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

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Abstract

Classical laws of thermodynamics apply only for reversible processes. Most processes however are irreversible and occur in open systems. That is the case of 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 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, 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. Empirical examples that provide quantitative data for these phenomena are presented. Results show that increases in free energy density are concomitant with decreases in entropy density. This may be a rule for synergistic processes in irreversible 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 system to discover empirically (through natural and sexual selection) types of order that increase their free energy.

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Nomenclature

ΔG	Change in Free Energy
ΔS	Change in Entropy
M	Mass
C	Complexity
Cr	Redundant Complexity
Co	Non-Redundant Complexity
I	Information (Ir, Io)

Introduction

Human knowledge has been advanced is different ways and with different methods, but during the last few centuries, the scientific method has proofed to be the most efficient and productive in advancing our understanding of the world and ourselves (Jaffe 2009). 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 (Jaffe 2014). This exercise has opened opportunities to refocus on fundamental dynamical properties of complex social systems that where formerly regarded as not computable and dismissed as irreversible, far-from-equilibrium phenomena, that can not be a analyzed with thermodynamic sciences. Again, complex system sciences have allowed to tackle quantitatively issues that were regarded as diffuse, but important, such as synergy (Jaffe 2020). 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 by laboratory. This summary may be relevant to thermodynamics as applied to complex open systems suffering irreversible processes. The intuitive idea underlying this effort is that biological evolution is the task of self reproducing irreversible synergistic system that discover types of order that increase their free energy (Smith 2008, Frank 2009).

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 works 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 physiologist working on neuro-muscular interactions (Charles Scherrigton). This is the earliest scientific reference to synergy I could find. Then researchers introduced the concept into mainstream physics (Haken 1981). At the same time, engineering started to exploit this concept successfully (Buckminster Fuller). The concept synergy was thus established as a phenomenon that emerged in complex open system 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 gases 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 though combustion.

Aggregation occurs when resources are accumulated, such as in warehouses, or armies expand the territory of a nation, sediments accumulate of 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 is the process 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 cannon ball after the explosive burning of the constrained powder is very large indeed.

The cannon produces work (G) through a devise 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 exist, 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).

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

Table 1. Processes that might occur in open systems

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

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 (Jaffe & Febres 2016), the synergistic systems considered 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 type 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 (Jaffe & Hebling-Beraldo 1993).
2. Size of social aggregates of ant colonies and of human cities and their relation to social synergy measured as energy

consumption (Jaffe 2010)

3. Quantitative data of the complexity of the scientific system of a nation and economic growth (Jaffe et al. 2013a, b and Jaffe, Rios, Florez 2013a).
4. The working of division of labor and the invisible hand in simulations of virtual economies (Jaffe 2015)
5. The relationship between brain complexity and size of ant societies and thir complexity regarding worker polymorphism (Jaffe & Perez 1989)
6. The entropy content of texts and their literary quality and readability in two language (Febres, Jaffé, Gershenson 2014 and Febres & Jaffe 2015).
7. The entropy content of pieces of classical music and their popularity achieved. (Febres & Jaffé 2016)

Table 3. Synergistic processes in open system where ΔG and ΔS have been quantified empirically (expanded from Table 2 to include qualitative data)

System	Entropy estimate	Free Energy estimate	
Ants and Termites	Social complexity	Energy consumption	Griffon, et al 2015; Jaffe 2010; Muradian et. al. 1999
Human Cities	Size as complexity	Electricity consumption	Cabrera & Jaffe 1998.
Human economies	Scientific development	Economic development	Jaffe 2013b
Social Simulations	Division of labor	Economic efficiency	Jaffe 2015. 2017
Ant Anatomy	Brain complexity	Polymorphism, Colony size	Jaffe & Perez 1989
Literary Texts	Text entropy	Literary impact (NP)	Febres & Jaffe 2016, 2017, Febres et al 2014
Music	MIDI entropy	Popularity	Febres & Jaffe 2015, 2017
Human Organizations	Organizational structure	Functional performance	Jaffe et al 2021,2022

We have now 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 constrains 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 Autopoieses by Humberto Maturana and the Forth Law of Thermodynamics by Stuart Kauffman.

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 (Jaffe et al 2022). These facts are summarized in Table 4.

Table 4. Miscellaneous processes that might occur in open systems

Name	ΔG	ΔS	Process
Hell	-	0	Unknown
Heaven	+	0	Unknown
Neutral	0	-	Evolution
Neutral	0	+	Degradation

Conclusion

Increases in entropy are coupled to decreases in free energy in reversible systems as acknowledged by the first and second law of thermodynamics: The total energy is the sum of free energy and entropy. Here we show that this also occurs in certain open systems which we classify as synergistic systems. The sum of entropy and energy, however, is not straight forward in irreversible processes as different dimension of entropy may intervene. 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 (Jaffe 2020). A thermodynamic asymmetric law deduced purely by empirical means, making it is less likely to suffer from distorting preconceptions and dogma (Jaffe 2009), 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 system to discover empirically (through natural and sexual selection) types of order that increase their free energy. I hope these data may widen our exploration of complex systems using thermodynamics.

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