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Review Article

Thermodynamics, Infodynamics and Emergence

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Emergence of novel processes, properties, structures, and systems is a poorly understood phenomenon. Emergence, information, and energy are interrelated properties of nature: it takes free energy (energy that produces work, designated as F) to acquire information, and it takes information to increment free energy. Useful information (Φ) is the one that increases free energy and differs from information not producing free energy or producing entropy. Energy obeys all laws of thermodynamics, while information may not. When the energy and information of systems interact, novel properties or levels of energy and information may emerge. Information can reveal itself in different forms (as entropy, order, complexity, physically encoded, mechanical, biological, structural, in neural or social networks, etc.). Information may increase free energy by reducing entropy in an open system or by capturing free energy from the surroundings. The dynamics of information and energy have been studied mostly in physical chemistry and engineering. Now we find it everywhere, including in computer sciences, genetics, biotechnology, experimental social sciences, and experimental law. In emergent systems, new possibilities of increasing free energy and useful information appear. Emergent complexity is visible in the transitions from subatomic particles to atoms, from atoms to molecules, to cells, to organisms, to societies, and ecosystems. A law for irreversible thermodynamics stating that $\Delta F \sim \Delta \Phi$ is evidenced empirically in all these levels of complexity, confirming that increases in useful information and increments in free energy are coupled. As free energy helps access more information, and more information produces more free energy, evolution by natural selection accumulates ever more useful information, giving birth to life. In contrast, increases in entropy decrease free energy and might affect the amount of useful information available in the system. More noise or misleading information decreases useful information, which decreases free energy. These relationships help us understand the evolution of life, societies, ecosystems, and autonomous artificial life. Quantifying concomitant changes in energy and information is needed to understand the relationship between them. The endeavor to achieve this has begun[1].

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Introduction

Information and energy are fundamental properties of nature, and emergence is a concept frequently used in complex system sciences. Here, we refer to emergence as the phenomenon that makes novel unpredictable properties and features appear in complex systems. We will use the dynamics of energy and information to understand emergence in simple and complex far-from-equilibrium systems. This research has the potential to revolutionize our understanding of the physical world, and it could lead to the development of new technologies that have the potential to improve our lives and that of our planet. Only by recognizing the multidimensional nature of information and energy will we be able to understand the emergence of complexity. The aim here is to formulate a conceptual framework that consiliently

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bridges our understanding of the dynamics of energy (thermodynamics) and that of information (infodynamics) to better understand the phenomenon of emergence in physics, chemistry, biology, social sciences, politics, and religion. In order to do so, we need to recall relevant fundamental knowledge of basic natural science to have a shared understanding of it.

Among the **fundamental physical forces of nature** , we recognize the existence of the following: **inertial force**, g**ravity**, e**lectromagnetism**, the w**eak nuclear force** , and the s**trong nuclear force**. These forces produce e**nergy** that can be used to do w**ork**. We can define **energy** as the capability of a system to do work, such as to exert a **force** causing the displacement of an object.

Energy

We recognize different forms of energy that are interrelated. For example:

- **Mechanical Energy** (kinetic energy, energy derived from inertia and gravitational forces).
  Galileo identified gravity as a force and Newton postulated in physics that, if a body is at rest or moving at a constant speed in a straight line, it will remain at rest or keep moving in a straight line at constant speed unless it is acted upon by a force. He called it Inertia. These forces produce kinetic energy whose thermodynamic properties are fairly well understood.
- **Electromagnetic Energy** (radiation, light, heat). Electromagnetic fields produce forces that create energy that are involved in electromechanical and chemical processes including radiations such as light and x-rays. Electromagnetic forces bind atoms forming molecules. They work in vision, photosynthesis and in many other vital processes. These forces may produce heat.
- **Chemical Energy** (oxidation, fire, ATP, heat). As an emergent property of the combination of kinetic energy and electromagnetic forces, chemical energy emerges through the interactions between molecules. Examples include exothermic chemical oxidation which is expressed as fire; and physiological reactions in living organisms powered by the controlled oxidation of ATP (Adenosine triphosphate molecules) that produce the energy required to power all living organisms.
- **Nuclear Energy, Strong and Weak** (radioactivity, heat). These forces produce energy stored at the nuclear level. They are responsible for nuclear power and atomic bombs.
- **Dark Energy** (?). Little is known of this energy besides that it probably exist and is used to explain the expansion of our Universe

These types of energy might express themselves as **Free Energy** or as **Entropy**. We call an energy as Free Energy if it produces work; and **Entropy** or thermal energy if it dissipates to the surroundings as **Heat** without producing work.

These energies interact with matter and these interactions are studied by thermodynamics. Thermodynamics studies the relationships between heat, work, and energy, and it provides a framework for understanding the behavior of physical systems. Thermodynamics has been dealing traditionally with systems at equilibrium or near equilibrium. It focused on closed systems that are isolated from the environment, and on reversible processes that do not produce entropy. Thermodynamics of open systems, that are far from equilibrium, and experiencing irreversible processes, are much less understood. But these systems are the ones which are more important for humans to understand. Our knowledge of thermodynamics can be summarized in its laws.

Laws of Thermodynamics

- **The zeroth law** of thermodynamics says temperature is an empirical parameter in thermodynamic systems. It states the transitive relationship between the temperatures of multiple bodies in thermal equilibrium. The law says: If two systems are both in thermal equilibrium with a third system, then they are in thermal equilibrium with each other. This law implies that energy can flow spontaneously from high to low temperature systems but not the other way round.
- **The first law** of thermodynamics is a version of the law of conservation of energy, adapted for thermodynamic systems. The law of conservation of energy states that the total energy of an isolated system is constant; energy can be transformed from one form to another, but can be neither created nor destroyed. It can also be stated in the following form: The energy gained (or lost) by a system is equal to the energy lost (or gained) by its surroundings.
- **The second law** of thermodynamics says that some things can't be undone after they are done. This indicates that entropy is a form of energy. It states that, in an isolated system, entropy can increase but cannot decrease. It can be stated as follows: Natural processes tend to go only one way, toward less usable energy and more entropy.
- **The third law** of thermodynamics can be stated as: A system's entropy approaches a constant value as its temperature approaches absolute zero. Or, at 0 degree Kelvin, the entropy of a system is 0.

Dissipative systems

A proposed law or rule of irreversible thermodynamics for open far-from-equilibrium systems with a structure of minimum dissipation[2] states that these systems maintain a stable state thanks to synergic processes that increase free energy concomitantly with gains in appropriate information. Let's call them **synergistic systems**. Quantitative empirical evidence from a variety of different systems[1] suggests that synergistic systems occur at all levels of organizational complexity. In all known cases, free energy increases are coupled with increases in useful information. No counterexamples have been produced so far. That is, we do not know of any stable systems that increase their free energy while reducing their useful information. This proposed law might turn out to be a rule if deduced from other laws and principles.

Free Energy

Energy might or might not be used to produce work. When it produces work, we call it Free Energy, whereas Entropy is the energy that dissipates (as heat, for example) without producing work. This work can be mechanical or chemical, but other kinds of work may also exist. Exergy is an alternative approach to this concept.

Helmholtz Free Energy

Our thermodynamic understanding of systems driven by kinetic energy is far more advanced than that of other forms of energy. As the relationship between information and emergence is rather diffuse, we might as well start with kinetic energy to get an understanding of it. In order to understand the fundamental meaning of information, we have to explore the physical concepts upon which it is built. Basically, we want to understand the deep meaning of the equation defining Helmholtz Free Energy:

$$F = E - TS$$

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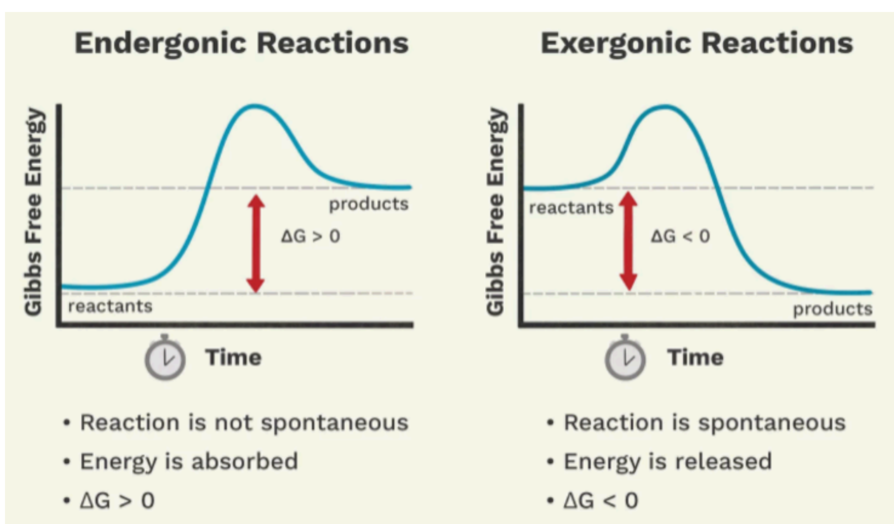
Where the abbreviations mean:
F: Free Energy: the energy available in a system to do work
E: Total Internal Energy of a system
T: Temperature or the average kinetic energy of the system
S: Entropy. The amount of total energy that cannot be used to produce work, measured in calories per kelvin per mole. In information theory, entropy of a random variable is the average level of "information", "surprise", or "uncertainty" inherent to the variable's possible outcomes.

Free energy is a thermodynamic potential used to calculate the maximum amount of work that may be performed by a thermodynamically closed system at constant temperature and pressure. But energy also exists in systems not governed by pressure-volume work or chemical reactions. Thus, we need to expand the concept of free energy. For example, in a steam locomotive, **E** relates to the total energy produced by the fire heating the water to produce vapor, and **F** refers to the actual pulling power the locomotive might exert using the vapor pressure. **S** relates to the energy lost in heat and other unusable forms during the process. Free energy also powers chemical reactions. In the example of the steam locomotive, the fire may be produced by burning coal. That requires the oxidation of coal or $C + O_2 = CO_2 +$ Heat. The direction and extent of chemical change of this reaction can also be quantified using the free energy. In addition, the transfer of heat from the fire to the water molecules in order to produce vapor is also a process described by **F**.

The entropy concept applies to mechanical energy as a loss of energy due to the production of heat caused by friction. It is because a macroscopic collective movement energy is partially distributed to the chaotic, thermal movement of molecules. In thermodynamics, the transformation of order into disorder is what defines an increase in entropy[3]. Further expansions of the concept of free energy and entropy to other kinds of complex phenomena will be attempted here. The following concepts are relevant for this expansion.

Endergonic Processes

Processes that dissipate energy are called exothermic. Those that absorb energy are called endothermic. If what is dissipated is not heat but some other kind of energy, such as sound or light, we call the processes exergonic or endergonic. This last term is more general as it considers any kind of energy.



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Endergonic reactions require a catalyst in order to proceed. This catalyst is a device that contains structural information (see below). These processes may reduce entropy as they absorb heat or other kinds of energy from the environment. Here, an example for Gibbs free energy is given. Equivalent plots can be drawn using other kinds of energy.

Potential Energy

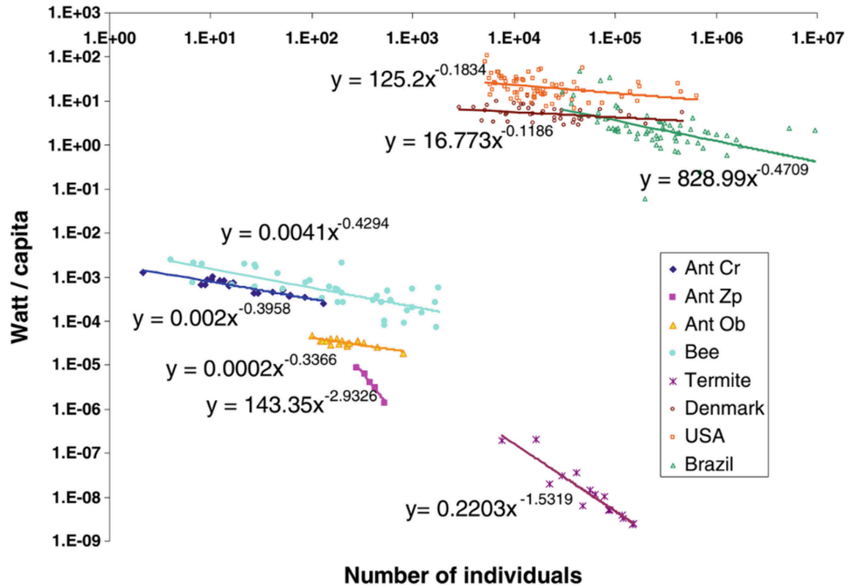
Potential energy emerges when forces over a system are such that any trigger or change in border conditions can unleash a torrent of energy. We might refer to mechanical, electrical, or chemical energy, and examples include water dams, weights suspended in the air, chemical compounds that unleash energy, multidimensional systems that can store different kinds of energy to be used on special occasions such as armed forces prepared for war. All of these energies can be used to produce work.

Biological Energy

Biological organisms use different types of energy in their workings. The synergistic interactions between physiology and anatomy produce behaviors that can harness and/or produce energies of different kinds. These energies drive biochemical reactions and physiological processes and are expressions of free energy. For example, the energy used for muscle contraction, the energy accumulated by a blood-sucking mosquito, or the energy stored in a seed. These are mixes of chemical and mechanical energy studied by physiologists.

Social Energy

Biological aggregates of cells, organisms, and/or ecosystems use different types of energy in their workings. The synergistic interactions between different components of a social system can harness and/or produce energies of different kinds. These energies are used by the system to fuel the workings of its components. They are free energy. An illustrative example Jaffe[4] is given by the per capita energy consumption in societies of different sizes or complexity. As energy consumption per capita decreases, the free energy of the social system increases, as presented quantitatively for insect colonies and human cities in the figure.



Cognitive Energy

Conscious information or knowledge increases due to learning and research. These activities require work to produce the energy that increases information. Thus, free energy can be identified in music and language. These increases in free energy are conspicuous when relating the economic productivity of a country with the amount of scientific research activity. Several examples are given in Jaffe[1].

Synergy

Synergy refers to quantitative changes in energy due to nonlinear processes. This process might involve any of the types of energy listed above. Synergy occurs when information produces free energy.

Information

Information is a measure of a characteristic of energy and matter. In physics, information is used to describe the state of a system. For example, the position and momentum of a particle can be used to describe its state. In biology, information is used to describe the structure and function of biological systems. For example, the DNA sequence of a gene can be used to describe its structure, and the protein that is encoded by the gene can be used to describe its function. Thus, several types of information exist:

- **Encrypted information** such as that encoded in DNA or other biosemiotic devices, in music, and in language. Transmissible information is normally encrypted onto a messenger. It is regarded as noise if the receptor has no clues as to how to decode it. Different types of information can be encrypted in different ways.
- **Negentropy** or negative entropy. Often used as a proxy for information. But negative entropy is forbidden by the third law of thermodynamics, although negative changes in entropy are possible. That is always $S > 0$, but $\Delta S < 0$ is possible. It is best to avoid relating entropy to information in complex systems.
- **Chemical information** contained in molecules that allow for specific interactions between different types of matter.

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- **Electromagnetic information** is transmitted through waves that interact at a distance.
- **Structural information** or border conditions of machines and organisms, and that of catalysts or molecules or structures that modulate chemical reactions or other processes.
- **Networks** storing information. Neural networks in a brain, cell networks in an organ, computers, and social networks, for example. This information is not necessarily available to observers outside the system.
- **Spatial-Temporal** information that allows synchronizing processes so as to produce work or synergy.
- **Others**

No single tool exists to quantify all of these types of information. Strings of code can be analyzed with simple tools developed by physicists and information scientists, but they are of no help in quantifying the structural information of complex catalytic molecules. A deeper understanding of the nature of information might help in this endeavor. Even as quantification of information is an unresolved challenge, some attempts to do so include:

- Claude Shannon's[5] paper "A Mathematical Theory of Communication". 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. In information theory and statistics, negentropy is used as a measure of distance to normality. Out of all distributions with a given mean and variance, the normal or Gaussian distribution is the one with the highest entropy.
- Kolmogorov A,[6]. Three Approaches to the Quantitative Definition of Information, Problems Inform. Transmission; is the root of what we now call Kolmogorov complexity. This type of complexity of an object, such as a piece of text, is the length of a shortest computer program (in a predetermined programming language) that produces the object as output. It is a measure of the computational resources needed to specify the object, and is also known as algorithmic complexity, Complexity and information related concepts. Complexity refers to the difficulty of understanding or describing a system, while information refers to the amount of knowledge that is needed to specify a system
- Schwartz, K.[7] in "On the Edge of Chaos: Where Creativity Flourishes ¨ describes the concept of the "edge of chaos" as a metaphor for a state of dynamic balance between order and disorder. In this state, systems are able to adapt and change in response to new information and challenges, while still maintaining a basic level of structure and stability. This state is often associated with creativity, as it allows people to think outside the box and come up with new ideas.
- Deutsch, D. & Marletto, C[8]. "Constructor theory of information". The Constructor theory of Information is expressed solely in terms of which transformations of physical systems are possible and which are impossible - i.e. in constructor-theoretic terms. It includes conjectured, exact laws of physics expressing the regularities that allow information to be physically instantiated. Although these laws are directly about information, independently of the details of particular physical instantiations, information is not regarded as an *a priori* mathematical or logical concept, but as something whose nature and properties are determined by the laws of physics alone.
- Kolchinsky A., Wolpert D.H.[9] "Work, Entropy Production, and Thermodynamics of Information under Protocol Constraint" assumes that the thermodynamics of information in the presence of constraints can be decomposed into the information acquired in a measurement into "accessible" and "inaccessible"

components. This decomposition allows considering the thermodynamic efficiency of different measurements of the same system, given a set of constraints.

- Smith, J.[10] describes Biological information as a product of Natural selection. Smith E[11] explores the "Thermodynamics of natural selection" and proposes how to measure the representation of information in the biosphere, and the energetic constraints limiting the imposition or maintenance of that information. Biological information is inherently a chemical property, but is equally an aspect of control flow and a result of processes equivalent to computation. The aim is a theory of biological information capable of incorporating three characterizations and their quantitative consequences linking energy and information by considering the problem of existence and resilience of the biosphere.
- Parrondo, J., Horowitz, J. & Sagawa, T.[12] write about "Thermodynamics of information" Theoretical framework for the thermodynamics of information based on stochastic thermodynamics and fluctuation theorems,
- Varley, T and Hoel E.[13] present "Emergence as the conversion of information: A unifying theory". Dimension reduction (macroscales) can increase the dependency between elements of a system (a phenomenon called "causal emergence") and complexifies any notion of universal reduction in the sciences, since such reduction would likely lead to a loss of synergistic information in scientific models.
- Kelso, J. A. S.[14]. Unifying Large- and Small-Scale Theories of Coordination. Here coordination is viewed as information coupling among component parts and processes. This is an alternative view of the process of synergy or of the production of free energy by coordinated actions.
- Rainer, F., Ebeling, W.[15] tackle information and self-organization and relate it with information and value. It seems clear that the concept of information permeates all disciplines and that some more rigorous conceptualization of self-organization and information is needed.
- Haken, H., Portugali. J.[16] presented Shannon's information that deals with the quantity of a message irrespective of its meaning, semantic and pragmatic forms of information that deal with the meaning conveyed by messages, and information adaptation that refers to the interplay between Shannon's information and semantic or pragmatic information.
- Gershenson, C., & Fernández, N.[17] review in "Complexity and information: Measuring emergence, self-organization, and homeostasis at multiple scales" the relationship between these concepts. This comprehensive review on the subject shows that fundamental issues in the relationship between information and thermodynamics remain to be solved.

None of these approaches leads us to find a universal physical definition of Information. This justifies the present effort to build one such quantitative description. The description grows from the nature of information as a shadow of energy. Information becomes quantifiable in the interaction between energy and matter. The definition of Free Energy will guide us in this endeavor.

Complexity and Information

Complexity is more of a characteristic of information than an independent concept. Complexity refers to the degree of order or disorder in a system, while information refers to the amount of knowledge that is required to describe a system. In general, more complex systems require more information to describe. It also refers to patterns and representations. For example, a simple system like a rock can be described with a few simple properties, such as its size, shape, and color. A more complex system like a human being, on the other hand, requires much more information to describe, including its physical features, its personality, its memories, motivations, and its thoughts.

The relationship between complexity and information has been nicely explored in biological evolution[18], showing that because natural selection forces genomes to behave as a natural "Maxwell Demon," within a fixed environment, genomic complexity is forced to increase.

Yet not all increases in complexity lead to an increase in useful information. Longer constitutions with more articles do not achieve better socioeconomic results for their countries than shorter ones[19]. Nor do organisms that have longer DNA chains in their genome always have a higher complexity than others with less DNA. For example, the Australian lungfish has a genome with 43 billion base pairs, which is around 14 times larger than the human genome. Few would consider a lungfish more complex than a human. In general, though, genome size is smaller for viruses than for bacteria, which in turn is smaller than that of vertebrates, etc.

Structural Information

The structure of an enzyme, the arrangements of components of a jet engine, or the architecture of a building carries information. The information required to build an enzyme, and the information that it transmits to the compounds it handles in chemical reactions, is somehow reflected in its tridimensional structure. This information is directly related to the complexity of the structure. The more complex the structure, the more information it carries and the more information is required to build it. Structural information is also related to the border conditions of a process (the restrictions the form of a cannon places on the interaction between the exploding powder and the cannonball). A chemical reaction is modulated by an enzyme that constrains the reaction, and thus imposes border conditions on it. However, not all information in a structure is useful in producing work.

Knowledge and Information

Information is the facts or details of a subject, whereas knowledge is awareness, understanding, or skills that involve this information. Information and knowledge refer to the same phenomenon. We might thus consider knowledge as another form of understanding information that can be coded in words or other means, or can be stored in neural or social networks.

Negentropy and Information

The concept of information entropy was introduced by Claude Shannon[5] in his paper "A Mathematical Theory of Communication" and is also referred to as Shannon entropy. Shannon's theory defines a data communication system composed of three elements: a source of data, a communication channel, and a receiver. Complex systems have many components, each of which has different thermodynamic processes. Thus, properties such as Entropy (S) may not be uniform. S, by definition, cannot be negative, as the third law of thermodynamics states that at $T = 0^{o}$ K, S = 0. Thus, negentropy, although having properties that are opposite to that of **S**, is of a different nature and can be better called information **I** that refers to information that increases Free Energy **F** and produces **Synergy**. In physics, the simile of Maxwell's demon seems to be more appropriate in dealing with the relationship between energy and information[20].

Conclusions

We need to discern between useful and useless information, analogous to our perception of energy, which can (Free energy) or cannot (Entropy) be used to produce useful work. But different kinds of information have to be measured differently. Shannon information is useful for strings of data, and Kolmogorov complexity can be estimated using the length of verbal descriptions or computer algorithms. Structural information can be estimated by the number and diversity of the parts. Each system might have a peculiar way to measure information content. As we are interested in the change in the amount of information, the units are of less importance than the relative change in the estimate or proxy for information used. Information is revealed in many different forms, such as complexity, knowledge, entropy, structures, order, dynamics, codes, and networks, among others. Quantification of changes in each of these forms is possible, expanding previous notions of infodynamics[21]. This allows us to study the relationship between infodynamics and thermodynamics in systems of different levels of complexity. In practical situations, complexity and its different forms are a first choice to estimate information, but many other forms exist[1].

Infodynamics and Thermodynamics

Information may increase free energy, as has been explained in physics by the story of Maxwell's demon. Real-life versions occur, and in all cases, their entropy-lowering effects are duly balanced by an increase of entropy elsewhere. Increases in free energy due to information are possible in open systems, as entropy can exit the system and free energy can enter it. In these systems, quantitative empirical evidence shows that increases in information correlate with increased free energy in a multitude of different complex systems, from ant colonies to human society, and from music to legal norms[1].

We might formalize these relationships by generalizing the Helmholtz equation, incorporating **T** in the conceptualization of **S**, as follows:

$\Delta \mathbf{F} = \Sigma \Delta \mathbf{E_i} - \Delta \mathbf{S}$

Where $\mathbf{E_i}$ are the different types of energy and **S** is the entropy due to energetic processes

and $\Delta \mathbf{\Phi} = \Sigma \Delta \mathbf{I_i} - \Delta \mathbf{N}$

Where **Φ** is useful information or the information that accounts for $\Delta\mathbf{F}$, $\mathbf{I_i}$are the different types of information, and **N** is noise, useless information, or information that produces entropy.

This last expression is consilient with Kolchinsky and Wolpert[9] definition of "accessible" and "inaccessible" components of information, although they refer to different processes.

Using these abstractions, we can write $\Delta\mathbf{F} \sim \Delta\mathbf{\Phi}$ as proposed by the fourth law[1], based upon empirical evidence so far. 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

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information **N** or noise. For now, the type of information, **Φ** or **N**, can only be assessed empirically by its effect on **F**. When increases in **F** are concomitant with increases in **Φ**, we may refer to 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, I propose to use **Φ** as a proxy for useful information, order, complexity, and negative changes in entropy, until better concepts are developed. The following examples may illustrate the issues.

Examples

Examples of far-from-equilibrium systems that suffer an increase in free energy coupled with an increase in information content.

Engine (heat)

All engines produce heat when working. Their combustion process is exothermic. That is, only part of the energy contained in the fuel is converted to work. Another part is dissipated as heat. In physics, the first part is called Free Energy, the second part Entropy. During the process, **F** diminishes. The concept of information is needed to explain the thermodynamic behavior of this system regarding how the engine produces work.

Cannon (powder and ball)

A cannonball placed upon a heap of fire powder will hardly move when the powder is burned. But if the fire powder is placed into a cannon with a cannonball on top, the work produced by the flying cannonball after the explosive burning of the constrained powder is very large indeed. The cannon has more structural information modulating the power liberated by the burning powder (see also Constructor Theory by [8]) than the heap of powder. Also, an engine has structural information that converts fuel to power. But not just any border conditions or structure will do. The information relevant to obtaining this free energy **F** we call useful information **Φ**.

Division of Labor

Already, Adam Smith recognized that the division of labor confers greater economic capabilities on systems employing it. That is true for ants and for human societies alike. Evidence at the country level worldwide seems to suggest that a more complex division of labor (more sophisticated technological networks) leads to more economic output[22]. This increase in information production by country seems to be based mainly on increases in information in the natural sciences[23]. Thus, higher **Φ** produces more **F**.

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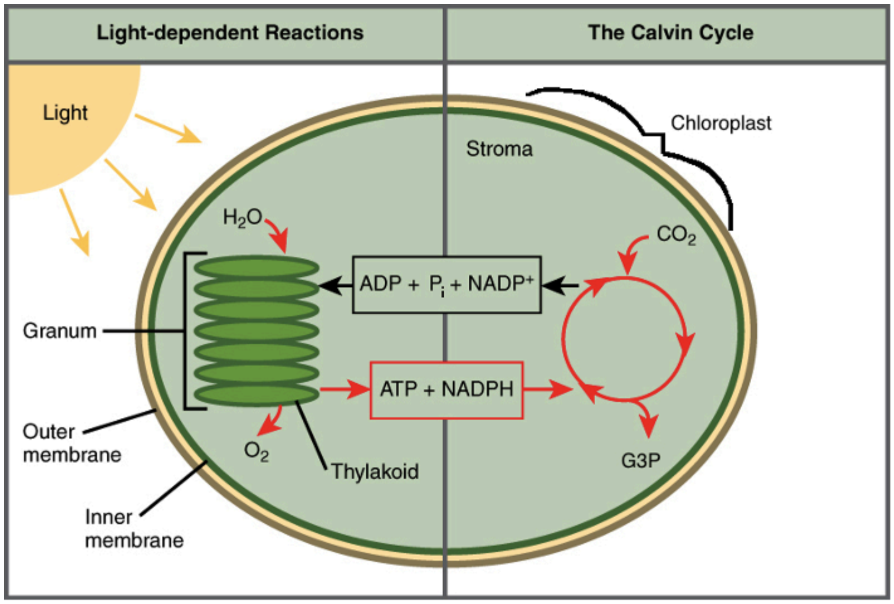
Photosynthesis



A clever catalytic arrangement of molecules in an organelle in plant cells called the chloroplast transforms light energy, water, and carbon dioxide into oxygen and energetic organic molecules (glucose). The process is endergonic in that it absorbs energy from the environment in the form of light photons and transforms it into chemical energy. It produces Free Energy **F** due to its highly complex structural information content **Φ**.

Life and Sex

Erwin Schrödinger made the famous remark, "What an organism feeds upon is negative entropy," referring to the fact that the organism succeeds in freeing itself from all the entropy it cannot help but produce while alive. But it is also often stated that life feeds on negentropy, which in addition implies it consumes order that it harnesses for its benefit. I recommend avoiding the term negentropy and using that of Information instead. Information management is a fundamental requirement for evolution among living organisms[24], and it allows the incremental achievement of synergies that favor evolution. Specifically, sex achieves increases in genetic information that increase the useful information (**Φ**) for future generations. Life is a complex system that invented sex and cognition as a means to accelerate evolution to manage increments of **Φ** thanks to natural selection. That is, useful information (∆**Φ**) produces increments in free energy (∆**F** >**0**). As ∆**F** helps access more information, triggering an evolutionary process aiming at ever more complexity and more **F** and **Φ**, it is possible[25]. This process is analogous to that described as autopoiesis by Maturana and Varela[26]. From the present perspective, natural selection favors useful information and discards the useless kind.

Socioeconomic and Politics

The more complex and multilevel a system is, the more tangled up the information dynamics become. Free energy may be reduced by a lack of adequate information or by an excess of misleading information, such as excess religiosity[27]. Canova et al. [19] showed that wordy, long constitutions using many populist words are typical of

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countries with high infant mortality and a low rule of law. The opposite relation also holds: countries with short constitutions rank high in socioeconomic indices. This excess of wrong information may lead to the loss of useful information. An everyday concrete example of this, for me, is the deterioration of wealth and the smooth functioning of a society due to misleading or wrong information and the dismissal of scientific information. At the moment of writing this article, an electricity blackout is hindering my connection to the internet in Caracas (and my ability to cook, to have air-conditioning, hot water, music, etc.). By exploring the deep causes of the blackout, I discovered that the electricity network where I live was installed some 80 years ago. Thanks to a political revolution 20 years ago, most experts and people with knowledge about the electricity network have retired or left the country (I live in Caracas and write this in May 2023). More impactful was the dismissal for political reasons by Hugo Chavez in 2003 of about 18,000 engineers and highly trained personnel from the state oil company. This personnel was substituted by politically chosen personnel with scant professional qualifications. This brain drain provoked a reduction in oil extraction in Venezuela from 3.2 million barrels a day in 2002, dropping to 2.5 million in 2008, and to about 0.5 million in 2022. The same misleading politicized information led to the exile of over 7 million citizens, 2 million of them with university degrees, causing the collapse of the productive infrastructure of the country and an increase in economic activity in countries receiving the migrants.

Conclusion

Our conclusion is based on the sample of examples given above and on 15 more detailed quantitative empirical studies presented in (Jaffe[1]). It takes free energy to acquire information, and it takes information to increment free energy. This is the meaning of $\Delta\mathbf{F} \sim \Delta\mathbf{\Phi}$**.** This definition is consilient with that given by the Constructor Theory[8] and the Constructal-theory[28]. One way for information to increase free energy is by reducing entropy; but other more direct means are also possible in open systems. Information and energy are two different physical concepts: energy obeys all laws of thermodynamics, information may not. For example, information seems to increase in time concomitantly with entropy[29][30]. This might be due to the fact that entropy favors errors and mutations, which reflect in increases of information. Information can be structural or otherwise, and its action or connection to energy is studied mostly by applied sciences such as engineering, computer sciences, genetics, biotechnology, experimental social sciences, and experimental law.

These conclusions imply that $\Delta\mathbf{\Phi}$ is not necessarily related to $\Delta\mathbf{S_e}$. That is, more or better information ($\mathbf{\Phi}$) may reduce the production of entropy in a process (increase efficiency) and thus increase the free energy of the open system (**F**); but it might increase both, kinetic entropy ($\mathbf{S_e}$) and free energy (**F**), but at different rates, by allowing the system to capture more energy from the environment. But **F** may only increase if $\mathbf{\Phi}$ does, when no external flux of energy exists. However, increases of the wrong kind of information might reduce **F**, as the effect of fake news on social harmony and many other examples attest.

Multidimensional Systems and Emergence

A **multidimensional system** is a system in which more than one independent variable exists. Possible independent variables are, for example, time, color, odor, selection pressure, utility function, consilience, energy, information, etc. In multidimensional systems, the output often depends on more than one input. Multidimensional systems are used to model complex phenomena, such as the

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weather, human behavior, societies and their dynamics, the stock market, and life. However, most mathematical developments deal with up to 2 to 3 spatial dimensions. Some even include a fourth dimension: time. But very few include more. String theory includes up to eleven or more dimensions, but all these dimensions are mathematical constructs and have no known relation to reality.

Structural information emerges as a kind of multidimensional type of information, as relevant information can be stored in different elements in a multidimensional system. A social structure, for example, must account for the different types of factors affecting its dynamics, some of them based upon very different dimensions. Thus, emotions run on different natural laws than rational thinking, which in turn is dissociated from ecological constraints or from psychological experience. Each of these factors requires a different dimension if we want to have an integral model of the system.

A single organism is dependent on features in multiple dimensions. The anatomical and physical constitution of the organism limits its possibilities to interact with space, whereas its metabolic structures limit its possibilities to extract order (to feed) from the environment, and its neurophysiological systems constrain its cognitive capabilities. All these features run on different dimensions that are required to describe an organism. Other dimensions such as chemical composition, physical features, energetic requirements, etc., are additional dimensions to be taken into account.

This is also true for the information dimension of any object, including organisms and societies. Interactions between different dimensions produce synergy and create novel properties of the system.

Emergence is a somewhat confusing term. It might refer to order or to complexity. In both cases, it relates to information but in different thermodynamic conditions. A salt solution spontaneously settles into a crystal, and thus, a spontaneous order emerges. But a seed spontaneously develops into a tree, and a very much more complex order emerges. Both cases are referred to as self-organized. During crystallization, the chemical potential of the solution is lost, diminishing **S** and **F** of the system. For systems experiencing synergy, **F** increases while **S** decreases. Both phenomena are called self-organized emergent order, but one process describes equilibrium thermodynamics, whereas the other describes a far-from-equilibrium dissipative structure. Thus, the term self-organization is too general to be useful. Here, I use the term emergence in the sense that synergetic processes allow novel properties to emerge.

In physics, emergence is the phenomenon of a complex system exhibiting properties that are not present in any of its individual parts. For example, a colony of ants can exhibit emergent behavior such as collective foraging, even though each individual ant is simply following its own instincts. This is also true for energy and entropy. In many complex systems with multiple types of energy, **F** and **S** can be hard to measure. Some kind of energy is an emergent phenomenon of the interactions of other types of energy. A chain of emergent systems can be envisioned as follows:

The atom

Subatomic particles assemble to form atoms. Quantum mechanics and nuclear physics are in charge of studying these processes. Nuclear forces and electromagnetic interactions are involved in these processes.

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From atoms to molecules

Atoms form chemical bonds between them, producing ensembles of atoms called chemical compounds. Chemistry is the science studying these emergent phenomena. Here, nuclear forces play a negligible role, and electromagnetic forces are prevalent.

From molecules to cells

Molecules aggregate in complex ways with a high degree of structural information to form biological cells. Cell biology and biochemistry are in charge of studying these emergent phenomena. Mechanical and chemical forces are prevalent in the functioning of these systems.

The working of catalysts

As a fundamental part of the interactions of molecules and cells in achieving emergent phenomena, catalysts, a special science, is dedicated to studying them. These catalysts are able to direct mechanical and electromagnetic forces to a small part of the system, allowing for the appearance of modulation of free energy by structural information. They achieve this by providing spatial-temporal information so as to synchronize processes and reactions that allow synergies to emerge.

From cell to organisms

Cells aggregate in complex ways with a high degree of structural information to form multicellular organisms. Medicine and organismic biology study them. Organisms develop cellular systems (brains, for example) that form networks of neurons that can store and process information in ways a single cell cannot. Cells and organisms of different kinds can form functional groupings called Holobionts, or can assemble to form ever more complex systems.

From organisms to society and ecosystems

Sociology and sociobiology study the emergent properties of groups of organisms. Ecologists study the emergent properties of groups of diverse types of organisms. Here, layers of different structural information guide mechanisms to harness free energy of diverse forms. Some of these emergent forms are forces and energies that emerge from interactions of these at lower levels (The most recent paper is [31]). So we can speak of social and/or ecological forces that are products of myriads of interactions of subsystems. But such forces, even if they are emergent, can be measured, and their effect on other systems can be monitored. Social networks store and process information in much larger amounts than individual organisms can, allowing the emergence of culture. Culture can produce machines to store and use information, such as computers.

The emergence of emotions

The interaction between perceived signals from outside our organism, with neurophysiological signals activating networks of neurons and glia, such as the action potential of neurons, filtered transmission of neuronal communication, and hormones that communicate with all parts of our body, is perceived by our proprioceptors, producing feelings, some of which we call emotions. The emergent psychological forces are the drivers of behaviors and drive the production of new levels of information. Love is a complex emotion that emerges from the interaction of many factors, including memory, physiology, motivation, culture, personal

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experience, and more. It is essential for the formation of strong, lasting bonds between people, which in turn are necessary for the survival and successful development of offspring. Love uses information to increase free energy, and free energy is needed to acquire more information. In colloquial words, love requires us to invest energy in our relationships, but this investment pays off in the long run by increasing our psychological and material well-being. Love has its evolutionary origins in biological reproduction, but it has expanded its role in human society. In addition to promoting reproduction, love can also foster creativity, innovation, and other adaptive behaviors. This is because love taps into the same instinctive and cognitive tools that we use for mate selection.

The emergence of conscience

With neural networks and social networks, new possibilities emerge, such as the mind, for example (The most recent paper is [32]). The interactions of hormones with physio-electric signals, emotions, neuronal memory, anatomical memory, complex molecular structures embedding information in synapses, high-level information stored in networks of neurons, superimposed upon networks of glia, proprioceptors, and sensory receptors that maintain constant contact with itself and the environment, produce emergent properties that we call conscience. Conscience cannot exist without any of its components. A simplified version of consciousness states that it is the capacity to view the position of oneself in the environment, to forecast, even with errors, the effect of one's action on the environment and vice versa, and to plan actions according to a desired goal. If so, most animals have a certain degree of consciousness. Intelligence and science are the next steps of emergence that accelerate their development with the inclusion of computer networks and artificial intelligence.

Conclusion

When more than one dimension of reality interacts, novel properties emerge. By knowing the individual properties of Hydrogen (H) and Oxygen (O), we cannot predict those of water (H_2O), despite the fact that water contains only hydrogen and oxygen.

Each level of complexity draws upon other levels of lesser complexity. Any science studying the interaction between levels of complexity must be aware that jumping between levels that are far apart will result in huge errors in the interpretation of the knowledge between the different sciences studying each level. Two examples show that such inter-level extrapolation in science risks misleading us. Trying to explain consciousness using only knowledge from quantum mechanics, for example, without ensuring consilience between the sciences studying the intermediate levels of complexity[33], is sure to produce more noise than knowledge and is best left to charlatans. The other example is economics. It is clearly a multidimensional dynamic system. Trying to explain economic behavior using simple models such as Rational Utility Functions, or even apparently more sophisticated tools of experimental economics such as "The Prisoner's Dilemma," without attending to emotional dimensions, expectations, social positioning, past experience, moral dimensions, learned attitudes towards strangers, and elements studied by sociobiological ethology, is a dysfunctional approach most likely to produce only noise.

A difference regarding information between the various levels of emergent complexity is the type of structural information relevant to producing free energy in each case. The curious fact expressed in a proposition for a fourth law of thermodynamics is that at all these levels, increases in free energy are always

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associated with increases in information[1]. This is true for processes occurring in open systems that are far from thermodynamic equilibrium. This relationship between information and energy drives synergies that produce unexpected results, and often new dimensions of organization emerge.

Energy, Information, and Emergence

Summarizing our proposition, we redefine:

Emergence is the phenomenon whereby complex systems exhibit properties that are not present in their individual components, and it provides a framework for understanding the effect of information on the production of free energy in the system, including those of living systems.

Infodynamics. Complex multi-component systems increase their free energy by discovering novel ways for their component parts to interact with each other and with their environment. Novel ways that unleash synergies that augment the free energy of the system will be selected by evolutionary processes of natural selection. Thus, the concept of fitness in evolutionary biology actually refers to a free energy or useful energy in terms of the survival of an organism or gene pool. These novel ways represent new information that must be stored and transmitted for future interaction of the system. However, there is no theoretical recipe to discover useful information. Only by empirically finding that the information produces free energy do we know it is useful. In evolutionary terms, complex systems need heuristic mechanisms to produce information which then is selected according to its usefulness, or discarded if shown to be noise.

Thermodynamics, information theory, and emergence are all interconnected but not in a straightforward way. We can summarize our exercise, the conceptual decantation of this relationship, to the formula:

$\Delta \mathbf{F} \sim \Delta \mathbf{\Phi}$

where $\Delta \mathbf{F} = \Sigma \Delta \mathbf{E_i} - \Delta \mathbf{S}$ and $\Delta \mathbf{\Phi} = \Sigma \Delta \mathbf{I_i} - \Delta \mathbf{N}$

The proposition is:

$\Delta \mathbf{F} = \Sigma \Delta \mathbf{Ei} - \Delta \mathbf{S} + \mathbf{k_1} \Delta \mathbf{\Phi}$

and

$\Delta \mathbf{\Phi} = \Sigma \Delta \mathbf{I_i} - \Delta \mathbf{N} + \mathbf{k_2} \Delta \mathbf{F}$

where $\mathbf{k_1}$ and $\mathbf{k_2}$ are constants to be assessed experimentally

This means that we have two coupled realities: that of thermodynamics and that of infodynamics, and both are transformed by emergence. The different types of energy ($\mathbf{E_i}$) and of information ($\mathbf{I_i}$) in multidimensional systems have to be identified in order to understand this dynamic relationship. No theoretical guide for it exists today, but only empirical exploration helps in this identification. To advance, we need more efforts in bridging the communication gap between the different disciplines involved in studying these phenomena so as to accelerate the growth of knowledge we have about these concepts and make them more useful for eventual practical and theoretical implementations.

Useful information increase ($\Delta \mathbf{\Phi} > \mathbf{0}$) produces increments in free energy ($\Delta \mathbf{F} > \mathbf{0}$). As $\Delta \mathbf{F}$ helps access more information, as evolutionary processes powered by natural selection achieve ever more $\mathbf{\Phi}$, more $\mathbf{F}$ is possible. Increases in entropy ($\Delta \mathbf{S} > \mathbf{0}$) decrease free energy ($\Delta \mathbf{F} < \mathbf{0}$) and might affect the amount of useful information available in the system ($\Delta \mathbf{\Phi} < \mathbf{0}$). More noise or misleading information ($\Delta \mathbf{N} > \mathbf{0}$) decreases useful information ($\Delta \mathbf{\Phi} < \mathbf{0}$) which decreases free energy ($\Delta \mathbf{F} < \mathbf{0}$).

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These complex relationships help us to better understand the evolution of life, societies, and ecosystems and make the creation of independent artificial life feasible. Analogous explanations for this phenomenon include what has been referred to as The Edge of Chaos[34] and Autopoiesis[26]. I believe the rationale exposed here is easier to operationalize.

Research can identify changes in useful information (∆**Φ**), producing changes in free energy (∆**F**), quantify their relationship in different complex, open, far-from-equilibrium systems, and identify modulators and constraints of this relationship. This may help in focusing on relevant features of these complex systems. What we know so far is that the proposed law for far-from-equilibrium thermodynamics[1] has many examples to support it and has not been shown to be false so far. The present conceptual clarification might help in eventually falsifying this proposal. A better understanding of information might allow us to deduce this proposed rule from other more fundamental laws. Despite very broad and impressive empirical knowledge in many disciplines, we have only a very superficial grasp of the relationship between information and work, or in abstract terms, between ∆**F** and ∆**Φ**. Research in the relation between infodynamics and thermodynamics can change our future!

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Author Contributions

KJ conceived and wrote the manuscript.

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No new data were created or analyzed in this study. This study is a theoretical review and synthesis based on previously published work cited herein.

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