THERMODYNAMICS, INFORMATION, AND COMPLEXITY IN ARTIFICIAL AND LIVING SYSTEMS

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ABSTRACT
The history of thermodynamics has generated the list of systems that obey, without exceptions, the principles established by Clausius, Kelvin, Carnot, Boltzmann, Gibbs and Maxwell. In spite of this, the understanding of ‘transformations’ in living organisms, originating from studies initiated at the beginning of the 20th century, has opened the question on the universal validity of the second principle of thermodynamics. In fact, even some of the aforementioned eminent physicists were aware of possible paradoxes when the system contains nonlinear elements, or when there are constraints due to rules referring to ‘codes’ present in the system. This article deals with an introduction to the Gibb’s paradox applied, as simple examples, to thermodynamics and information and to entropy and energy flux.

Keywords: $k \ln 2$, living organisms, Maxwell’s demon, photosynthesis, second principle.

1 INTRODUCTION
In 1865, Rudolph Clausius introduced the entropy function with the purpose of having a quantitative expression for a physical law, at least for certain types of systems: the second principle of thermodynamics. Clausius’s definition refers only to macroscopic variables, without any hypothesis on the microscopic nature of the observed system [1]. However, entropy being an upcoming intrinsic property, the research for deriving it from microscopic properties has never been abandoned. James Clerk Maxwell was the first researcher who thoroughly investigated such derivations using a statistical approach.

The way he overcame the problem of mixing two gases is particularly important. He observed that the entropy for two volumes of gas diffusing into one another changes only if the gases in the two volumes are different; whereas it does not change if they are the same. The explanation proposed by Maxwell for this apparent paradox is indeed original: entropy is not a property of the system per se, but it comes from the inner nature of the system and its knowledge by the observer becomes at this point essential (it is not possible to use a black box approach anymore) [2, 3]. The adoption of this perspective brought Maxwell towards the idea of an internal control of the system using the famous Maxwell’s demon. Here we consider Gibb’s paradox and Maxwell’s demon conjecture applied to different contexts such as complex artificial and living systems, evidencing how information management, internal or external, can create very different behaviours in spite of the common complexity.

2 THE GIBB’S PARADOX AND MAXWELL’S DEMON
If $N$ is the number of particles of a gas in a given volume $V$, the entropy $S$ at a certain temperature ($T$) has the following simplified expression [4]:

$$S = Nk(\ln V) + S_0,$$

(1)

The paradox rises when dividing the volume into two identical parts ($V/2$); the effect of this space structuring reduces the total entropy. In fact, for each volume ($V/2$), the entropy value is:

$$S' = (N/2)k(\ln V - \ln 2) + (1/2)S_0,$$

(2)
and so the sum of the two gives:

\[ S'' = N k (\ln V - \ln 2) + S_0. \] (3)

This value differs from the starting entropy value for the term \( N k \ln 2 \). The solution of the paradox goes through the information that is necessary to determine in which side of the total volume each particle finds itself. Such information has to be stored in a device capable of memorizing \( 2N \) states and so the corresponding increase in entropy in the external environment is \( N k \ln 2 \) (Landauer). This counterbalances the entropy decrease obtained by structuring the gas volume [5].

The value of the paradox and its classical solution applies only if the gas particles are distinguishable. However, it is still useful considering that similar considerations need to be applied to the macroscopic world. On this line, it is even more intuitive to observe, as Maxwell did, that two communicating cavities having a given volume \( (V/2) \), but filled with different gases, have their total entropy rising up to \( N k \ln 2 \), if the gases are allowed to merge. What is important is that the entropy increase is derived from the loss of information about the properties of the two semi-volumes, and hence on the structure and properties of the physical space.

By means of the Gibbs paradox, the distribution of matter in space is strongly linked with information and entropy. Hence, the information about the status of the system is managed only in the external environment.

Let us consider the case where a Maxwell’s demon is supposed to operate in a system similar to that of the Gibbs’s paradox, just to gradually enter the connection between information and entropy. It may be worth remembering that Maxwell made a conjecture (1868) where an imaginary creature, a demon, is quick enough to open the gate between two cavities when only one of the two gas molecule is heading that way, hence being able to separate the two [5].

Figure 1a and b shows the activity of Maxwell’s demon (purposely trained) while selecting the molecules of the two mixed gases. Its task is to separate the two gases by opening and closing the separation gate until the two species are perfectly separated, one on the left side and the other on the right side.

If this process were to happen without increasing the entropy outside the system, the second principle of thermodynamics would be violated. It is clear that this is only a hypothetical conjecture, for the moment. Nevertheless, for what will follow, it is important to note that for Maxwell’s demon, the information is completely managed inside the system. Again, if the entropy decrease is calculated, it is given by \( \Delta S = N k \ln 2 \).

2.1 Thermodynamics and information

The attempts to manufacture a device able to behave like having a Maxwell’s demon inside, with the most important one done by Leo Szilard in 1929, were all affected by a strong limitation that can be summarized with a twofold observation: (1) in practice, Maxwell’s demon has always been treated like a programmed mechanism able to perform a very limited range of choices, usually discriminating only two states; (2) the system status has to be continuously communicated to the outside system and somehow recorded. In synthesis, it has been possible to make nothing more than a simple actuator, without any autonomy and totally dependent on the outside system: nothing different from what has been seen in the Gibbs’s paradox. So, there is no way to reduce the internal entropy without an equivalent external increase. In this situation, the hypothesis of the violation of the second principle, following Maxwell’s idea, fails, missing the main presupposition, i.e. the ability of the demon to act without being trained and without communicating the results of its work to the external environment [5].
If we observe the methodology implied in manufacturing anything generated by human intelligence, comparing it to what is behind the Gibbs’s paradox and Maxwell’s demon conjecture, we can easily recognize interesting analogies. This is particularly evident in the transformation of matter and energy, using information (in a set of instructions), to force the construction of artificial systems going from the initial dispersed materials to the final manufactured object shape. In fact, in any of the following actions – making an object, setting materials in a given arrangement, painting a picture or writing music we operate in analogy with a Maxwell’s demon, making a specific choice in matter arrangement among the numerous possible arrangements. This determines an entropy decrease proportional to the quantity of matter and $\ln p$, where $p$ is the probability of the chosen configuration. The only obvious difference is that in Maxwell’s conjecture, the demon operates inside the system, while human intelligence and derived tools operate only outside it [6].

2.2 Work needed to lower the entropy in complex systems

Among artificial systems that human intelligence can design and manufacture, the most difficult ones to make are electronic microchips. This is due to the need to arrange very complex architectural geometries in a scale size level largely below the micrometer. In synthesis, the work to be done to make microchips consists in structuring very thin layers on top of the silicon monocrystalline substrates (the electrical properties used in integrated circuits require very pure silicon substrates and a perfect crystalline structure). The arrangement of each layer defines the characteristics of adjacent portions having a certain minimum size, similarly to what happens in the Gibbs’s paradox and for the Maxwell’s demon conjecture. The minimum size determines the maximum number of configurations obtainable for a single layer. The total number of stacked layers may be greater than 30, and the total
process is conceived in a way to maintain certain ‘independence’ (not only in statistical sense) in the single layer manufacturing. The final configuration resembles a memory with a defined content of ‘bits’. According to Landauer’s principle, a decrease in entropy of \( nk \ln 2 \) is produced as indicated in Fig. 2, corresponding to a minimum external equivalent entropy increase due to the ‘erasure’ (transferring) of \( n \) memory bits. The quantity of work to be done to make this configuration will depend on the quantity of matter used (the mass or the number of moles) \([7]\). So, structures with the same number of possible configurations will require different amounts of work (extracted from a suitable energy source). In fact, a different amount of energy is necessary in arranging tiny tiles in a mosaic, or bricks for a house, even if the number of possible configurations is the same.

The entropy variation for a single information ‘bit’, still considering what happens in a layer used in integrated circuit manufacturing processes, is given by the entropy variation \( \Delta S \) in the material associated with the ‘bit’ creation process. For a given configuration, the entropy value is: \( S_c = k \ln (1/p) \) (Landauer), where \( S_c \) is the configurational entropy and \( p \) is the probability of a single configuration.

To fix a specific configuration in an ergodic process it needs to go through all the others (this would explain the very low efficiency in the manufacturing of complex systems like integrated circuits). Hence, if the configuration number is \( 1/p \), to determine the value of the work \( (L) \) needed to obtain the configuration at a given temperature \( (T) \), the entropy variation should be multiplied by \( 1/p \), and the required work will then be:

\[
L = T \Delta S (1/p),
\]

and because

\[
1/p = e^{S_c/k},
\]

then

\[
L = T \Delta S e^{S_c/k},
\]

where, \( S_c \) is the configurational entropy.

Remembering that

\[
S_c/k = (A/a) \ln 2,
\]

and substituting in eqn (7):

\[
L = T \Delta S e^{(A/a) \ln 2}.
\]

\( \Delta S \) accounts for the contribution to the work \( (L) \) due to the ‘mass’ of the ‘bit’. Because of the above-mentioned considerations, it is clear that the work needed to create complexity is usually huge. This is one of the reasons for the small size of microchips \([7]\).
3 ENTROPY AND ENERGY FLUX

Consider a system B receiving energy from a source A and releasing part of that energy to a system C; that is, A is a radiation source, B is a gas container and C is a mass of water transparent to the source radiation and completely surrounding B.

In Fig. 3, the energy flux $Q$ increases the entropies of B and C such that $\Delta S_A + \Delta S_B + \Delta S_C \geq 0$.

It should be noted that $\Delta S_A < 0$, because the energy flows outside system A. Moreover, for any fraction of $Q$ released to C, in dependence of $m$, the positive terms of the above-mentioned equation overcome the negative ones, i.e. the temperature $T_C$ of C is lower than the temperature $T_B$ of B and $T_B$ is lower than the temperature $T_A$ of A; otherwise the energy flux cannot flow in the proper direction. It is worth noting that entropy cannot increase without limits, but will stop increasing when the amount of radiation emission from B due to the increase in $T_B$ will become equal to the received one ($Q$) [8].

Figure 4 shows a system configuration similar to that of Fig. 3, but with Maxwell’s demon using incoming energy to make the selection of gas molecules. In this case, if the Maxwell’s demon uses the energy $(Q - Q/m)$ to reduce the entropy of system B, and the thermal capacitance of system C is so high that the temperatures of B and C are the same, then the relative entropy decrease $\Delta S'_B$ due to the release of the $Q/m$ energy fraction and the corresponding increase in $\Delta S_C$ are identical in value but opposite in sign. So their contributions to the total entropy variation will be zero: $( (Q/m)/T - (Q/m)/T ) = 0$. Considering that $\Delta S_A$ will remain negative and $\Delta S'_B$, representing the entropy decrease operated by Maxwell’s demon, is negative too, we find that for such a system, the overall entropy variation will be negative, violating the second principle of thermodynamics, independently from the nature of the energy source A.

This is only a hypothetical conjecture, impossible to realize in practice, also highlighting what we have described in Section 2.1 [9, 10].

Moreover, considering the very high inefficiency in manufacturing complex systems, with the huge entropy increase in the environment caused by human activities, we can conclude that the second principle of thermodynamics cannot be violated.
3.1 Thermodynamics and living systems

In the previous considerations, we have seen the difficulty in manufacturing a complex system in terms of entropy. If the simplest living systems are much more complex than whatever the human intelligence can make, then in living systems, the second principle of thermodynamics should be managed in a different way. This kind of observation led Erwin Schrödinger to propose that living beings are fed by negative entropy obtained from the surrounding environment [11]. The evidence of this fact cannot be recognized if we do not take into account the essential role of the information stored either inside or outside the system [12, 13].

In this frame, the specificity of the biological world emerges with all its evidence. In fact, complexity for biosystems appears as the essential structural element. As a consequence, it is necessary to start with a deeper investigation of what is the precise information concept to link with the specific entropy in living systems. These systems are able to produce spatial and temporal characteristics themselves, i.e. they show auto-organized levels completely disconnected with microscopic constituents.

In the Section 1, we have seen that thermodynamic development is based on observations of systems with parts subjected to conservation laws or to constraints from a group of invariants, so that for a given initial configuration it is possible to know what transformation of the system is compatible with those constraints. However, living systems, like artificial ones made by human designs, in spite of them following the mentioned conservation and invariant rules in their microscopic constituents, throughout an instruction set, are able to operate a very precise selection among the configurations ruling in space and time the arrangement and the sequence of those transformations [14, 15].

Molecular structures (enzymes, proteins) exist inside living organisms which operate like a true Maxwell’s demon based on the DNA instructions [1]. In particular, with reference to aquatic plants, it is easy to note that the temperature conditions ($T_{\text{plant}}$ versus $T_{\text{environment}}$) are just right to allow a negative sign for the total entropy variation [9].

3.2 Photosynthesis

To understand the behaviour of the system shown in Fig. 5, let us consider the photosynthesis process in more detail. First, if photosynthesis is considered only as a bioenergetic process of a plant to produce oxygen and convert CO$_2$ into carbohydrate, then we have made a reductive and erroneous observation from a biological viewpoint. In fact, photosynthesis is an extremely complex vital process as Hill and Calvin (Nobel Prize 1961) and other eminent scientists well demonstrated with their research.

![Figure 5: A closed system with a living system inside.](image-url)
activities. It is well known that the photosynthetic process takes place in two fundamental phases: (a) light reactions (photophosphorylation) and (b) Calvin Cycle, the so-called ‘dark reactions’, where energy (ATP), protons and NADPH are provided by the first phase. By mean of these two reaction phases, the absorbed electromagnetic energy is partially used in structuring the present products available in different states (gaseous, solution) and different chemicals (inorganic, organic) to build extremely complex biological structures based on the instructions contained in the DNA of the cells. The thermodynamic transformations, the storage, the structures, the production and the used energy are managed similar to a hierarchic distribution energy chain process. It is also easy to observe that the incoming energy flux, through the photosynthetic process, rather than downgrading the energy ‘quality’ from electromagnetic to heat and vice versa, acts like an energy upgrading process, considering the ability increase produced by the biological transformations and the system growth. Does this observation modify any conclusion concerning the entropy?

Another aspect to be considered, to correctly attribute the process management to the system itself, is that certain components of the plant cells (like chloroplasts and mitochondria organelles, both involved in the photosynthetic activity) develop different functions and they are able to select information finalized by their specificity evolution. The plant cells can also discriminate the wavelength of the light spectrum useful to excite the different types of chlorophyll molecule and other pigments. From the thermodynamical viewpoint, we also know that the electrons flux implied on the transport chain in the excitatory states are associated with the redox process, which deals with ATP and NADPH (molecules synthesised through cell bioactivity).

What is mentioned above is an evident sign of the presence of a photochemical component which shows a catalytic enzymatic need to transfer packets of energy (excitons).

In *Principles of Biochemistry* we can see the description of one of these complicated steps by the way of the electrochemical viewpoint, where the potential of the standard reaction of the centre of the photochemical reaction must have a negative value. This value is needed to transfer the electron in cascade to NADP, because the redox couple NADP+–NADPH presents a standard negative potential of $-0.32 \text{ V}$ [16].

Furthermore, during the photosynthesis steps there is no significant heat production. On the contrary, in animals and more generically in heterotrophic organisms, the total metabolic pathways are obviously unbalanced for catabolism and heat production, because the efficiency of cellular work is not at 100%. So, in animals, during growth, a dynamic and temporary decrease of entropy is observed, but at the same time there is an increase of entropy in the system animal/environment.

Now, considering the total biosphere and the sun as a closed system, it can be seen that the total autotrophic phytomass is larger than the heterotrophic biomass, owing to the pyramidal structure of the trophic chains. This means that in the biosphere the anabolic pathways are quantitatively more important than the catabolic ones, owing to the energy coming from the sun. Is the entropy balance negative? In a climax system (ecosystem evolved into a stabilized steady-state system with biomass at maximum level) a correct answer to this question may be very difficult. But during the growth and development of the biosphere’s seral phases, in the earth’s history, the entropy balance was certainly negative.

In summary, even if the solar energy determines and feeds the planet’s life (vegetal, in this particular case), nonetheless, the qualitative steps, so finely structured, have an additional value to add to the energy balance, only apparently unfavourable as input–output for vegetal cell.

In other words, a very well-organized expression of viability in the photosynthesis process, like the ability to optimize, to choose, to transform, to share, and to finalize environmental information (also sometimes to modify it), must impose ideas that go beyond the boundaries set by classical thermodynamics.
4 CONCLUSIONS

To conclude, let us recollect the main statements that can lead to very relevant conclusions. The first concerns the analogy between what happens during the manufacturing of high technology complex systems, coming from many years of experience in the field, and the entropy decrease in the growth of living systems, both due to a ‘programmed’ space structuring and matter distribution: any system submitted to such kind of processes lowers its own entropy. The second concerns the ergodicity of the artificial systems manufacturing processes. This characteristic derives from the need to select the designed configuration among all the possible ones after passing through all of them. Because of this, the information contained in the set of instructions propagates into all the materials and tools used in the manufacturing process, resulting in the need for a peculiar entropy evaluation approach. As an example, the need to purify all the materials used in manufacturing integrated circuits is considered to avoid any impurity on the silicon surface which might affect the proper designed configuration: this preprocessing of all the materials implies a drastic efficiency decrease as the system complexity increases. The last statement concerns living systems, in which the ergodicity process does not occur at all (as evident in plants, which do not need any purification of air, water and soil). Hence, they can demonstrate a very high efficiency in making all the choices they need for self-organization: even the photosynthesis process is submitted and managed by the information contained in the system itself, just like it would happen if a group of Maxwell’s demons were inside, operating very precise tasks using the energy coming from the outside environment.

In conclusion, as for hypothesis from eminent scientists, it seems that a physical law may exist that is valid only for the living systems and does not belong to the group of physical laws that are valid for non-living systems. This clearly copes with the problem of physical non-reducibility of living systems.

On this subject, Prigogine, in one of his books [17] wrote: ‘What are the main events in the world? For sure the birth of universe and life. There exists on the subject an intriguing Asimov’s tale titled “The Last Question”. Will we be able one day to defeat the second principle of thermodynamics? …’

REFERENCES