements associating entropy and the Second Law with life phenomena.

4.2 Some more blunders on Entropy, the Second Law and life

Open any book discussing the question of "What is Life?" and you are likely to read grandiose statements ranging from "life violates the Second Law of Thermodynamics," to "life emerges from the Second Law," and that the Second Law explains many aspects of life, perhaps life itself.
The involvement of the Second Law in life is based on the misconstrued (I would even say, perverted) interpretation of entropy as a measure of disorder, on one hand, and the view that life is a process towards more order, more structure, more organization, etc. on the other hand. Combining these two erroneous views inevitably leads us to the association of life phenomena with a *decrease* in entropy. This in turn leads to the erroneous (perhaps meaningless) conclusion that life is a "struggle" against the Second Law. I should add that even if the two

assumptions were correct, the conclusion will still be wrong! The fact is that entropy *cannot be defined forany living system*, and the Second Law, in its entropy formulation does not apply to living systems.

Here is an example from Katchalsky[19] in (1963):

"*Life is a constant struggle against the tendency to produce entropy by irreversible process. The synthesis of large and information-rich-macromolecules…all these are powerful anti-entropic force…living organism choose the least evil. They produce entropy at a minimal rate by maintaining a steady state.*"

This is a beautiful statement but devoid of any meaning. No one knows how to define the entropy of a living system, and how much entropy is produced by a living organism.

Volkenstein [20], comments on the "anti-entropic" by saying:

"At least we understand that life is not "antientropic," a word bereft of meaning. On the contrary, life exists because there is entropy, the export of which supports biological processes…"

Indeed "anti-entropic" is as meaningless as "anti-volume," (see also reference [2]). Unfortunately, Volkenstein's statement is far more meaningless than the concept of "anti-entropic."

Here is another outstanding example:

In Atkins' (1984) introduction to his book [11] he writes:

"*In Chapter 8 we also saw how the Second Law accounts for the emergence of the intricately ordered forms characteristic of life.*"

Of course, this is an unfulfilled promise. No one has ever shown that the Second Law accounts for the emergence of… life! At the end of Chapter 7, Atkins writes:

"We shall see how chaos can run apparently against Nature, and achieve that most unnatural of ends, life itself."

Finally, after discussing some aspects of processes in a living organism, Atkins concludes his book:

"*We are the children of chaos, and the deep structure of change is decay. At root, there is only corruption, and the unstemmable tide of chaos… This is the bleakness we have to accept as we peer deeply and dispassionately into the heart of the universe.*

Yet, when we look around and see beauty, when we look within and experience consciousness, and when we participate in the delights of life, we know in our hearts that the heart of the universe is richer by far."

So beautiful and so empty combination of words!

4.3. Do we feed on negative entropy?

Brillouin [21], "*feeding on the negative entropy*" ideas pronounced by Schrödinger, goes even further and claims that:

"*If living organism needs food, it is only for the negentropy it can get from it, and which is needed to make up for the losses due to mechanical work done, or simple degradation processes in living systems. Energy contained in food does not really matter: Since energy is conserved and never gets lost, but negentropy is the important factor.*"

This is quite strange. If this is the case, why do all food products reflect caloric value on their labels? The food manufacturers should instead print the "important factor" of negentropy in units of calories per degree or perhaps in bits, on their labels. Thus, next time you look at the labels on food products you can ignore the "energy value" as they are not important. What matters and the only important information to watch out for is the meaningless *negentropy*!

While I am still baffled with the concept of *negative entropy*, or its shorter version *negentropy*, I was greatly relieved to read Hoffmann's [22] explanation:

"*Life uses a low-entropy source of energy (food or sunlight) and locally decreases entropy (created order by growing) at the cost of creating a lot of high-entropy "waste energy (heat and chemical waste).*"

In more modern books the meaningless notion of negative entropy (or neg-entropy) is replaced by the more meaningful term of *low entropy*.

Is it meaningful to claim that we, living organisms feed on low entropy food?

If you are convinced that feeding on low entropy food is the thing that keeps you alive you should take your soup (as well as your coffee and tea) as cold as possible. This will assure you of feeding on the lowest possible liquid food. As for solid food, you should try to eat frozen food (but be careful not to put anything at very low temperatures into your mouth, that's going to be very dangerous).

As we have noted before, the entropy of a living system is not defined – not yet, or perhaps never. The main reason is that we do not know how to define the *state* of a living system.

In a recent book by Rovelli [23], the nonsensical idea that "entropy is more important than energy is elevated to highest peak. You will find there a statement written in all capital letters:

"IT IS ENTROPY, NOT ENERGY THAT DRIVES THE WORLD"

This very sentence has been praised by some of Rovelli's reviewers. Here, I will briefly say that the entropy of the universe (or the world) is not definable. Therefore, entropy does not, and cannot drive the universe. In fact, (yes, it is a fact) entropy does not drive anything, not even processes in systems for which the entropy is defined.

Besides this nonsensical statement, Rovelli goes on to discuss the idea of living beings feeding on low entropy. In another copycat statement which is attributed to Schrödinger, he suggests something which I think is deceiving, irresponsible and dangerous. On page 164 he writes:

"If all we needed was energy rather than entropy, we would head for the heat of the Sahara rather than toward our meal."

First, I think it is unfair (to say the least) to say "if all we *needed* was energy." No one needs *only* energy. We need energy, for certain, but we also need some minerals, vitamins, and more than anything, water is essential for our general well-being. For the sake of argument, suppose that we already have everything, and all the rest we need is energy. But then, the author suggests that one should head for the heat of the Sahara.

This comment is dangerous because the energy that we need is energy stored in some chemical compounds, not the "heat of the Sahara." If one were to believe that energy is important (and assuming that all other things including water, are available) then going to the Sahara instead of having the next meal, will kill you, so better not to heed the Rovelli's advice.

Besides, the danger of the author's suggestion is also an absurd one. As I wrote above if you believe that entropy is more important than the energy of food, then you should drink water as cold as possible (preferably iced) which has a lower entropy than hot water. To paraphrase the author's suggestion (not to be taken seriously), I would say that if all we need is entropy rather than energy, we should head for the cold arctic rather than towards our next meal. I repeat that this is just to paraphrase the author's statement. I am not really suggesting that you do it.

If you swallow a cube of ice at 0°C, or drink the equivalent amount of liquid water at 0°C, you will get the same benefit from the water molecules. If you have a choice between the two options I recommend drinking water (with a higher entropy) rather than the ice (with the lower entropy), not because of the entropy difference between the two, but simply because the latter might get stuck in your throat.

To conclude this section, it should be stressed that my objection to the usage of entropy and the Second Law applies to the *entire* living system and the whole life phenomena. There is no objection to studying specific chemical, mechanical, or electrical processes occurring within a living system. However, phenomena involving mental or conscious activities cannot be included in such process.

4.4 Entropy and evolution

Evolution is usually described as a process which involves transition or evolving from disorder to order, or to more organization, or more *complexity*.

In fact, we cannot claim that evolution is associated with a one-way increase in some property; order, organization or complexity. In one environment, the bigger (the more ordered, stronger, organized…) might have an advantage and will therefore survive. But in another environment, the bigger (or the more ordered, etc.) might have a disadvantage compared to the smaller, and therefore the smaller one will survive. Thus, in general we cannot pinpoint any property that changes in evolution in a one-direction except evolution itself which always evolves, and this brings us to the connection to the Second Law. First, the misconception about evolution that proceeds from less order to more order. Second, the misconception that the Second Law requires that a system (isolated!) goes from order to less order, and we have an apparent conflict between evolution and Second Law which is anything but conflict.

In an article entitled: "*Entropy and Evolution*," Styer [24] begins with a question, "Does the Second Law of thermodynamics prohibit biological evolution?" Then he continues to show quantitatively that there is no conflict between evolution and the Second Law. Here is how he calculates the "entropy required for evolution." Suppose that due to evolution each individual organism is 1000 times "more improbable" than the corresponding individual was a hundred years ago. In other words, if Ω_i is the number of micro-states consistent with the specification of an organism 100 years ago, and Ω_f is the number of micro-states consistent with the specification of today's "improved and less probable" organism, then $\Omega_f = 10^{-3}\Omega_i$." From these two numbers he estimates the change in entropy per one evolving organism, then he estimates the change in entropy of the entire biosphere due to evolution. His conclusion:

"*The entropy of the earth's biosphere is indeed decreasing by a tiny amount due to evolution, and the entropy of the cosmic microwave background is increasing by an even greater amount to compensate for that decrease.*"

In my opinion this *quantitative* argument is superfluous. In fact, it weakens the *qualitative* arguments I have given above. No one knows how to calculate the "number of states" (Ω_i and Ω_f) of any living organism. No one knows *what the states* of a living organism are, let alone *count* them. Therefore, the estimated change in entropy due to evolution is meaningless.

Life does not violate the Second Law, nor does it emerge from the Second Law. The Second Law does not apply to a living system!

Finally, I will present an example of an abuse of the concept of entropy. In a book titled "Genetic Entropy and the Mystery of the Genome," Sanford [25] writes:

"For decades, biologists have argued on a philosophical level that the very special qualities of natural selection can easily reverse the biological effects on the Second Law of thermodynamics. In this way, it has been argued; the degenerative effects of entropy in living systems can be negated – making life itself potentially immortal. However, all of the analyses of this book contradict that philosophical assumption. Mutational ***entropy*** *appears to be so strong within large genomes that selection cannot reverse it. This makes eventual extinction of such genomes inevitable. I have termed this fundamental problem* ***Genetic Entropy****. Genetic Entropy is not a starting axiomatic position – rather, it is a logical conclusion derived from careful analysis of how selection really operates."*

Nothing in this entire paragraph makes any sense.

Obviously, the author has no idea what entropy means, yet he uses this term in the title of the book. In most of the book, neither entropy nor the Second Law are mentioned. Only towards the end of the book do we find the above quoted paragraph – which at *best* can be described as pure nonsense. A more detailed review of this book may be found in Ben-Naim [2].

5. Some concluding remarks on entropy, the Second Law, and Life

A great deal of knowledge (or information) has been accumulated on many aspects of life. Yet, there is one aspect of life which is elusive and that is, life itself. We do not know how to define life, how life was created and whether or not life succumbs to the laws of physics. Specifically, we do not know how to describe the state of being "alive," for any living organism. We can tell when something is alive or not alive, but we cannot specify these states in any of the available physical terms. Therefore, there is no point of applying the concept of *entropy*, or of the Second Law to a living system.

We can still apply the concept of information both in its colloquial sense, and in its informational theoretical sense. In spite of many claims in the literature, the *information* we have about life is in general, not measurable. On the other hand, we can use the Shannon Measure of information (SMI) to many probability distributions associated with living systems. We can define the probability distribution of compounds in a cell, in an organ, or in the entire organism. We can assign distribution to the letters in the DNA or the letters of proteins, and so on. To each of these distributions we can define the corresponding SMI. All these SMI are well-defined quantities but they are not entropy. Entropy, when viewed as a particular case of a SMI is defined for a specific distribution at a specific state of equilibrium. We know that a living system is not an equilibrium state. We do not know whether a living system *tends* to an equilibrium state, and whether it will ever reach an equilibrium state. Therefore, as long as a living system is *alive*, it is meaningless to apply to it the concept of entropy, nor the Second Law of thermodynamics. It also follows that life does not violate the Second Law, nor does it emerge from the Second Law. The Second Law does not apply to a living system.

At this stage of our knowledge of life we can be satisfied with applying the SMI to well specified distribution functions associated with a living system.

Unfortunately, we do not know whether or not the SMI or information theory can be applied to life itself. Certainly, it cannot be applied to explain aspects of life that are far from being understood such as consciousness, thoughts, feelings, creativity, etc. Yet again, statements claiming that information theory can help us with the comprehension of these aspects of life abound in the literature. These statements are no doubt very impressive, but unfortunately they are far from being true.

References

1. Ben-Naim, A. (2016), *Entropy: The Truth the Whole Truth and Nothing but the Truth*, World Scientific Publishing, Singapore

2. Ben-Naim, A. (2020), Entropy: *The Greatest Blunder in the History of Science, involving Entropy, Time, Life and the Universe.* Independently Publisher, Amazon.

3. Schrödinger (1944), *What Is Life? : The Physical Aspect of the Living Cell,* Based on lectures delivered under the auspices of the Dublin Institute for Advanced Studies at Trinity College, Dublin, in February 1943

4. Penrose, R. (1989), *The Emperor's Mind. Concerning Computers, Minds and the Law of Physics,* Penguin Books, New York

5. Penrose, R. (1994), *Shadows of the Mind: An Approach to the Missing Science of Consciousness,* Oxford University Press, Oxford

6. Crick, F. (1994), "*The Astonishing Hypothesis*," The Scientific Search For the Soul," Touchstone, Simon and Shuster, New York

7. Dennett, D. (2017), "*From Bacteria to Bach and Back*," The Evolution of Minds," W. W. Norton, Inc. USA, Henry Holt and Co., New York (2018)

8. Ben-Naim, A. (2017), *The Four Laws that do not drive the Universe,* World Scientific Publishing, Singapore

9. Ben-Naim A. and Casadei D. (2017*), Modern Thermodynamics*, World Scientific Publishing, Singapore

10. Ben-Naim, A. (2018), *Time's Arrow*? *The Timeless Nature of Entropy and the Second Law of Thermodynamics.* Lulu Publishing Services

11. Atkins, P. (1984), *The Second Law*, Scientific American Books, W. H. Freeman and Co., New York

12. Atkins, P. (2007), *Four Laws That Drive the Universe*, Oxford University Press

13. Brush, S. G. (1976), *The Kind of Motion We Call Heat. A History of the Kinetic Theory of Gases in The 19th Century, Book 2: Statistical Physics and Irreversible Processes*. North-Holland Publishing Company

14. Brush, S. G. (1983), *Statistical Physics and the Atomic Theory of Matter, from Boyle and Newton to Landau and Onsager*. Princeton University Press, Princeton.

15. Ben-Naim, A. (2020), *Time for Everyone and Time for Everything*, Independent Publisher, Amazon

16. Boltzmann, L. (1877), *Vienna Academy*. **42**, *"Gesammelte Werke"* p. 193.

17. Hager, T. (1995), *Forces of Nature, the Life of Linus Pauling,* Simon and Schuster, New York

18. Perutz, M.F. (1987), *Physics and the riddle of life*, *Nature*, **326**, 555–558

19. Katchalsky, A. (1963), *Nonequilibrium Thermodynamics*, Int. Sci. Technol, 43

20. Volkenstein, M. V. (2009), *Entropy and Information*, translated by A. Shenitzer and A. G. Burns, Birkhauser, Berlin

21. Brillouin, L. (1962), *Science and Information Theory*, Academic Press, New York

22. Hoffman, P.M. (2012), *Life's Ratchet, How Molecular Machines Extract Order from Chaos*, Basic Books, New York

23. Rovelli, C. (2018) *The Order of Time,* Riverhead books, New York

24. Styer, D.F. (2008), *Entropy and Evolution*, Am. Journal of Physics, 76, 1031

25. Sanford, J. C. (2005), *Genetic Entropy and the Mystery of the Genome*, Ivan Press, a division of Elim Publishing, New york