Commentary

Infodynamics, Information Entropy and the Second Law of Thermodynamics

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Information and Energy are related. The Second Law of Thermodynamics applies to changes in energy and heat, but it does not apply to information dynamics. Advances in Infodynamics have made it clear that Total Information contains Useful Information and Noise, both of which may be gained or lost in irreversible processes. Increases in Free Energy of open systems require more Useful Information, reducing or increasing Thermodynamic Entropy. Empirical data show that the more Free Energy is created, the more Useful Information is required; and the more Useful Information is produced the more Free Energy is spent. The Energy – Information relationship underlies all processes where novel structures, forms and systems emerge. Although science cannot predict the structure of information that will produce Free Energy, engineers have been successful in finding Useful Information that increases Free Energy. Here I explore the fate of information in irreversible processes and its relation with the Second Law of Thermodynamics.

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Introduction

Surprisingly, the concept of Information is still fuzzy and controversial and many conceptual, theoretical and practical problems regarding information remain unsolved. From the start of the use of Information in physics, problems arose. Brillouin [1] for example showed that Maxwell's demon cannot operate because there is a relation between information and entropy [2]. Energy is required to find, use and apply information. That is, information requires energy, but it is not energy. However, Information and Energy are related. Despite the fact that the Second Law of Thermodynamics applies to changes in energy and heat, thus the descriptor Thermodynamics, it is often used when referring to information dynamics, assuming that information and energy may be lost in irreversible processes. This, however, is not true [3].

There is a strong relationship between changes in Energy and the Information required by a given system to increase its Free Energy and reduce its thermodynamic Entropy [4]: the more Free Energy needed, the more Information is required; and the more Information is produced the more Free Energy is spent. In irreversible processes, information is not necessarily consumed. The Energy – Information relationship underlies all processes where novel structures, forms and systems emerge [5] and is a basic feature of irreversible processes in thermodynamics.

Developments in mathematical statistics, including those of Fisher [6] presented a way of measuring the amount of information that an observable random variable carries. Formally, it is the variance of the score, or the expected value of the observed information. Similarly, Shannon's Information Entropy [7] is the probability of a particular event occurring from a random variable. Both definitions overlap. In other sciences, different conceptions of information do not overlap in all their considerations. For example in quantum mechanics [8] information can suffer entanglement [9], and for many, but not all [10], quantum information is indestructible [11][12]. In contrast, biological information can be lost, as exemplified by species and ecosystem extinction [13].

Thermodynamic entropy has been very successful in explaining complex irreversible processes in chemistry and mechanics and even in biological evolution [14]. Although several authors [15][16][17][18] have made efforts in clarifying the relation between Entropy and the Second Law of Thermodynamics, and to dispel widespread misleading misconceptions [19][20][21]. Misconceptions remain, most arising from an interpretation of thermodynamic entropy based on information, and therefore relating the second law of thermodynamics to information entropy.

For example, contradictions appeared when Thermodynamic Entropy was confused with Shannon's Information Entropy by Brillouin [22]. He wrote "Whenever an experiment is performed in the laboratory, it is paid for by an increase of entropy, and a generalized Carnot Principle states that the price paid in increased entropy must always be larger than the amount of information gained". He assumed that thermodynamic entropy and statistical information can be measured with the same units. This rational flaw shared by many researchers has hindered our understanding of the interaction between energy and information.

Here I attempt to clarify some of these issues by rethinking the concept of information from its roots. I will focus on differences that are relevant to entropy as the product of the Second Law of Thermodynamics. Thermodynamic Entropy is energy that is not available to produce useful work, and is

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evidenced as heat. Information Entropy is a different concept: It refers to the probability of a given variable to contain novel or new information. Due to its fuzzy definition, it tends to be referred to as negative thermodynamic entropy or negentropy. However, thermodynamic entropy and information entropy are two completely different concepts. This confusion also leads to misleading interpretations of the relation between the Second Law with Information. Some fundamental differences between Energy (i.e Thermodynamic Entropy) and Information (i.e Information Entropy) are:

- Thermodynamic Entropy and in Information Entropy are measured differently. The former uses units of energy whereas the later uses units of probability.
- Thermodynamic entropy follows the Third Law of Thermodynamics: Entropy = 0 at absolute temperature = $0^{\{m/0/\}}$ K, whereas information entropy can be > 0 at $0^{\{m/0/\}}$ K
- Information entropy can have negative values of entropy, grossly contradicting the Third Law.
- In thermodynamics, energy in the form of heat flows from warmer to colder parts of the system; whereas information can travel from complex systems with high information content to simpler ones with less information, and the other way round.
- Belavkin, et al wrote [23] "The second law of thermodynamics forbids in an isolated system, the existence of processes accompanied by an increase of entropy. If there exists an influx of information $d\mathbf{I}$ about the system, i.e. if the physical system is isolated only thermally, but not informationally, then the above law should be generalized by substituting inequality $d\mathbf{H} \geq 0$ with inequality $d\mathbf{H} + d\mathbf{I} \geq 0$. Therefore, if there is an influx of information, then the thermal energy of the system can be converted (without the help of a refrigerator) into mechanical energy. In other words, the existence of perpetual motion of the second kind powered by information becomes possible". This statement assumes that creation and accumulation of information can be achieved with no energetic cost. This of course violates the First Law of Thermodynamics.
- Landauer [24] argued that "computing machines inevitably involve devices which perform logical functions that do not have a single-valued inverse. This logical irreversibility is associated with physical irreversibility and requires a minimal heat generation". He however overlooks that the work is done by a machine where the information is stored and is not a direct product of information dynamics. The energy to mold a substrate to engrave information varies depending on the substrate: a scripture in stone will require more energy than one written in the sand. But the value of the information does not depend on the substrate where it is encrypted!

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Clearly, we have to distinguish between Thermodynamic Entropy **S** and Information Entropy **I**. In information theory, the entropy of a random variable is the average level of "information", "surprise", or "uncertainty" inherent to the variable's possible outcomes. Whereas Thermodynamic Entropy refers to the relationship of the internal energy **E** that is available or unavailable for transformations in form of heat **S** and work **F**. Thermodynamic and Information Entropy refer to very different physical phenomena. Sometimes, negative Thermodynamic Entropy (negentropy) is linked to Information Entropy, a mistake I and many others [25][26] did many times in the past. Negentropic processes do exist: processes that reduce the production of **S** to favor **F**; but the relationship between **S** and **I** is much more complex than formerly acknowledged [27][28]. Here is an attempt to unravel this confusion.

How the Second Law of Thermodynamics affects Information

The material substrate where information is stored suffers the effect of the Second Law: genomes and proteins degrade in time and so does any physical system storing information. But living systems, located far from thermodynamic equilibrium, not only store information but may increase their stored information. An empirical law for irreversible thermodynamics states that the thermodynamic free energy **F** and the information used to produce the energy required for the work done **Φ** are related. That is expressed as $\Delta F \sim \Delta \Phi$ [4], recognizing that increases in useful information and increments in free energy are coupled. This means that far from equilibrium systems suffering irreversible processes dissipate energy but can increase their available useful information or reduce their useless information. Useful here refers to the ability to produce Free Energy **F** which in turn produces useful Work.

Let's consider Information Complexity as the total amount of information in a system **I**, and Useful Information **Φ** the one producing Free Energy **F** and thus work. Free Energy and Work are thermodynamic concepts so that Helmholtz Free Energy can be represented as $F = E - TS$, where **F** is Free Energy, **E** total energy, **T** temperature and **S** thermodynamic entropy.

We might generalize this equation incorporating **T** in the conceptualization of **S**, as follows:

$\Delta F = \Sigma \Delta Ei - \Delta S$, where **Ei** represents the different types of energy and **S** the entropy due to energetic processes, and $\Delta \Phi = \Sigma \Delta Ii - \Delta N$, where **Φ** is useful information or the information that accounts for ΔF, **Ii** are the different types of information and **N** is noise, useless information or information that produces entropy.

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Using these abstractions we can write $\Delta\mathbf{F} \sim \Delta\mathbf{\Phi}$, which seems to be a law for irreversible thermodynamics, as suggested by empirical evidence [2]. The exact relation between **F** and **Φ** remains to be untangled but one link is the relation between **S** and **N**. In energetic terms **S** is related to the order or predictability of a system, and so is **N**. The problem here is that order and complexity are related, and these measures depend on the level of complexity addressed. This introduces distortions when comparing multiple levels or multiple dimensions of energy and information. This relationship means that in order to increase **F** there needs to be an increase in **Φ** by increasing **I** or decreasing **N**. That is, not any type of information will do. Information may be misleading, false and/or destructive provoking a reduction of **F**. We call this type of information **N** or noise. For now, the type of information, **Φ** or **N**, can only be assessed empirically through its effect on **F**. When increases of **F** are concomitant to increases in **Φ** we have a synergistic process. These limitations do not occur with energy, as relations between the different forms of energy are much better understood in physics than those of information. Thus **Φ** is as a proxy of Useful Information.

How is this relationship affected by the Second Law of Thermodynamics? The Second Law states that an open system must dissipate thermodynamic entropy **S**. Maintenance of information requires energy and thus adds to the dissipation of this entropy. However, information might reduce the production of thermodynamic entropy by increasing free energy **F** of the system Thus, information has a dual role: its maintenance and creation increases and its working decreases thermodynamic entropy! When does one effect overcome the other? In living autopoietic systems, information increases and free energy increases. Total consumption of energy generally also increases but efficiency gains in production of free energy might reduce it. Evolution through Natural Selection in systems living in resource poor environments might accumulate information that make them more efficient in resource use, whereas organisms evolving in environments saturated with energetic resources might skip that trend.

Proposal

The relation between Information Entropy and Thermodynamic Entropy in this context can be described as follows.

$\mathbf{F} = \mathbf{E} - \mathbf{S}$ Where **E** is total energy and **S** the thermodynamic entropy due to energetic processes

Φ is useful information or the information that accounts for **F** is **I** the total information accounting for its complexity, and **N** useless information or noise

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$\mathbf{\Phi = I - N}$ and $\mathbf{F = E - S}$ then

$\mathbf{\Phi} = k(\mathbf{F})$ and $\mathbf{F} = j(\mathbf{\Phi})$

were ***k*** and ***j*** are two different functions relating **F** with **Φ**

We have empirical tools to measure **Φ** and **F** quantitatively and experimentally and Total Information **I** can then be estimated as complexity or $\mathbf{I = \Phi + N}$ [29]

The fact that energy can be present in useful or useless form regarding the power to produce work $\mathbf{F = E - TS}$, and the insight that information can also be classified as useful or useless for the purpose of creating **F**, $\mathbf{\Delta F \sim \Delta\Phi}$ force us to accept that $\mathbf{\Phi = I - N}$ as not all information serves to produce **F**. This is fundamental in understanding the working of information in thermodynamics and requires accepting a clear difference between Thermodynamic Entropy (**S**) and Information Entropy (**I**).

Discussion

Colloquial language may describe genetic information inside an organism that codes all necessary tools for swimming in the water are useless information if the organism lives in a desert. The usefulness of information is determined by its environment. The same is true for energy. Energy in the form of light is completely useless to a plant that lacks photosynthetic capabilities. The heat produced by its reflection on the leaves produces might dry them. This same heat from the sun reacting the skin of a reptile might activate its metabolism helping to digest its last meal. Thus, the usefulness of energy and information depends on the ability to produce or capture Free Energy **F** which is able to generate Work. The structural information in chloroplast, and the metabolic information in endotherm animals allow for the capture of energy that can be used to produce work and is therefor called Free.

No unique way to transform energy into Free Energy exists. Information **Φ** may arrange existing energy **E** changing the balance between **F** and **S**. An examples of how **F** can create **Φ** is biological evolution where **F** is spend in sexual selection, meiosis and reproduction. Selection found that sex by diploid cells are the most efficient in handling, conserving and increasing useful information [30] which seems impossible to achieve without sex [31]. Modern science seems to have achieved something similar with **F** spend pursuing empirical sciences to produce **Φ** [32]. The detailed relationship between **Φ** and **F** remains to be worked out for each level of complexity. Science cannot predict the structure of information that will produce Free Energy as no general formula for $\mathbf{F \sim \Phi}$ exists. Engineers, including social engineers [33],

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have been successful in finding empirically **Φ** to increases **F** for specific situations and are now the most specialized in producing knowledge in a large scale.

This relation **F ~ Φ** is consilient with many recent theories relating information with the Second Law of Thermodynamics and may serve as a unifying element for different perspectives such as:

- David Deutsch and Chiara Marietto [34] proposition of the Constructor Theory of Information, describing physical transformations, or *tasks*, that are possible versus those that are impossible
- Adrian Bejan and Sylvie Lorente [35] proposition of the Constructal Law describing the design and evolution in nature. “For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed (global) currents that flow through it¨. That is, **Φ** must increase in time to compensate increases in **S**
- Adami, C., et al [36] proposition that natural selection forces genomes to behave as a natural “Maxwell Demon”
- Haken, H. and Portugali. J. [37] proposition of a Synergic Computer to resolve the interplay between Shannon’s information and semantic or pragmatic information.
- Kolchinsky A., Wolpert D.H. [38] classification of information acquired in a measurement into "accessible" and "inaccessible"
- Smith, E. [39] representation of information in the biosphere, and the energetic constraints limiting the imposition or maintenance of that information
- Parrondo, J., Horowitz, J. & Sagawa, T. [40] presentation of a theoretical framework for the thermodynamics of information based on stochastic thermodynamics and fluctuation theorems
- Varley T, Hoel E. [41] evidence that coarse-graining can convert information from one ‘type’ to another and reduction of complexity leads to a loss of synergistic information in scientific models.
- Rainer, F., Ebeling, W. [42] evidence that information emerges from structural information in the course of evolution processes.

However, other perspectives are incompatible with the conception of infodynamics presented here. For example, the theoretical mix-up of heat with information, as presented by Vopson [43] with no basis in physics; or equating the cost of transmitting information to that of creating the information [44], can not be integrated with the concept **Φ**.

Much work remains to be done.

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