Research Article

A Law for Irreversible Thermodynamics? Synergy Increases Free Energy by Decreasing Entropy

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Synergy is defined as an interaction giving rise to a whole that is greater than the simple sum of its parts. Here I explore empirically some thermodynamic properties of phenomena that are intuitively recognized as synergetic in a wide range of disciplines, searching for common features. In all cases studied, a decrease in entropy (S) was coupled to an increase in free energy (G). This is congruent with the assumption of the first and second law of thermodynamics that the total energy in a closed system is constant and is the sum of G and S. As no law of thermodynamics was deduced by theory but originated by pure empirical data, I propose a law for open synergistic systems that states that increases in G are coupled to decreases in S, allowing to thermodynamically recognize synergy. Open systems where S decreases without increases in G are not synergetic. This insight can be applied in a wide range of disciplines in natural and social sciences.

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Introduction

Nomenclature: G: Energy; S: Entropy; -S: Negentropy; G Free Energy; Δ: Change.

Classical thermodynamics focused on reversible processes in closed systems. Most processes however are irreversible, in both closed and open systems. A non classical thermodynamics is being developed to tackle complex open systems suffering irreversible processes. That is the case for Synergy that emerges from synchronized reciprocal positive feedback loops between a network of diverse actors. For this process to proceed, compatible information from different sources synchronically coordinates the actions of the actors resulting in a nonlinear increase in the useful work or potential energy the system can manage. In contrast noise is produced when incompatible information is mixed. This synergy produced from the coordination of different agents achieves non-linear gains in free energy and in information (negentropy). Free energy G can be estimated by proxies such as individual autonomy of an organism, emancipation from the environment, productivity, efficiency, capacity for flexibility, self-regulation, and self-control of behavior; whereas entropy S, or the lack of it, is revealed by the degree of synchronized division of ever more specialized labor, structural complexity, information, and dissipation of energy. Here I present empirical data that provide quantitative and qualitative data for G and S that show that increases in free energy density are concomitant with decreases in entropy density. I propose this as a rule for synergistic processes in non-equilibrium thermodynamics, which is consilient with the first and second laws of classical thermodynamics. Under this light, biological evolution is the task of self reproducing irreversible synergistic systems to discover empirically (through natural, inclusive, and sexual selection) types of order that increase their free energy.

Human knowledge has been advanced in different ways and with different methods, but during the last few centuries, the scientific method has proved to be the most efficient and productive in advancing our understanding of the world and ourselves[1]. This method is often thought not to be applicable to certain realms of our knowledge such as humanities and many social sciences. However, complex system science has allowed us to extend the empirical scientific method to a much broader range of the social sciences[2]. This exercise has opened opportunities to refocus on fundamental dynamical properties of complex social systems that were formerly regarded as not computable and dismissed as irreversible far-from-equilibrium phenomena. Specifically research with non-equilibrium thermodynamics has shown its potential to tackle complex issues (see review by [3] for example). In addition, complex system sciences has allowed us to tackle quantitative issues that were regarded as diffuse, but important, such as synergy[4]. Synergy has been found to be a very useful heuristic concept, both in natural and social sciences. The present work attempts to present a coherent review of a large number of scattered experimental results, produced over decades of research, in different areas of science, by my laboratory. This summary may be relevant. The intuitive idea underlying this effort is that biological evolution is the task of self reproducing irreversible synergistic systems that discover types of order that increase their free energy[5][6].

The oldest use of the term synergy in the scientific literature that I could find is from 1910 by the physiologist Charles Scott Sherrington[7]. He pointed out that the modular organization of the motor control system is based on the flexor reflex as the mother of all modules and synergies, He proposed that

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stepping was basically a series of flexion reflexes, with extension occurring merely as the "rebound" following the flexion. The extension during the stance phase of gait could be provided as some type of "extensor thrust," evoked by "the weight of the animal applied through the foot against the ground". His experimental studies on reciprocal innervation of muscles showed that the relationship between the effort made as input and the work output was nonlinear and had synergistic properties, winning him the Nobel Prize in Physiology and Medicine in 1932.

Today, the terms synergy, synergetic, and synergies have acquired a multitude of meanings. My aim here is to propose a definition that can be applied across different disciplines and is amenable to quantitative exploration.

Materials and Methods

Summary of past research by the author. Other relevant research is available in abundance but measuring tools and concepts used to devise them differ. In order to avoid comparing different physical quantities used as proxies for entropy in the different studies, I restricted the data used to those I produced myself. This work aims to produce a blueprint for more extensive reviews and research in the future.

Results and Discussion

One of the first scientific studies on synergy was performed by a physiologist working on neuro-muscular interactions[7]. This is the earliest scientific reference to synergy I could find. Then researchers introduced the concept into mainstream physics[8]. At the same time, engineering started to exploit this concept successfully[9]. Synergy was thus established as a phenomenon that emerged in complex open systems and had non-linear properties in increasing the output variable of a process exponentially instead of geometrically. With advances in irreversible thermodynamics applied to open systems, as contrasted with classical equilibrium thermodynamics that apply to closed systems, we can group dynamic phenomena of open systems in at least four categories. I will refer to them as: Dissipation, Aggregation, Equilibration and Synergizing.

Dissipation refers to processes where energy and entropy is released by the system. A classical example is combustion, where a low entropy material, such as wood, is transformed into a high entropy mix of gasses and heat. Here, G decreases as less wood will be available, and S increases as the entropy of the gas mix will be higher than that of the wood that originated them through combustion.

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Aggregation occurs when resources are accumulated, such as in warehouses, or armies expand the territory of a nation, sediments accumulate on the bottom of a dam, or wealth in the stock-market. Here, both S and G increase, as more produces larger possibilities for work and larger possible arrangements between the parts.

Equilibration or drifting to equilibrium occurs when a system is not disturbed and natural forces act to minimize both S and G. A classical example is crystallization, where a high entropy salt solution settles as a crystal, reducing S and G in the system.

Synergizing process are those where S production is reduced or delayed and G is increased due to a clever use of constrained border parameters. For example, a cannon ball 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 cannon ball on top, the work produced by the flying cannonball after the explosive burning of the constrained powder is very large indeed.

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The cannon produces work (G) through a device that achieves a reduction of S. But once the explosion has occurred, the energy of the explosion is dissipated. Thus, S is reduced only if the appropriate time window is taken into account. It seems then that a Law of Thermodynamics exists, where the more border constraints, information, or structures defining the system, are present, the less Entropy (S) the system has, and the more Work (G) a system can produce. Life can then be defined thermodynamically as an open self-reproducing multi-component synergistic system (see also autopoiesis by Humberto Maturana[10]).

A summary of the differences between these four processes that might occur in open systems is given in Table 1.

Name	ΔG	ΔS	Process	Example
Dissipation	-	+	Combustion	Engine
			War	Losing army
			Stock market	Unlucky broker
Aggregation	+	+	War	Winning army (Sometimes)
Equilibration	-	-	Crystallization	Salt Solution
Synergizing	+	-	Life	Table 2

Table 1. Processes that might occur in open systems

Note that only in crystallization and synergic systems does S diminishes. This phenomenon is often called emergent order. But during crystallization, the chemical potential of the solution is lost, diminishing G of the system. Only for Synergy does G increase while S decreases.

Both ΔG and ΔS can be measured and quantified. Table 2 presents the different systems where quantitative data of a synergistic process have been published. In all of them, G increased and and S decreased, although the way these quantities were measured varied. In data for Table 2 as published before[11], the synergistic systems assumed no increasing influxes of G from the outside that could affect ΔG.

Example	Entropy measure	W Measure of work output	P(W) Ratio W	P(N) Ratio Negentropy	P(W)/P(N)
1a	Social Complexity in Myrmicinae ants	Efficiency in energy consumption	1.70	2.00	0.85
1b	Social Complexity in Attini ants	Efficiency in energy consumption	2.00	2.20	0.91
2	Social complexity in aggregates	Exponent of energy efficiency function	2.50	2.60	0.96
3	Scientific development	Economic development	2.60	3.10	0.84
4	Division of labor	Economic efficiency	2.96	3.00	0.99
5a	Brain Complexity	Polymorphysm	2.70	4.00	0.68
5b	Brain Complexity	Log Colony size	3.00	4.00	0.75
6a	Spanish text	Readability	1.05	1.14	0.92
6b	English text	Readability	0.93	1.06	0.88
6c	Spanish text	Nobel Prize / average	> 1	1.14	-
6d	English text	Nobel Prize / average	> 1	1.06	-
7a	Entropy in music	Popularity	> 1	1.04	-
7b	Entropy in music	Number of instruments	> 1	1.10	-

Table 2. Impact of synergy estimated for several types of systems using a proxy estimate of free energy or useful information to perform work (W) and the negentropy of the system (N). Data is presented in unit-free scalars calculated from as the proportional change (P) in the system after the synergistic process divided by the value before this process

The system studied were:

1. Social complexity of ant societies, measured as colony size and polymorphism in worker castes, and the minimal cost of its maintenance[12].

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2. Size of social aggregates of ant colonies and of human cities and their relation to social synergy measured as energy consumption[13]
3. Quantitative data of the complexity of the scientific system of a nation and economic growth[14][15][14].
4. The working of division of labor and the invisible hand in simulations of virtual economies[16]
5. The relationship between brain complexity and size of ant societies and their complexity regarding worker polymorphism[17]
6. The entropy content of texts and their literary quality and readability in two languages[18][19].
7. The entropy content of pieces of classical music and their popularity achieved.[20]

System	Finding	Reference
Ants	Social complexity and colony size increases as energy consumption per capita decreases	[13]
Termites	Increased colony size reduces energy consumption per capita	[21]
Termites	Optimization in foraging network architecture	[22]
Ant Society	More social species have more complexity polymorphic colonies	[23]
Ant Recruitment	More social species have more complexity chemical communication systems	[24]
Ant Brain Anatomy	More social species have better developed corpora pedunculata	[17]
Computer	Multiple scales of complexity	[25][26][27]
Simulations	Division of labor is evolutionary sustainable only if it produces synergistic effects	[16][28]
Quality of Literary Texts	Nobel prize winners produce texts richer in word diversity, decreasing Shannon entropy	[20][29][18]
Text readability	Readability of a text relates to their entropy content in English and Spanish	[30][31]
Music	MIDI entropy of classical music decreases in more recent composers	[19][29]
Human economies	Economic development increases as scientific development expands	[32][15][33]
Human Cities	Per capita electricity consumption decreases in cities of different countries as their size increases	[34]
Governments	Countries with a strong Rule of Law have low infant mortality and a high Human Development index.	[35][36]
Constitutions	Countries with a long constitution under perform in indices like infant mortality and Human Development index.	[35][36]
Populism	Countries with many populist words in their constitution underperform in Human Development	[36]

Table 3. Synergistic processes in open system where ∆G increases while ∆S decrease (Data from Table 2 was expanded including qualitative studies)

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We now have an instrument to recognize synergy when it is present: Increases Free Energy and decreased Entropy. Using this tool we can identify features present in all situations where synergy has been identified. These are: Open systems that harvest energy and negentropy fluxes in the environment, where Diversity, Cohesion, Synchrony and Complementarity occur between the parts of the system, constraining border conditions (S) to increase the potential to do work (G). The constraints of the border condition can be measured as information or complexity. When these open systems self-reproduce we have life. Analogous conclusions have been presented by other authors. For example the concept of Autopoiesis[37] and a proposed Fourth Law of Thermodynamics by [38].

Cases where Free Energy increases without a decrease in entropy are unknown to me. Cases where entropy decreases without increases in Free Energy have been reported[36] and can be regarded as sclerotizing or accumulation of spandrels[39] and should be investigated further. That is, using the example of the cannonball and the powder, if the cannon ball and powder are placed on top of a high tech quantum computer, no increase in the free energy of the cannonball can be expected. These and other possibilities extend the classification of irreversible processes given in Table 1 and allow for a more complete table of possible irreversible processes as given in Table 4.

Name	ΔG	ΔS	Process
Dissipation	-	+	Combustion
Aggregation	+	+	Energy capture
Equilibration	-	-	Crystallization
Synergetic	+	-	Life
Hell	-	0	Unknown
Heaven	+	0	Unknown
Sclerotic	0	-	Spandrels
Neutral	0	+	Degradation

Table 4. Processes that might occur in open systems

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Conclusion

No law of thermodynamics was deduced by theory. They are the outcome of pure empirical experience. Increases in entropy are coupled to decreases in free energy in closed systems as acknowledged by the first and second law of thermodynamics: The total energy in a closed system is constant and is the the sum of free energy G and entropy S. Here we show that G and S are also related in certain open systems which we classify as synergistic systems. The sum of entropy and energy, however, is not straightforward in irreversible processes as different dimensions of entropy may intervene. This feature makes it very hard to use a uniform unique scalar to measure S and G.

Although precise quantitative measures of energy information or complexity are reported here for specific studies, I believe much more research is needed to achieve this goal. A synergistic open system increases the production of work only with more non redundant border constraints i.e. information, structure or complexity. Other kinds of order may diminish dissipation or potentiate production of free energy by other means by reducing entropy. Not any kind of increased order increases free energy. Negentropy achieved by rigid structures or mismatched interactions diminish free energy. Empirical exploration or experiments are often the only way to discover the appropriate kind of order required to increase the free energy of a given system[4]. A thermodynamic asymmetric law deduced purely by empirical means, making it is less likely to suffer from distorting preconceptions and dogma[1], seems to indicate that increases in G density require decreases in S density: $\Delta G = F(\Delta S)$, but not the other way. Under this light, biological evolution is the task of self reproducing irreversible synergistic systems to discover empirically (through natural and sexual selection) types of order that increase their free energy. Defining entropy is not straight forward. In the paper we present data (detailed in the references) for metabolic energy, electric energy, Kolgomorov complexity, Shannon information, systems size, and subjective complexity. The challenge for future research in this area is to devise means to actually measure entropy and to define the different dimensions where entropy is found (energy, information, structures, border conditions ....).

As with other laws of thermodynamics, this one only points to what is not possible (synergy with increases in G without decreases in S). This of course is very easy to falsify, A single clear example will do it. The present insight might help avoiding blind streets and to favor serendipity to discover laws of nature. The realm of the possible negentropies is infinite, but only a few may increase ΔG. Solutions to complex multidimensional problems can be found through empirical experimentation and exploration, in both, social and natural science. Biological and cultural evolution seem to work in this way as some evolutionary stable processes depend on the existence of synergy for their evolutionary maintenance such as altruism[40], Science[1], economic markets[28], and sex[41]. The best phrase I know of, synthesizing this subject is "Living organisms feed on negative entropy" Schrödinger coined the best phrase I know of, synthesizing this subject: "Living organisms feed on negative entropy"[42].

An interesting finding here is that the increase in G requires decrease in S. This can be stated as the fact (or law) that the production of Free Energy, that produces useful work, requires useful information, approximated here as -S. This reality, together with the empirical fact that getting information requires energy[43], constitute the foundation of Infodynamics, the science that studies the interactions between information and energy, as presented in more detail elsewhere[44]. The relationship between S and information is confusing, as the meaning of S in Information Theory differs from that used in Thermodynamics[45].

Many more examples of synergy exist for which this principle may apply, from the quantum chemistry of vision (capture of photons to trigger an action potential in a neuron), photosynthesis, (capture of the energy of a photon to catalyze a chemical reaction) to symbioses (cooperation between two different species for the advantage of both), and socioeconomic processes among human society (see comment by T. Sosa in a former version of this paper: https://www.qeios.com/read/Z7CJ0M). I hope a new generation of scientists might engage in this exploration.

Statements and Declarations

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No potential competing interests to declare.

Author Contributions

KJ conceived and wrote the manuscript. This study is a theoretical review and synthesis based on previously published work cited herein.

Data Availability

No new data were created or analyzed in this study.

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