

[Open Peer Review on Qeios](#)

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

Klaus Jaffe¹

¹ Universidad Simón Bolívar

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.

Abstract

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 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 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.

Klaus Jaffe

Universidad Simón Bolívar, Caracas, Venezuela

Keywords: Entropy, Free energy, Synergy, Thermodynamics.

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 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 (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 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 Prigogine 2017 for example). In addition, complex system sciences has allowed us to tackle quantitative 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 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 (Smith 2008, Frank 2009).

The oldest use of the term synergy in the scientific literature that I could find is from 1910 by the physiologist Charles Scott Sherrington (1910). 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 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, synergizing, 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 (Scherrigton 1910). 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 (Fuller 1982). 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.

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 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 cannonball after the explosive burning of the constrained powder is very large indeed.



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).

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 War Stock market	Engine Losing army Unlucky broker
Aggregation	+	+	War	Winning army Sometimes
Equilibration	-	-	Crystallization	Salt Solution
Synergizing	+	-	Life	Table 2

Note that only in crystallization and synergizing 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 S decreased, although the way these quantities were measured varied. In data for Table 2 as published before (Jaffe & Febres 2016), 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 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 their complexity regarding worker polymorphism (Jaffe & Perez 1989)
6. The entropy content of texts and their literary quality and readability in two languages (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 increases while ΔS decreases (Data from Table 2 was expanded including qualitative studies)

System	Finding	Reference
Ants	Social complexity and colony size increases as energy consumption per capita decreases	Jaffe 2010;
Termites	Increased colony size reduces energy consumption per capita	Muradian et. al. 1999
Termites	Optimization in foraging network architecture	Griffon et al 2015
Ant Society	More social species have more complexity polymorphic colonies	Holldobler & Wilson 1990
Ant Recruitment	More social species have more complexity chemical communication systems	Jaffe K. 1984
Ant Brain Anatomy	More social species have better developed corpora pedunculata	Jaffe & Perez 1989
Computer Simulations	Division of labor is evolutionary sustainable only if it produces synergistic effects	Jaffe 2015. 2017
Quality of Literary Texts	Nobel prize winners produce texts richer in word diversity, decreasing Shannon entropy	Febres & Jaffe 2016, 2017, Febres et al 2014
Text readability	Readability of a text relates to their entropy content in English and Spanish	
Music	MIDI entropy of classical music decreases in more recent composers	Febres & Jaffe 2015, 2017
Human economies	Economic development increases as scientific development expands	Jaffe 2013b
Human Cities	Per capita electricity consumption decreases in cities of different countries as their size increases	Cabrera & Jaffe 1998.
Governments	Countries with a strong Rule of Law have low infant mortality and a high Human Development index.	Jaffe et al 2021,2022
Constitutions	Countries with a long constitution under perform in indices like infant mortality and Human Development index.	Jaffe et al 2021,2022
Populism	Countries with many populist words in their constitution underperform in Human Development	Jaffe et al 2022

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 (Maturana & Varela 1991) and a proposed Fourth Law of Thermodynamics by Kauffman (2022).

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). 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.

Table 4. Processes that might occur
in open systems

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

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 (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 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 (Jaffe 2002), Science (Jaffe 2009), economic markets (Jaffe 2017), and sex (Jaffe 2018).

The best phrase I know of, synthesizing this subject is “Living organisms feed on negative entropy” (Schrödinger 1944)

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 socio-economic processes among human society. I hope a new generation of scientists might engage in this exploration.

Acknowledgments

Thanks are due to Soeren Nors Nielsen, Ying Xu, Masahiko Yamaguchi, Mahnoor Sarfraz, Rafael M Gutierrez, Burak Erman, Stefano Giordano, Sean Devine, Robert Ulanowicz, for their comments on this manuscript.

References

- Cabrera S, Jaffe K. 1998. On the energetic cost of human societies: energy consumption as an econometric index. *Interciencia* 23: 350-354.
- Febres G 2019. Basis to Develop a Platform for Multiple-Scale Complex Systems Modelling and Visualization: Monet. *J Multidis Res Rev* 1, 2 (35-46).
- Febres G Jaffe K. 2015. Calculating entropy at different scales among diverse communication systems. *Complexity* 2015 DOI: 10.1002/cplx.21746.
- Febres G and Jaffe K. 2016 Quantifying structure differences in literature using symbolic diversity and entropy criteria. *Journal of Quantitative Linguistics*, 24, 16-53.
- Febres G and Jaffe K 2017. Music viewed by its Entropy content: A novel window for comparative analysis. *Plos One* 0185757.
- Febres G, Jaffe K, Gershenson C. 2014. Complexity measures of natural and artificial languages. *Complexity* 20: 25-48; doi:10.1002/cplx.21529 2014.
- Flesch, R. 1951 How to test readability. New York: Harpe & Brothers.
- Frank, S.A. Natural selection maximizes Fisher information. *J Evol Biol* 22, 231-244.
- Georgiev, G. Y. et al. 2014 Mechanism of Organization Increase in Complex Systems. *ArXiv*:1301.6288. 1-12.
- Fuller, R.B., 1982. Synergetics: explorations in the geometry of thinking. Estate of R. Buckminster Fuller.
- Griffon D, Jaffe K, Andara C. 2015. Emergence, self-organization and network efficiency in gigantic termite-nest-networks built using simple rules. *Arxiv*1506.01487
- Hausmann R, Hidalgo CA, Bustos S, Coscia M, Chung S, Jimenez J, Simoes A, Yıldırım MA. 2011. The Atlas of

Economic Complexity: mapping paths to prosperity

- Haken H. 1981. The Science of Structure: Synergetics (Van Nostrand Reinhold)
- Humberto Maturana: https://en.wikipedia.org/wiki/Humberto_Maturana
- Holldobler B. & Wilson E.O. 1990: The Ants. Harvard University Press.
- Jaffe K. 1984. Negentropy and the evolution of chemical recruitment in ants. Journal of theoretical Biology, 106, 587-604, 1984
- Jaffe K, 2002. An economic analysis of altruism: Who benefits from altruistic acts? Journal of Artificial Societies and Social Simulations 5: 3, 2002
- Jaffe K. 2009. What is Science?: An interdisciplinary perspective. University Press of America.
- Jaffe K. 2010. Quantifying social synergy in insect and human societies. Behavioural Ecology and Sociobiology 64(11): 1721-1724.
- Jaffe K. 2014 The Wealth of Nations: Complexity Science for an Interdisciplinary Approach in Economics. Amazon books. ISBN 1503252728
- Jaffe K. 2015. Visualizing the Invisible Hand of Markets: Simulating complex dynamic economic interactions. Intelligent Systems in Accounting, Finance and Management 22(2) 115-132.
- Jaffe K. 2016. Extended Inclusive Fitness Theory: Synergy and assortment drives the evolutionary dynamics in biology and economics. SpringerPlus 5 1, 1-19.
- Jaffe K 2017. The Invisible Hand of economic markets can be visualized through the synergy created by division of labor. [Complexity/ 2017/4753863](https://doi.org/10.1002/cplx.21800).
- Jaffe K. 2018. Synergy from reproductive division of labour and genetic complexity drive the evolution of sex. Jaffe, K. Journal of Biological Physics 44: 317-329, 2018
- Jaffe K. 2020 The Roots of Synergy. Amazon books. ISBN 1974021734
- Jaffe K and Gerardo Febres 2016. Defining synergy thermodynamically using quantitative measurements of entropy and free energy. Complexity. DOI:10.1002/cplx.21800
- Jaffe K and Hebling-Beraldo MJ, 1993. Oxygen consumption and the evolution of order: Negentropy criteria applied to the evolution of ants. Experientia 49, 587-592.
- Jaffe K, Perez E., 1989. A comparative study of brain morphology in ants. Brain Behav. Evol., 33, 25-33.
- Jaffe K, Rios, A, Florez A., 2013a. Statistics show that economic prosperity needs both high scientific productivity and complex technological knowledge, but in different ways. Interciencia 38: 150-156.
- Jaffe, K, Caicedo M, Manzanares M, Rios A, Florez A, Montoreano C, Davila V. 2013b. Productivity in physical and chemical science predicts the future economic growth of developing countries better than other indices for knowledge. PloS One 0066239
- Jaffe K, E Martinez, AC Soares, JG Contreras, JC Correa, A Canova 2021. Relation between Constitutions, Socioeconomics and The Rule of Law: a quantitative thermodynamic approach. SSRN-3898521
- Jaffe K, E Martinez, AC Soares, M Scolaro, A Canova 2022. Constitutions, Rule of law, Socioeconomicas... and Populism. [SSRN-4077340](https://doi.org/10.32388/2VWCJG.3),
- Muradian R, Issa S, Jaffe K 1999. Energy consumption of termite colonies of *Nasutitermes ephratae*. Physiol. Behav.

66: 731-735, 1999.

- Kauffman S. 2022. Is there a 4th law for non-ergodic systems that do work to construct their expanding phase space? ArXiv:2205.09762
- Kolmogorov A, 1965. Three Approaches to the Quantitative Definition of Information, Problems Inform. Transmission, vol. 1, pp. 1-7.
- Maturana, H.R. and Varela, F.J., 1991. Autopoiesis and cognition: The realization of the living (Vol. 42). Springer Science & Business Media.
- Prigogine, I. 2017. Non-equilibrium statistical mechanics. Courier Dover Publications.
- Sherrington, C.S. 1910. Flexion-reflex of the limb, crossed extension-reflex, and reflex stepping and standing. The Journal of physiology 40.1-2.
- Schrödinger E. 1944. What is Life?
- Shannon C E, A Mathematical Theory of Communication, The Bell System Technical Journal, vol. 27, pp. 379–423., 623–656, July, October 1948.
- Smith, E. 2008. Thermodynamics of natural selection J Theor Biol 252 2, 185-197.