TECHNOPHANY
A Journal for Philosophy and Technology

Technophany Vol.2 No.2

The Thermodynamics of Life as a Speculative Model for Planetary Technology

Cristian Hernandez-Blick

Abstract

Originating from nineteenth century physics, the concept of entropy—a measure of disorder, randomness, and/or the dissipation of useful energy—underlay a cosmology where order and complexity were seen as highly improbable phenomena in a universe tending toward chaos and disorganisation. Nearly a century later, theoretical frameworks were developed for understanding the production of entropy as an enabling feature of self-organized complexity in the natural world. These ideas would contribute to establishing connections between the origins, development, and evolution of life and the principles of a thermodynamic universe. For some, they also supplied the conceptual foundations for theorizing about a universal natural tendency driving the development of increasingly complex and ordered systems which amplify processes of entropy production and energy dissipation and dispersal. In this paper I chart a path through the aforementioned ideas and present their relevance in framing a relationship between our technological civilization and the Earth system. I then speculate about the prospect of a technosphere whose constitution and activity are aligned with thermodynamic principles of dissipation and entropy-production, drawing on theoretical biology and recent developments in bioengineering to envision a paradigm where technology becomes living matter itself.

Keywords: Dissipative systems, entropy, thermodynamics, biology, self-organization, living technology.

Corresponding author: Cristian Hernandez-Blick, hernandez.cristian@proton.me

ISSN 2773-0875

Biology in the Context of Cosmological Entropy

The concept of entropy originates from nineteenth century thermodynamics and is meant to describe a measure of disorder, randomness, and/or the dissipation of useful energy in a system. It's often associated with the general idea that natural processes tend to move toward more disorderly states over time. A few simple examples will serve to illustrate this concept. Consider a drop of ink inside a glass of water. Initially, the molecules which make up the ink are concentrated in a small area. However, as time passes, they disperse and spread throughout the molecules of water, leading to a more disordered and random distribution. Eventually, the molecules will become uniformly distributed within the glass, mixing completely with the water and reaching a highly entropic state of thermodynamic equilibrium. Another example is observed when you place a warm object, such as a cup of hot tea, inside a room with a lower temperature. Over time, the temperature differential between the cup and the room will become equalized as heat, or thermal energy, from the tea transfers to the surrounding molecules in the air of the room. Similar to the dissipation of ink in water, the temperature of the tea and the room together will eventually reach an equilibrium where the entropy of the whole system has increased, and heat has been evenly distributed over the total space.

The latter example of heat flow in a system was precisely what physicist and mechanical engineer Sadi Carnot discovered through his analysis of the efficiency of steam engines[1]: i.e., that heat always moves down a gradient from hotter to cooler states. This basic insight would later become the basis for the second law of thermodynamics. The transformation of thermal energy into mechanical energy—as in the case of a temperature differential powering a steam engine—also, perhaps unsurprisingly, involves the dissipation of useful energy into the environment in the form of heat, becoming spread out into the surroundings and therefore incapable of performing work once more.

In the mid 1800s, Carnot's idea would be refined by Lord Kelvin (William Thomson) and Rudolf Clausius[2], two seminal physicists who were instrumental in unifying the emerging field and providing formal clarity and rigour to the notion of entropy as well as the first two laws of thermodynamics. Together, these two laws described a universal tendency toward the dissipation of mechanical energy in a cosmos where the total amount of energy is fixed and conserved, while entropy referred to a measure of the energy in a system which is no longer available for work. Physicist Ludwig Boltzmann supplemented these ideas with a statistical interpretation of the second law which defined the tendency for orderly

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[1] Sadi Carnot, Rudolf Clausius, and William Thomson Baron Kelvin, *The Second Law of Thermodynamics: Memoirs by Carnot, Clausius, and Thomson* (New York: Harper & Brothers, 1899).

[2] Carnot, Clausius, and Kelvin, *The Second Law of Thermodynamics: Memoirs by Carnot, Clausius, and Thomson.*

components of a system—particularly molecules in a container—to spread out toward more probable arrangements, or dispersed and disorderly configurations, until they approach a state of elevated entropy and thermodynamic equilibrium. It follows, therefore, that the spontaneous generation of orderly configurations from disordered states was considered by Boltzmann to be infinitely improbable.[3] These ideas played a significant role in shaping a cosmological model where living systems were thought to be anomalous, improbable, and contingent accidents in a universe running down toward a "heat death,"[4] with all its parts drifting toward increased disorder and degradation.[5]

However, unlike purely physical, non-living processes, biological systems seem to strike a peculiar balance between the second law of thermodynamics and the ability to generate, maintain, and propagate complexity and order. This kind of activity appears at odds with the above description of the nature of physical reality: if the state of the universe is thought to be lurching toward an increase in cosmic disorder—as the second law of thermodynamics is often interpreted—why then do we observe an abundance and increasing development of structure, order, organization, and complexity within our planet's biosphere?

During the last century, the notion of living systems as thermodynamically open systems operating in far from equilibrium conditions has emerged as a compelling theoretical framework to clarify this

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[3] Ludwig Boltzmann, "The Second Law of Thermodynamics," in *Theoretical Physics and Philosophical Problems: Selected Writings*, ed. Brian McGuinness, Vienna Circle Collection (Dordrecht: Springer Netherlands, 1974), 13–32, https://doi.org/10.1007/978-94-010-2091-6_2.

[4] Boltzmann uses the term "thermal death" in his 1886 essay *The Second Law of Thermodynamics*, while others like physicist Hermann Von Helmholtz, in his 1854 lecture *On the Interaction of Natural Forces*, referred to Lord Kelvin's work in identifying the conditions for a universe threatened with "eternal death" or "condemned to a state of eternal rest." Hermann von Helmholtz, *Science and Culture: Popular and Philosophical Essays*, ed. David Cahan (University of Chicago Press, 1995). The impact these ideas had on intellectual culture may have been existentially profound. For instance, in correspondence with physicist John Tyndall, philosopher and scientist Herbert Spencer wrote "your assertion that when equilibrium was reached life must cease, staggered me. Indeed, not seeing my way out of the conclusion, I remember being out of spirits for some days afterwards." David Duncan, *Life and Letters of Herbet Spencer* (New York: Appleton and Company, 1908). Charles Darwin himself wrote of the "intolerable thought that … all sentient beings are doomed to complete annihilation." Charles Darwin and Nora Darwin Barlow, *The Autobiography of Charles Darwin, 1809-1882* (London: Collins, 1958). Scholarship has also shown the effects of nineteenth century thermodynamics on philosophical discussion concerning time, cosmology, and ethics among thinkers such as Eugen Dühring, Friedrich Engels, Eduard von Hartmann, and especially Friedrich Nietzsche. Joel White, "How Does One Cosmotheoretically Respond to the Heat Death of the Universe?," *Open Philosophy* 6, no. 1 (January 1, 2023), https://doi.org/10.1515/opphil-2022-0233.

[5] William Thomson Baron Kelvin, "On the Age of the Sun's Heat," in *Popular Lectures and Addresses: Constitution of Matter*, vol. 1, 3 vols., Nature Series (London: Macmillan and Company, 1889).

enigmatic property of biology and reconcile it with the laws of thermodynamics.[6] In this view, living systems engage in a dynamic interplay with their environment, selectively exchanging matter and energy with their surroundings in order to generate the work required to produce and maintain a self-organized state of organic individuation and local entropy minimization. Put plainly, biological systems transform external resources into internal order.

The process of localized entropy reduction embodied by self-organized living systems is non-contradictory with respect to the physical laws it appears to evade, since the flows of matter and energy underpinning organic form necessitate the exogenous displacement of entropy from the living process in the form of waste and heat. This consequently produces a global net increase of entropy within the surroundings of a given biological system. In his pioneering work, *What Is Life?* physicist Erwin Schrödinger offered one of the earliest articulations of this general idea. In Schrödinger's words, what a biological system "feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive."[7]

In Schrödinger's writing, these intuitions about the generation and stabilization of order in living systems aren't supported by much empirical knowledge and are expressed primarily through statistical equations and speculations about the organism "feeding" upon negative entropy or "sucking orderliness from its environment."[8] Schrödinger would ultimately connect these ideas to the unique molecular arrangements of "aperiodic solids" with hereditary properties, a hypothesis which would later inform geneticists in their understanding of the structure of DNA and the role this was thought to play in supplying informational content for organismal form and function. However, subsequent work by researchers in biochemistry, biophysics, theoretical biology, complexity science, and other related areas, would also build upon Schrödinger's impressions to flesh out a more robust theory of the relationship between non-equilibrium thermodynamics, self-organization, and the complexity and order found in biological systems.

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[6] Stephen Ornes, "How Nonequilibrium Thermodynamics Speaks to the Mystery of Life | PNAS," accessed June 4, 2023, https://www.pnas.org/doi/10.1073/pnas.1620001114; Ilya Prigogine and Isabelle Stengers, *Order Out Of Chaos: Man's New Dialogue With Nature* (New York, NY: Bantam Books, 1984); Eric D. Schneider and Dorion Sagan, *Into the Cool Energy Flow, Thermodynamics, and Life* (University of Chicago Press, 2005); Jeffrey S. Wicken, *Evolution, Thermodynamics, and Information: Extending the Darwinian Program* (Oxford University Press, 1987).

[7] Erwin Schrödinger, *What Is Life? The Physical Aspect of the Living Cell with Mind and Matter & Autobiographical Sketches* (Cambridge University Press, 2013).

[8] Schrödinger, *What Is Life?*.

In the following section, I turn to some of this work to provide an overview of the entangled and dialectic nature of entropy and dynamic order, self-organized complexity, and life. In doing so, I will highlight a spectrum of self-organizing processes by drawing a path from non-living dissipative systems to the far-from-equilibrium thermodynamics of life and its activity.

Dissipative Systems: From Self-Organization to Autopoiesis

Physical chemist Ilya Prigogine's work on dissipative systems is arguably one of the most significant contributions to the line of thought connecting thermodynamic principles with the generation of natural order. In a nutshell, dissipative systems—a term coined by Prigogine and his colleagues in a number of publications produced during the late 1960s, and first introduced at a conference on theoretical physics and biology[9]—are complex dynamic structures operating far from conditions of thermodynamic equilibrium. These open systems tend to spontaneously self-organize into spatiotemporally ordered processes whose metastable steady states are reproduced by exchanging energy and matter with their environments. Such systems can be both naturally occurring, like whirlpools, flames, tornados, or Jupiter's Giant Red Spot, as well as artificially generated, as in the case of Bénard cells.[10] In a recent paper on the topic of Schrödinger's *What Is Life?* lectures, theoretical biologist Stuart Kauffman discusses the illustrative example of Bénard cells in some detail:

> there is a pan with a shallow layer of viscous liquid … heated slowly from below, creating a temperature gradient, hotter on the bottom than top of the fluid. The temperature gradient induces an overall heat flow to the environment … When the temperature gradient surpasses the Rayleigh threshold, convective cells arise and dissipate heat more effectively. The convective cells are the Bénard cells … [whose] patterns are sustained by the continuous flow of energy through the system that results by heating the pan from below.[11]

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[9] René Lefever, "The Rehabilitation of Irreversible Processes and Dissipative Structures' 50th Anniversary," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376, no. 2124 (June 11, 2018): 20170365, https://doi.org/10.1098/rsta.2017.0365.

[10] Rod Swenson, "Autocatakinetics, Evolution, And the Law of Maximum Entropy Production: A Principled Foundation Toward The Study of Human Ecology," *Advances in Human Ecology* 6 (1997): 1–47; E. B. P. Tiezzi et al., "Dissipative Structures in Nature and Human Systems," in *Design and Nature IV*, vol. I (DESIGN AND NATURE 2008, Algarve, Portugal: WIT Press, 2008), 293–99, https://doi.org/10.2495/DN080301; John Dupré and Daniel J. Nicholson, *Everything Flows: Towards a Processual Philosophy of Biology* (Oxford University Press, 2018).

[11] Stuart Kauffman, "Answering Schrödinger's 'What Is Life?,'" *Entropy* 22, no. 8 (July 25, 2020): 815, https://doi.org/10.3390/e22080815.

Much like Bénard cells, cyclones such as tornados or hurricanes, and other similarly structured natural phenomena like whirlpools or turbulent flow, maintain the emergent macroscopic patterns which constitute their dynamical form through the incessant flux of their components—i.e., via the constant flow of energy and matter through the system supplied by an energy gradient. In other words, the dynamic regularities, or structural identity, of a dissipative system emerges and develops through a continuous and directed flow of energy and matter which is resultantly dispersed more effectively into the surroundings as entropy.

We can see here the beginnings of a theory of natural phenomena which describes the tendency for order to emerge from the enabling conditions of a thermodynamic universe. From this perspective, the relationship between entropy and order is dialectically entangled such that the production of entropy acts as a natural, generative condition for the emergence of structure, organization, and complexity, and not simply disorder and equilibrium. In other words, entropy functions as a progenitor of dynamic order for a certain class of physical systems which leverage or exploit, so to speak, the same thermodynamic principles which lead to disorganization and decay in other contexts. The spontaneous development of complexity and organization is therefore equally as natural as the propensity for chaos and disorder in a universe whose activity conforms with thermodynamic laws.[12]

This theoretical framing is thought to provide a basis for understanding certain primordial and fundamental properties of biological systems, as well. For instance, biophysicist Jeremy England has suggested that non-equilibrium physical systems tend to vary in their structure over time in a manner which correlates with their ability to optimally absorb and dissipate energy from their environment. England bridges physics and biology by connecting this historical and quasi-adaptive property with the evolutionary dynamics of living systems,[13] proposing maximal entropy production as a common principle driving the activity and morphology of self-organizing physical systems, as well as minimal molecular systems and more complex biology. Kauffman has also offered a related narrative in his work on self-organization and complexity, building on various frameworks in the complexity sciences to study the relationship between laws of spontaneous order and self-organization and questions regarding the origin and evolution of life.[14] For Kauffman, the universe supplies order for free as a result of deeply natural laws shaping the behaviour of non-equilibrium systems. In this view, living

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[12] Prigogine and Stengers, *Order Out Of Chaos: Man's New Dialogue With Nature*; Schneider and Sagan, *Into the Cool Energy Flow, Thermodynamics, and Life*.

[13] Nikolay Perunov, Robert A. Marsland, and Jeremy L. England, "Statistical Physics of Adaptation," *Physical Review X* 6, no. 2 (June 16, 2016): 021036, https://doi.org/10.1103/PhysRevX.6.021036.

[14] Stuart Kauffman, *At Home In The Universe: The Search for the Laws of Self-Organization and Complexity* (New York, NY: Oxford University Press, 1995).

systems are seen as expressions of the coupling of spontaneous, self-organizing complexity and the dynamics of evolutionary selection.

Similarly, environmental scientist Eric Schneider and theorist Dorion Sagan have maintained that the tendency for non-equilibrium systems to optimize for dissipation, via their exploitation of various energy sources, is fundamental to all complex biological structures and processes—from the origin of life to evolution and ecology.[15] The authors elevate this tendency to the status of a natural principle, arguing that biological systems are enabled by the same physics of energy flow operating in non-living dissipative systems: "[non-equilibrium thermodynamics] connects life to nonliving complex systems … life's complexity is a natural outgrowth of the thermodynamic gradient reduction implicit in the second law."[16] Echoing this sentiment in an earlier publication, biochemist Jeffrey Wicken has also linked thermodynamics with the historical and ecological development of molecular and organismal complexity. Wicken argues that "life's emergence was not at all accidental" but arose quite naturally from "the free energy gradients (solar and geothermal) of prebiotic Earth," continuing to produce entropy at elevated rates by discharging these gradients, and others, during the history of its continued evolutionary diversification.[17]

We might also turn to Prigogine once again to explore a related set of ideas. One crucial theoretical development to emerge from Prigogine and his collaborators' work on dissipative systems was the Brusselator, a theoretical model for an autocatalytic system.[18] Autocatalysis—a process whereby one or more reaction products act as a catalyst for the same reaction—can be seen as a minimal requirement for defining living systems and their metabolic and replicative properties.[19] These kinds of looping reaction cycles are thought to be vitally important for describing self-organizing, far-from-equilibrium structures as well as certain regulatory mechanisms underpinning metabolic functioning and specific organizational processes unique to biological systems.[20] Others have formulated comparable ideas through the lens of their own work, most notably Kauffman's theory of autocatalytic sets and neuro-anthropologist Terrence Deacon's model of the autogen. With the latter, a synergetic loop between multiple thermodynamic self-organizing processes generates the conditions for the maintenance and

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[15] Schneider and Sagan, *Into the Cool Energy Flow, Thermodynamics, and Life*.

[16] Schneider and Sagan, *Into the Cool Energy Flow, Thermodynamics, and Life*.

[17] Jeffrey S. Wicken, "Evolution and Thermodynamics: The New Paradigm," *Systems Research* 6, no. 3 (1989): 181–86, https://doi.org/10.1002/sres.3850060301.

[18] Ilya Prigogine, *From Being To Becoming: Time and Complexity in the Physical Sciences* (New York: W. H. Freeman and Company, 1980).

[19] Olga Taran and Günter von Kiedrowski, "Autocatalysis," in *Encyclopedia of Astrobiology*, ed. Muriel Gargaud et al. (Berlin, Heidelberg: Springer, 2011), 128–29, https://doi.org/10.1007/978-3-642-11274-4_138.

[20] Prigogine and Stengers, *Order Out Of Chaos: Man's New Dialogue With Nature*.

replication of a self-enclosed system and its autocatalytic components.[21] A similar logic informs the idea of autocatalytic sets, whereby the general metabolic activity and self-replicating behaviour which underlie all organismic activity is posited as a typical outcome of the dynamic stability of autocatalytic networks.[22]

A handful of thinkers have also touched more specifically on the structural and organizational relationship between the thermodynamic properties of open systems and the continuous flow of energy and matter which sustains the self-organizing, self-maintaining, and self-producing behaviours of minimal biological systems. An early and influential contribution to this area can be found in the research of neurobiologists Humberto Maturana and Francisco Varela. Maturana and Varela's work on the concept of "autopoiesis" highlights not only the closed recursiveness of a self-producing network of molecular relations (much like autocatalytic sets) but the necessary and enabling condition of such a system to remain open to flows of matter and energy through it.[23] That is to say, a fundamental property of biological organization is its continuous realization through the process of incessant energy dispersal and material turnover.

Continuing in this tradition, theoretical biologists Alvaro Moreno and Matteo Mossio assert the need to ground this unique property of biology in thermodynamics, qualifying living systems as "dissipative systems dealing in a constitutive way with a thermodynamic flow that traverses them."[24] This perspective is also reflected in a recent compilation of essays titled *Everything Flows*, edited by philosophers and historians of biology John Dupré and Daniel Nicholson. In their introduction, Dupré and Nicholson write of the organism's existential condition of needing to be continuously thermodynamically active in order to exist.[25] Biological systems must metabolize matter from their

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[21] Terrence W. Deacon, Alok Srivastava, and Joshua Augustus Bacigalupi, "The Transition from Constraint to Regulation at the Origin of Life," *Frontiers in Bioscience-Landmark* 19, no. 6 (June 1, 2014): 945–57, https://doi.org/10.2741/4259.

[22] Stuart A. Kauffman, "Cellular Homeostasis, Epigenesis and Replication in Randomly Aggregated Macromolecular Systems," *Journal of Cybernetics* 1, no. 1 (January 1, 1971): 71–96, https://doi.org/10.1080/01969727108545830.

[23] H. Maturana, "Autopoiesis, Structural Coupling and Cognition: A History of These and Other Notions in the Biology of Cognition," *Cybernetics & Human Knowing* 9, no. 3–4 (March 1, 2002): 5–34; F. G. Varela, H. R. Maturana, and R. Uribe, "Autopoiesis: The Organization of Living Systems, Its Characterization and a Model," *Currents in Modern Biology* 5, no. 4 (May 1974): 187–96, https://doi.org/10.1016/0303-2647(74)90031-8.

[24] Alvaro Moreno and Matteo Mossio, *Biological Autonomy: A Philosophical and Theoretical Enquiry*, vol. 12, History, Philosophy and Theory of the Life Sciences (Springer Berlin Heidelberg, 2015).

[25] John Dupré and Daniel J. Nicholson, *Everything Flows: Towards a Processual Philosophy of Biology* (Oxford: Oxford University Press, 2018).

surroundings to acquire and dissipate energy, rebuild and replenish cells, and maintain their identity in a steady state. In other words, an organism's stability derives from a continuous circulation of its components, driven by the non-equilibrium dynamics of dissipating energy from its environment. Much like the Bénard cell, the maintenance of organized and ordered living states, or dynamic biological stability, requires a continuous movement of energy passing through an open system.

Philosopher Rod Swenson has explored related ideas in his work on the thermodynamics of self-organization, ecology, and evolution. In his research, Swenson expounds upon a notion of autocatakinesis, or "identity through flow,"[26] whereby both living systems and self-organizing physical systems maintain their dynamic spatio-temporal coherence through a circular causal regime realized by far-from-equilibrium thermodynamic conditions. Swenson draws on the likes of Prigogine and Schrödinger, as well as philosophers and scientists such as Heraclitus, Gottfried Wilhelm Liebniz, and Ludwig Von Bertalanffy, to stress the connection between dissipative systems and living beings, both of which are open non-equilibrium systems whose structural and organizational identity is constituted by continuous coordination of its parts via the relentless flow and degradation of energy and matter from their respective environments.[27]

It's important to pause briefly at this juncture to highlight an important distinction between living beings and non-living, strictly physical, dissipative systems, despite the continuity presented here between the thermodynamic properties of the latter and the origins, behaviour, and evolution of life. While biological systems are energetically open systems—operating in far-from-equilibrium conditions maintained by a constant throughput of energy and matter—they're also characterized by their ability to realize closure.[28] Closure refers to the collective activity and mutual dependence of various interrelated constraints which constitute bounded individuation, organizational complexity, and functional differentiation in living systems.[29] This notion is closely related to the concept of autopoiesis: i.e., a system constituted by the interdependence between an internal reaction network and a boundary, each of which continuously supplies the necessary conditions for the other's regeneration and enables the system to emerge as a topological unity distinct from its milieu.

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[26] Swenson, "Autocatakinetics, Evolution, And the Law of Maximum Entropy Production: A Principled Foundation Toward The Study of Human Ecology."

[27] Rod Swenson, "End-Directed Physics and Evolutionary Ordering: Obviating the Problem of the Population of One," in *The Cybernetics of Complex Systems: Self-Organization, Evolution and Social Change*, ed. F. Geyer (Salinas, California: Intersystems, 1991).

[28] The author would like to thank Reviewer A for their recommendation to clarify this distinction and their input regarding the significance and implications of this difference.

[29] Matteo Mossio and Alvaro Moreno, "Organisational Closure in Biological Organisms," *History and Philosophy of the Life Sciences* 32, no. 2–3 (2010): 269–88.

Indeed, it can be said that biological systems are a more sophisticated subset of far-from-equilibrium, self-organizing, dissipative systems. That is to say, life employs internal organizational and functional complexity to achieve intricate, selective, and adaptive means of pursuing, channelling, transforming, and dispersing the sources of matter and energy which must traverse them as a requirement of thermodynamic openness. These distinctive features are closely connected to a particular property of living beings which makes them especially unique as non-equilibrium systems: their persistence is not self-undermining, unlike dissipative systems whose entropy maximization exhausts the energy gradients which create and sustain their structural regularities.[30] I will return to this point in a later section, after first discussing the idea of a directional trajectory to the dynamics of energy transformation and dispersal favoured by the evolutionary development of living systems and their activity.

A relatively common theme for many of the authors referenced above is the idea that there is some progressive trajectory implicit in the emergent self-organizing and dissipative properties of non-equilibrium systems. That is to say, many of these thinkers champion the view that life and all its various features are inevitable outcomes of a physical reality shaped by thermodynamic principles. This lies in contrast with a cosmological interpretation of entropy which sees life as an improbable and aberrant phenomenon appearing inconsistent with the laws of physical reality. For some, this alternative view motivates theoretical explorations of the relationship between thermodynamics and the origins of rudimentary forms of intelligence, meaning, and/or cognition in living beings.[31] For others, the history of biological complexification also points to a tacit purposiveness in living systems of all scales to develop toward increasingly effective forms of accelerated energy exploitation, transformation, and dispersal. It is the latter of such views which I will describe in the following section, connecting it with theoretical frameworks such as Gradient Reduction Theory and the Maximum Entropy Production Principle, and relating these perspectives to ideas regarding planetary-scale energy transformations in the development of both natural and technological global spheres.

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[30] Terrence W. Deacon and Miguel García-Valdecasas, “A Thermodynamic Basis for Teleological Causality,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 381, no. 2252 (June 19, 2023): 20220282, https://doi.org/10.1098/rsta.2022.0282.

[31] Terrence W. Deacon, *Incomplete Nature: How Mind Emerged from Matter*, 1st ed. (W. W. Norton & Company, 2011).

Entropy and the Directional Trajectory of the Biosphere and Technosphere

Many of the researchers highlighted earlier share an interest in aligning their ideas about the relationship between life and dissipative, nonequilibrium systems with an historical or evolutionary framework of some kind.[32] Additionally, some seek to explore how such processes might manifest and operate in systems which occupy vast temporal and spatial scales such as ecosystems, civilizations, or the planetary biosphere. In the section that follows, I will provide a few examples of such thinking, each of which adopts a somewhat unique approach to this theme, yet both of whom share a common theoretical foundation in the dissipative properties of far-from-equilibrium thermodynamic systems. I will then highlight the relevance of such thinking for framing the relationship between the Earth system and our modern technological civilization.

One expression of this evolutionary, ecological perspective on non-equilibrium systems is Gradient Reduction Theory [henceforth GRT], proposed by Dorion Sagan and Earth scientist Jessica Hope Whiteside in their contribution to a collection of essays re-examining the conceptual foundations of the Gaia hypothesis.[33] In this publication, Sagan and Whiteside explore the idea that non-equilibrium thermodynamics connects purely physical flow structures to biological processes and systems of varying degrees of complexity—from prokaryotic metabolism to complex animals, human civilization, and the biosphere, or “Gaia”, itself. Furthermore, these biological systems are thought to be long-evolved manifestations of an inclination belonging to all natural processes on Earth: a tendency in the evolutionary development of far-from-equilibrium systems to accelerate increasingly effective forms of entropy production, or energy transformation and dispersal.[34]

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32 Jeremy England, *Every Life Is on Fire: How Thermodynamics Explains the Origins of Living Things* (Basic Books, 2020); Schneider and Sagan, *Into the Cool Energy Flow, Thermodynamics, and Life*; Kauffman, *At Home In The Universe: The Search for the Laws of Self-Organization and Complexity*; Swenson, “Autocatakinetics, Evolution, And the Law of Maximum Entropy Production: A Principled Foundation Toward The Study of Human Ecology”; Wicken, “Evolution and Thermodynamics.”

33 D. Sagan and J. H. Whiteside, “Gradient-Reduction Theory: Thermodynamics and the Purpose of Life,” in *Scientists Debate Gaia: The Next Century*, ed. Stephen H. Schneider et al. (MIT Press, 2004), 173–86, http://mitpress.mit.edu/books/scientists-debate-gaia.

34 It’s worth noting that Sagan and Whiteside technically do not subscribe to the notion that entropy is being explicitly maximized by the behaviour of gradient-degrading thermodynamic systems, preferring to focus the reader’s attention on the energy flows alone which organize such systems. In their thinking, GRT is a restating of the second law of thermodynamics, albeit one which emphasizes energy potentials and flow through complex systems over universal net entropy production. Despite this, their explanation of the general mechanics of their subject of interest remains relatively similar to most thinkers in this area and the difference they highlight does not seem considerable enough to put them appreciably at odds with others interested in the directed development of complex systems driven by thermodynamic principles. Indeed, in more recent work, Sagan uses the terms gradient reduction and entropy production interchangeably, suggesting that while the latter may not be maximized it is nonetheless thought to be amplified by living dissipative systems.

For instance, Sagan and Whiteside propose that the widespread proliferation of humans relative to other species "is in large part due to … a much enhanced ability to identify and deploy the food and other gradients necessary to move agricultural and technical civilization into the material evolutionary form which is humanity."[35] They also argue that the thermodynamic imperative to exploit energy potentials points not only to "the process of life's origination" but also to a directionality to life's development at the planetary scale, in the form of "growth (increase in biomass), reproduction, increase in respiration, energy efficiency, number and types of taxa (biodiversity), rates of circulation of elements, numbers of elements involved in biological circulation, and [an] increase in intelligence."[36] This sentiment is repeated in Sagan's 2016 article *Möbius Trip: The Technosphere and Our Science Fiction Reality*, wherein he writes of how "life's entropy-producing systems are completely natural within the cosmic context of the observed tendency of energy to spread. Indeed, life's ability to identify and delocalize concentrated pockets of energy is arguably its natural reason for being, why it is favored in a thermodynamic universe."[37] This tendency underpins energy-driven evolutionary "trends ranging from expansion of the area inhabited by life to increase in respiration efficiency … to increase in sensory modes, increase in information processed, and increase in energy stored, commandeered, and deployed in life's operations at Earth's surface."[38] For Sagan, this suggests "a more-than-human, thermodynamically driven, ecosystemic increase in biodiversity, net intelligence, perceptual and metabolic modes … over evolutionary time."[39]

We find a related perspective contained in the idea of the Maximum Entropy Production Principle [henceforth MEPP]. According to this view, non-equilibrium systems will develop toward optimizing for states where the rate of entropy production via energy flux and dissipation is maximized given their environmental constraints.[40] In addition to this generalized formulation, proponents hold that a variety of non-trivial features in the evolution of life can be traced to this thermodynamic property of

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[35] Sagan and Whiteside, "Gradient-Reduction Theory."

[36] Sagan and Whiteside.

[37] Dorion Sagan, "Möbius Trip: The Technosphere and Our Science Fiction Reality," Technosphere Magazine, accessed June 10, 2023, https://technosphere-magazine.hkw.de/p/Mobius-Trip-The-Technosphere-and-Our-Science-Fiction-Reality-fq6MUxZjiBx7pzKPMKZfcb.

[38] Sagan,. "Möbius Trip."

[39] Sagan, "Möbius Trip."

[40] L. M. Martyushev, "Maximum Entropy Production Principle: History and Current Status," *Physics-Uspekhi* 64, no. 6 (September 1, 2021): 558, https://doi.org/10.3367/UFNe.2020.08.038819; Leonid M. Martyushev, "The Maximum Entropy Production Principle: Two Basic Questions," *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, no. 1545 (May 12, 2010): 1333–34, https://doi.org/10.1098/rstb.2009.0295; Leonid M. Martyushev, "Entropy and Entropy Production: Old Misconceptions and New Breakthroughs," *Entropy* 15, no. 4 (April 2013): 1152–70, https://doi.org/10.3390/e15041152; Leonid M. Martyushev, "Life Defined in Terms of Entropy Production: 20th Century Physics Meets 21st Century Biology," *BioEssays: News and Reviews in Molecular, Cellular and Developmental Biology* 42, no. 9 (September 2020): e2000101, https://doi.org/10.1002/bies.202000101.

open systems. Physicist and mathematician Leonid Martyushev has published extensively on the topic, drawing from the work of mathematical biologist Alfred Lotka, Earth systems scientist Axel Kleidon, ecologist Howard Odum, and others to explore the relevance of the MEPP in describing evolving biological systems. Increases in the complexity and organization of living systems—from microbes to metazoans—are thought to develop in accordance with this common principle, whereby "increasing the metabolic rate in order to maximize the consumption of free energy" drives "organisms [to] gradually become more complex in a natural way."[41]

Contemporary advocates of the MEPP such as Kleidon and Odum also view these energy-driven evolutionary dynamics as pivotal to describing the activity of the Earth system more broadly, focusing on energy flow through large complex systems—such as economic systems and ecological networks—that emerge as a result of life's activity.[42] In a similar vein, Martyushev holds that the MEPP is "the most important principle explaining the direction (progression) of biological and technological evolution" as it corresponds with "the increase in complexity of living creatures in the course of evolution, the emergence of human beings, and the entire course of the development of our civilization (from humans that started using fire to humans widely using oil fuel and atomic energy)."[43] The scope of GRT or the MEPP therefore appears inclusive enough to address questions concerning the relationship between thermodynamics and the origin of life, its adaptive historical development, and various scales of its hierarchical organization. At their highest strata of application, these views encourage us to see the development and operation of large-scale biospheric, social, and technological organization in accordance with a natural principle driving the energetic dynamics of non-equilibrium systems.

What we have then, are various researchers working in areas related to physics, chemistry, biology, philosophy, complex systems, and Earth sciences who have developed kindred theoretical frameworks for understanding the production of entropy as an enabling feature of self-organized complexity in the natural world. From this perspective, spatiotemporally ordered systems tend to emerge spontaneously as a means to degrade energy at elevated rates, with their recursive, self-organized complexity facilitated by a continuous flux of matter and energy from the environment. Living systems are constituted in a similar manner and have evolved more complex and specific means of intentionally locating, exploiting, and dissipating energy in order to produce, maintain, and replicate their organizational identity.

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[41] Martyushev, "Life Defined in Terms of Entropy Production."

[42] Axel Kleidon, "Beyond Gaia: Thermodynamics of Life and Earth System Functioning," *Climatic Change* 66, no. 3 (October 1, 2004): 271–319, https://doi.org/10.1023/B:CLIM.0000044616.34867.ec; Howard T. Odum, *Ecological and General Systems: An Introduction to Systems Ecology* (University Press of Colorado, 1994).

[43] Martyushev, "Maximum Entropy Production Principle."

Phenomena such as this can therefore be understood as a natural outgrowth of the second law of thermodynamics, underpinning nonequilibrium systems both nonliving and living alike.

This principle of energy dissipation may also be implicated in the growth and adaptive development of increasingly complex living systems and many of the products of their activity. This is thought to include evolutionary developments in organismal complexity, ecosystemic biodiversity, social organization, and technological systems, and their total contribution to an expanded rate of energy transformation occurring on this planet. In other words, adopting the aforementioned perspectives on the role of entropy in the generation and development of biological order might allow us to understand the activity of life at multiple levels—including aspects of human civilization such as the technosphere[44]—in concordance with the conditions of a thermodynamic universe. In a sense, the universal thermodynamic principle of entropy production lies at the heart of a worldview which naturalizes life's activity, situating it in a quasi-purposeful cosmos directed toward generating increasingly sophisticated dissipative systems.

For the human species, a perspective such as this could have a significant impact on how we frame the relationship between our technological civilization and Earth system functioning. Insofar as we can talk about the evolutionary development of human technology, the pace at which such change occurs is thought to be significantly more rapid than that which transpires through the phylogenetic history of biological systems.[45] This accelerated rate of change in our technological landscape has also been at the centre of profound Anthropogenic transformations in multiple planetary spheres, while simultaneously imposing conditions of critical interdependence between our species, the biosphere, and the continued

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[44] The technosphere here refers to the term as it was recently popularized by geologist and engineer Peter Haff in a series of publications over the last couple of decades. See Peter Haff, "Technology as a Geological Phenomenon: Implications for Human Well-Being," *Geological Society, London, Special Publications* 395, no. 1 (January 2014): 301–9, https://doi.org/10.1144/SP395.4; Peter Haff, "Humans and Technology in the Anthropocene: Six Rules," *The Anthropocene Review* 1, no. 2 (August 1, 2014): 126–36, https://doi.org/10.1177/2053019614530575; Jan Zalasiewicz et al., "Scale and Diversity of the Physical Technosphere: A Geological Perspective," *The Anthropocene Review* 4, no. 1 (April 1, 2017): 9–22, https://doi.org/10.1177/2053019616677743. According to Haff, the technosphere is the technological analogue to the various natural geological paradigms or planetary spheres that constitute and sustain the Earth system, such as the geosphere, the hydrosphere, the atmosphere, or the biosphere. Put briefly, it is a global interconnected system of technological artifacts, social structures, and physical infrastructure which constitute the totality of the built human environment, the particular energy and resource transformations underpinning the system's metabolic profile, and the emergent principles that govern our relationship with the system's functioning.

[45] Robert Boyd, Peter J. Richerson, and Joseph Henrich, "The Cultural Evolution of Technology: Facts and Theories," November 1, 2013, https://doi.org/10.7551/mitpress/9894.003.0011; Sara Walker, "AI Is Life," April 27, 2023, https://www.noemamag.com/ai-is-life.

viability of a functioning technosphere.[46] It's possible that situating the technosphere within the context of a thermodynamic drive toward enhanced rates of energy transformation and dispersal might shed some light on how to ensure the viability of our technological systems by aligning aspects of their development with at least one crucial, deeply natural feature of planetary life.

Indeed, some researchers have already made efforts to explore the relationship between planetary technology, thermodynamics, and the Anthropocene, such as Axel Kleidon, who has written about the energetics of the technosphere, "the ultimate thermodynamic imperative to evolve to states of greater energy conversions and higher levels of entropy production at the planetary scale", and the Earth system's need for "the technosphere to make this evolutionary step to the next thermodynamic level of greater energy conversions."[47] How then might the technosphere complement this "thermodynamic imperative" which biological systems seem to embody so effectively? How might we characterize the technosphere's ability to dissipate energy, and how does it compare in this regard to living systems? In the final portion of this paper, I speculate about this conceptual relationship between the technosphere and biosphere by turning my focus toward the material constitution of human technological artifacts. The following considerations will be used to guide this inquiry:

> (i) How does current human technology differ from evolved, living nonequilibrium systems?
> (ii) Could modelling our technology on the dialectic of entropy and life be advantageous for the viability of the technosphere?
> (iii) How might theories of energy dissipation in living systems inform the design of human technology?

Nonequilibrium Thermodynamics: Biology Versus Technology

How does human technology differ from evolved, living nonequilibrium systems?

Many of the authors previously cited give us good reason to distinguish living systems, such as organisms, from existing artifactual systems, such as machines. One significant difference involves a comparison between the processual dynamism of biology and the engineered stability of mechanical artifacts. For instance, Swenson writes of machines being constituted by the static order of fixed and

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[46] Haff, "Humans and Technology in the Anthropocene."

[47] Axel Kleidon, "How the Technosphere Can Make the Earth More Active," Technosphere Magazine, accessed July 28, 2023, https://technosphere-magazine.hkw.de/p/How-the-Technosphere-Can-Make-the-Earth-More-Active-2sLVHbYfUTS8sKUtkZAGWq.

functional components, all of which have been designed by an artificer. In contrast with this, living systems are defined by a self-organized, dynamic order whose identity is self-produced "through the incessant flux of their components, which are continuously being replaced from raw materials in their environments and being expelled in a more dissipated form."[48] All extant human artifacts, machines, or other technological devices and systems lack this autocatakinetic property of being constituted through continuous, dynamic flows of material and energetic dissipation.

This difference has also been described in terms of the transitional and stable identities of biological systems and machines, respectively. Daniel Nicholson writes that while "an organism naturally maintains itself in a state of continuous flux" as a "temporary manifestation of the self-producing organizational unity of the whole," a machine and its components "remain distinct, stable, and identifiable over time."[49] That is to say, living systems are grounded in the thermodynamic principles which compel them to "break down the materials they take in from their environment in order to acquire the energy they need to rebuild their constituents … maintain themselves in a steady state far from thermodynamic equilibrium … and dissipate energy and excrete material wastes back into their environment."[50] Human technology does not operate like this in any credible sense, its structural and organizational identity is completely unlike the processual dynamism of open dissipative systems described here.[51]

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[48] Swenson, "Autocatakinetics, Evolution, And the Law of Maximum Entropy Production: A Principled Foundation Toward The Study of Human Ecology."

[49] Daniel J. Nicholson, "Organisms ≠ Machines," *Studies in History and Philosophy of Biological and Biomedical Sciences* 44, no. 4 Pt B (December 2013): 669–78, https://doi.org/10.1016/j.shpsc.2013.05.014.

[50] Dupré and Nicholson, *Everything Flows: Towards a Processual Philosophy of Biology*.

[51] There is a sizeable and growing body of literature in the history and philosophy of biology addressing the ontological and the epistemological relationship between biology/organisms and machines/technology which I am unable to adequately unpack within the limited scope of this paper. Those who are interested should see, for instance, Georges Canguilhem, "Machine and Organism," in *Knowledge of Life* (New York City, New York: Fordham University Press, 2022), 200; Andrea Gambarotto and Auguste Nahas, "Teleology and the Organism: Kant's Controversial Legacy for Contemporary Biology," *Studies in History and Philosophy of Science* 93 (June 1, 2022): 47–56, https://doi.org/10.1016/j.shpsa.2022.02.005; Hans Jonas, *The Phenomenon of Life: Toward a Philosophical Biology* (Illinois: Northwestern University Press, 2001); Tim Lewens, *Organisms and Artifacts: Design in Nature and Elsewhere* (Cambridge, Massachusetts: The MIT Press, 2005); Matteo Mossio, "Purposiveness, Directionality and Circularity" (Workshop on Goal-Directedness, Spain, February 3, 2022), https://www.youtube.com/watch?v=b7YZmNPnxPY; Nicholson, "Organisms ≠ Machines"; Daniel J. Nicholson, "The Machine Conception of the Organism in Development and Evolution: A Critical Analysis," 2014, https://philarchive.org/rec/NICTMC-2; Jessica Riskin, *The Restless Clock: A History of the Centuries-Long Argument over What Makes Living Things Tick* (Chicago: University of Chicago Press, 2016); Robert Rosen, *Life Itself: A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life* (New York, NY: Columbia University Press, 1991); Günther Witzany and František Baluška, "Life's Code Script Does Not Code Itself. The Machine Metaphor for Living Organisms Is Outdated," *EMBO Reports* 13, no. 12 (December 2012): 1054–56, https://doi.org/10.1038/embor.2012.166.

Framed alternatively, biological systems are ascribed as having a much greater degree of autonomy than machines. Part of what it means for dynamic living order to be constituted by a flux of energetic and material processes is that thermodynamically open systems of this kind acquire self-organizing and self-constructing properties and functions which contribute to the system's own determination, maintenance, and persistence. In other words, living systems are considered both causes and effects of themselves, capable of promoting the conditions of their own autopoietic existence through thermodynamically-grounded environmental interactions shaping intrinsic energetic and material circulation.[52] By contrast, nearly all of our technological systems are allopoietic or heteropoietic: that is to say, many "have as the product of their functioning something different from themselves," relying in nearly all respects on human agency, design, and intervention to become organized, perform functionally, and persist and evolve through time.[53]

Another salient difference between living and technological systems can be illustrated by their respective energy dissipation rates. Drawing considerably on the work of environmental scientist Vaclav Smil, philosopher Thomas Nail has argued that, despite an exponential rise in human-induced energy expenditure during the last century, the technosphere is still orders of magnitude less effective than the biosphere when it comes to rates of energy expenditure and dissipation, paling in comparison to biodiverse ecosystems such as old-growth forests.[54] For Nail, both vegetal and animal life are "massive energy-degrading [processes] of radical expenditure and waste," with plants acting as "powerful dissipative systems that degrade solar energy into low-grade heat energy, water, and oxygen" and animals dissipating 80–90% of the energy they consume as heat.[55] Schneider and Sagan similarly emphasize the powerful entropy producing features of biodiverse Amazonian rainforests,[56] which Sagan has differentiated from what he sees as the current technosphere's "unsustainable rates of entropy production, which tend to be associated with unsustainable exponential growth and the early, passing stage of pioneer monocultures in immature ecosystems."[57] In other words, despite an unprecedented era of accelerated, energy-intensive technological development—one which corresponds with the rapid growth of the modern technosphere—our contemporary technological systems appear largely incapable of matching the sustainable, biologically-effective rates of energy transformation and expenditure measured in the highly entropic activity of the biosphere.

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[52] Moreno and Mossio, *Biological Autonomy: A Philosophical and Theoretical Enquiry*.

[53] Humberto Maturana and Francisco J. Varela, *Autopoiesis and Cognition: The Realization of the Living*, vol. 42, Boston Studies in the Philosophy of Science (Holland: D. Reidel Publishing Company, 1980).

[54] Thomas Nail, *Theory of the Earth* (Stanford University Press, 2021); Vaclav Smil, "Harvesting the Biosphere: The Human Impact," *Population and Development Review* 37, no. 4 (2011): 613–36, https://doi.org/10.1111/j.1728-4457.2011.00450.x.

[55] Nail, *Theory of the Earth*.

[56] Schneider and Sagan, *Into the Cool Energy Flow, Thermodynamics, and Life*.

[57] Sagan, "Möbius Trip: The Technosphere and Our Science Fiction Reality."

Could modelling our technology on the dialectic of entropy and life be advantageous for the viability of the technosphere?

Comparisons between the dissipative properties of the technosphere and the biosphere are especially interesting because they suggest that the kind of entropic destruction resulting from contemporary fossil-fuel civilization is in fact quite different from the more widespread entropy-amplifying processes which have characterized the history of life on Earth. If anything, humans have reduced the planet's overall energy expenditure by eradicating dissipative biological systems, indirectly replacing them with technological systems of inferior entropy-producing capabilities. Nail's recent book *Theory of the Earth* builds on this idea in order to advance an ethics of dissipative energy expenditure which advocates for bringing environmental politics and philosophy into alignment with the thermodynamic principles shaping biospheric energy flow.[58] I wish to orient my thinking in a similar direction by speculating about aligning human technology with the principles of nonequilibrium thermodynamics which shape the identity and activity of biological systems.

As mentioned earlier, the uniquely self-sustaining tendencies of biological dissipative activity would likely be a critical consideration for any effort to contemplate the prospect of modelling technological systems on nonequilibrium thermodynamics, as it pertains to the dialectic of entropy and life. To reiterate, the structural order of non-living dissipative systems can only persist in the presence of an energy gradient and ceases as soon as the energy source is depleted. However, the patterns of dynamic regularity which constitute such systems emerge as pathways to amplify the rate at which energy passes through them. This has the consequence of reducing the long-term persistence and propagation of the system's self-organized identity.

Life, by contrast, extends this dissipative energetic process over much greater timescales, both ontogenetically—over organismal development and life-cycles—and phylogenetically—through reproduction and evolution. In other words, biology is capable of embodying the dynamics shared by open, nonequilibrium, dissipative systems while avoiding the process whereby such activity threatens to undermine the orderliness generated therefrom. While I am unable to provide a detailed account of how this is accomplished, I will quickly share a few examples which touch on how these dynamics might factor into minimal and proto-biological systems, as well as ecological or biospheric processes.

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[58] Nail, *Theory of the Earth*.

Firstly, previous works by Deacon[59] have sought to develop a theory of "the distinctive modification of thermodynamic processes that characterize the intrinsic end-directed dynamics characteristic of life."[60] Referred to as "teleodynamics," this theoretical approach is intended to highlight the teleological properties of living systems which are otherwise both continuous with, yet simultaneously transcend, the self-eliminating activity of purely physical nonequilibrium systems. Recall Deacon's autogen, a model for a minimal teleodynamic system. The autogen is a simple molecular cycle consisting of two dissipative self-assembling systems coupled synergistically such that each supplies a boundary condition for the other's activity. These mutually limiting, reciprocal constraints endow the emergent macrosystem with a primitive means of regulating otherwise self-terminating nonequilibrium thermodynamic processes, while enabling the global system to approximate end-directedness as a result of its ability to maintain historical continuity over generations of replication and repair.

Zooming out to a planetary scale, we might turn our attention back to the dynamics of one of life's maximally dissipative extant systems—the collective activity of photosynthetic organisms. Forest ecosystems, for example, are enormously dissipative although their transformation of solar energy crucially involves generating oxygen as a molecular waste product. Indeed, all photosynthetic life-forms, especially marine microorganisms, partake in this biospheric process of energy transduction and dispersal critical to sustaining the expansive diversity of aerobic life on Earth. Moreover, plants in particular play a role in global evapotranspiration, helping to regulate surface and air temperatures through feedback loops between warming environments and cooling mechanisms, involving the release of excess evaporated water and the resultant creation of cloud cover.[61] As put forward by ecologist James Lovelock and evolutionary biologist Lynn Margulis, there is reason to believe the Earth has maintained a relatively metastable state of atmospheric homeostasis for hundreds of millions of years as a result of complex regulatory feedback processes facilitated, more generally, by the living biosphere.[62]

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59 Deacon, *Incomplete Nature: How Mind Emerged from Matter*; Terrence W Deacon, "Teleodynamics: Specifying the Dynamical Principles of Intrinsically End-Directed Processes" (Superior, CO: International Association for the Integration of Science and Engineering (IAISAE), June 2020); Deacon and García-Valdecasas, "A Thermodynamic Basis for Teleological Causality."

60 Deacon, "Teleodynamics: Specifying the Dynamical Principles of Intrinsically End-Directed Processes."

61 "Seeing Leaves in a New Light," Text Article (NASA Earth Observatory, May 6, 2002), https://earthobservatory.nasa.gov/features/LAI/LAI2.php; Sagan, "Möbius Trip: The Technosphere and Our Science Fiction Reality."

62 James E. Lovelock and Lynn Margulis, "Atmospheric Homeostasis by and for the Biosphere: The Gaia Hypothesis," *Tellus* 26, no. 1–2 (1974): 2–10, https://doi.org/10.1111/j.2153-3490.1974.tb01946.x; Sagan, "Möbius Trip: The Technosphere and Our Science Fiction Reality."

With these examples in mind, it could be said that to some degree living dissipative systems owe their emergence and persistence to relational, regulative, and regenerative dynamics which they both embody internally and enact reciprocally with other dissipative systems. For example, a crucial ingredient in the emergence and perseverance of autopoietic systems is the intrinsic, mutually-regulating boundary conditions, and subsequently evolved organizational constraints, of various holistically interrelated thermodynamic processes—allowing the system to harness flows of energy and matter and effectively generate entropy without compromising its identity.[63] Furthermore, the far-from-equilibrium energetic landscape of the biosphere sustains dissipative activity through multi-metabolic processes which involve recycling waste products and exporting entropy as heat away from its surfaces and into outer space.[64] That is to say, life enables augmented entropy production through adaptive and self-regulatory activity, circumventing the self-eliminating properties of non-living dissipative systems while becoming ecologically integrated with other living systems. These properties seem especially well suited to facilitating elevated rates of long term, biologically-effective energy dispersal without undermining biospheric viability.[65] It might be interesting then to consider the idea of assimilating such properties into the constitution and operations of technological systems as a means to ensure the viability of an "energetically prodigious and sustainable"[66] planetary technosphere.

Orienting ourselves toward the possibility of a technosphere embodying far-from-equilibrium, continuously self-organizing, dissipative properties might also reframe our relationship with technological systems in a similar way to how theories regarding the thermodynamics of self-organization and biological order reframed life as a natural and expected feature of the cosmos. That is to say, it may give us reason to see the potential for technology to become more like the complex and ordered natural systems which appear to spontaneously emerge from, and thrive in, a thermodynamic universe. At the very least, it may motivate us to imagine how we might engineer the technosphere and its artificial components to be more reciprocally connected with the ubiquitous material and energy flows shaping bio-terrestrial expenditure. In both cases, human technology could be guided toward a paradigm where it operates in harmony with, and not distinct from or hostile to, living systems. At the core of such a transformation,

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[63] Moreno and Mossio, *Biological Autonomy: A Philosophical and Theoretical Enquiry*; Deacon and García-Valdecasas, "A Thermodynamic Basis for Teleological Causality."

[64] Sagan, "Möbius Trip: The Technosphere and Our Science Fiction Reality."

[65] The author would like to thank Reviewer B for prompting the inclusion of this admittedly under-developed point and the antecedent paragraphs which only begin to expand upon it. Relatedly, it should also be noted that biospheric dissipative activity has been operating in a relatively self-sustaining manner for billions of years, in contrast with only a few hundred years of entropy production generated by a modern technosphere that is currently straining the limits of planetary viability.

[66] Sagan, "Möbius Trip: The Technosphere and Our Science Fiction Reality."

should it happen to be feasible, would be an objective to approximate or reproduce with our technological systems the activity and associated dissipative properties of open, nonequilibrium, biological systems.

How might theories of energy dissipation in living systems inform the design of human technology?

This question is a highly speculative prompt, to be sure, and should be considered as no more than a loosely sketched thought experiment. I do not purport to offer any precise or concrete proposals for how one might go about developing living technology with thermodynamic properties that correspond precisely to those exhibited by biological systems. Instead, I wish to provide only a general outline of this hypothetical technological future by pointing to a few promising developments in bioengineering and synthetic biology, briefly elaborating on why these advances may warrant further attention in the context of our exploration of the dialectical relationship between entropy and open nonequilibrium systems.

One area of interest which may prove to be relevant to this conceptual endeavour is synthetic morphology. This emerging sub-discipline of synthetic biology began to take shape around 2008, when developmental biologist Jamie Davies published a paper outlining the prospects of engineering "self-constructing assemblies of cells."[67] Practitioners in this nascent field are generally interested in understanding the rules of morphogenesis and their application in the construction of devices using, or entirely comprised of, engineered living tissues.[68] In other words, these researchers are interested in how living matter self-organizes, studying the unique properties of individual cells and the collective behaviour they exhibit when assembling into various pluricellular configurations and using that knowledge to develop new hybrid living-technological systems.[69]

While thermodynamics does not currently play much of a role in this work, for our purposes, developments in synthetic morphology point toward a horizon where technological systems are brought into even closer proximity with living systems—not merely in an attempt to emulate biology, as is often the case

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[67] Jamie A. Davies, "Synthetic Morphology: Prospects for Engineered, Self-Constructing Anatomies," *Journal of Anatomy* 212, no. 6 (June 2008): 707–19, https://doi.org/10.1111/j.1469-7580.2008.00896.x.

[68] Philip Ball, "Synthetic Morphology Lets Scientists Create New Life-Forms," *Scientific American*, 2023, https://www.scientificamerican.com/article/synthetic-morphology-lets-scientists-create-new-life-forms/.

[69] Mo R Ebrahimkhani and Miki Ebisuya, "Synthetic Developmental Biology: Build and Control Multicellular Systems," *Current Opinion in Chemical Biology*, Synthetic Biology • Synthetic Biomolecules, 52 (October 1, 2019): 9–15, https://doi.org/10.1016/j.cbpa.2019.04.006; Mo R. Ebrahimkhani and Michael Levin, "Synthetic Living Machines: A New Window on Life," *iScience* 24, no. 5 (May 2021): 102505, https://doi.org/10.1016/j.isci.2021.102505.

in areas of biomimetic design, but by comprehensively devising novel engineered systems composed of living matter itself. Learning to design technological systems using “agential materials”[70] may require engineering considerations of the material, energetic, and organizational properties of living nonequilibrium systems and the characteristics of such systems which are instrumentally relevant to synthetic morphology—e.g., autopoietic and teleological causality, self-organization, adaptivity and agency.[71] Efforts in this field might also chart a path toward the symbiotic integration of a new class of biological artifacts into the broader dissipative flows that characterize the thermodynamic activity of organisms and ecologies.

This nascent field complements similar aims in other areas of synthetic biology, reflecting a general disposition toward engineering technological systems using biological and/or biochemical components and processes. These include applications in cellular agriculture and other bioeconomic platforms,[72] experiments in the design and construction of built environments grown using engineered living material,[73] as well as various efforts to transform industrial processes involved in chemical, pharmaceutical, and material manufacturing, energy and fuel production, and waste remediation via the deployment of metabolically engineered molecular systems.[74] Similarly, advances in biological computing point towards a potential future where emerging technological systems may hold the promise of operating more congruously with living dynamics as a result of biological embodiment. Notable examples include the development of microprocessors powered by photosynthetic algae[75] and early research into the use of stem cell-derived neural organoids in biological computing.[76]

Once more, although thermodynamics does not yet appear to be central to these advances in synthetic biology, the general impetus to explore the frontiers of engineered systems comprised of biological

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[70] Jamie Davies and Michael Levin, “Synthetic Morphology with Agential Materials,” *Nature Reviews Bioengineering* 1, no. 1 (January 2023): 46–59, https://doi.org/10.1038/s44222-022-00001-9.

[71] Deacon and García-Valdecasas, “A Thermodynamic Basis for Teleological Causality”; Tom Froese et al., “From Autopoiesis to Self-Optimization: Toward an Enactive Model of Biological Regulation” (bioRxiv, June 9, 2023), https://doi.org/10.1101/2023.02.05.527213.

[72] “Cellular Agriculture Society,” Cellular Agriculture Society, accessed June 23, 2023, https://www.cellag.org/.

[73] “HBBE – Biotechnology in the Built Environment,” accessed June 23, 2023, http://bbe.ac.uk/.

[74] “Ginkgo Bioworks | Industrials,” Ginkgo Bioworks, accessed June 23, 2023, https://www.ginkgobioworks.com/offerings/industrials/; Ahmad S. Khalil and James J. Collins, “Synthetic Biology: Applications Come of Age,” *Nature Reviews Genetics* 11, no. 5 (May 2010): 367–79, https://doi.org/10.1038/nrg2775.

[75] P. Bombelli et al., “Powering a Microprocessor by Photosynthesis,” *Energy & Environmental Science* 15, no. 6 (June 15, 2022): 2529–36, https://doi.org/10.1039/D2EE00233G.

[76] Lena Smirnova et al., “Organoid Intelligence (OI): The New Frontier in Biocomputing and Intelligence-in-a-Dish,” *Frontiers in Science* 0 (2023), https://doi.org/10.3389/fsci.2023.1017235.

matter may be a desired direction in the path toward living technology with embodied dissipative and metabolic properties.[77] It may indeed be one of the first steps toward the construction of a technosphere which can begin to match the amplified entropy-producing features of organisms and ecosystems, while reflecting life's ability to sustain dissipative activity without compromising its own existence. As researchers like Nail have indicated, a significant fraction of the planet's most effective dissipative systems (living ecosystems) have been, and continue to be, decimated as a result of the accelerated technological and economic growth associated with the Anthropocene, lowering the planet's total rate of entropic expenditure.[78] Relying on the affordances of our contemporary technosphere alone may be insufficient to compensate for this loss, as its dissipative properties appear to be both orders of magnitude less effective than the terrestrial biosphere's and its growth, self-maintenance, and stability are far from guaranteed.[79] Earth's biological systems may be incapable of evolving rapidly enough to respond to this change, as well, further deferring the emergence of novel entropy producing systems on a planetary scale. So, along with the many practical and imperative measures required to address various, profound transformations engendered by the Anthropocene, working towards the development of bio-engineered artifacts embodying the dissipative properties of living nonequilibrium systems could be a fruitful avenue towards post-Anthropocene terraforming in service of restoring and ideally augmenting a sustainable thermodynamic imperative for energy to spread—however abstract or imaginative this may seem at present.

Conclusion

In surveying a literature on the notion of entropy and its enabling role in the generation of self-organized complexity in open nonequilibrium systems, a throughline can be traced from non-living physical systems to forms of biological organization and activity at multiple scales—from individual autopoietic cells to planetary systems. The view that the conditions of a thermodynamic universe provide an impetus for the emergence and development of increasingly sophisticated vehicles for amplifying planetary rates of energy dispersal provides a conceptual paradigm for thinking about connections and

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[77] Perhaps one day we might traverse blurred boundaries between living and machinic in a manner similar to the Oankali of Octavia Butler's sci-fi novel *Dawn*, who maintain a symbiotic relationship with technological systems that are fully alive, composed of living tissues which are "both, and more" than plant and animal, and exhibit properties such as metabolism, growth and development, dynamic embodied responsiveness, and intelligence. Octavia E. Butler, *Dawn* (London : VGSF, 1988), http://archive.org/details/dawn0000butl.

[78] Nail, *Theory of the Earth*; Thomas Nail and Dorion Sagan, "A New Theory of the Earth: Thomas Nail and Dorion Sagan."

[79] For more on the possible shortcomings and self-undermining activity of the technosphere's energetic and material metabolic recycling processes, see Haff, "Technology as a Geological Phenomenon."

divergences between two global energetic systems: the biosphere and the technosphere. Drawing on theoretical biology and recent developments in bioengineering, we might aspire to imagine a future technosphere comprised of living matter, whose material, energetic, and organizational properties are more closely aligned with the nonequilibrium thermodynamics which permeate naturally ordered systems and the self-sustaining activity and constitution of life.

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