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Philosophy of thermodynamics

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Thermodynamics is regarded as a universal but not foundational theory because its laws for macroscopic quantities have not been derived from microscopic entities. Thus, thinking that the light quantum is the indivisible and permanent element, atomism is revived to root thermodynamics into the fundamental substance. Assuming the same basic building blocks constitute everything, the state of any system can be quantified by entropy, the logarithmic probability measure multiplied by Boltzmann's constant. Then, the change in entropy expresses the system's evolution toward thermodynamic balance with its surroundings. These natural processes consuming free energy in the least time accumulate sigmoidally, resulting in skewed distributions found throughout nature. In this way, thermodynamics makes sense of phenomena across disciplines and provides a holistic worldview to address questions such as what the world is, how we know about it, what is the meaning of life and how we should live.

This article is part of the theme issue ''Thermodynamics 2.0: Bridging the natural and social sciences (Part 1)'.

Research

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Cite this article: Annila A. 2023 Philosophy of thermodynamics. *Phil. Trans. R. Soc. A* **381**: 20220281.
https://doi.org/10.1098/rsta.2022.0281

Received: 20 December 2022
Accepted: 27 March 2023

One contribution of 11 to a theme issue 'Thermodynamics 2.0: Bridging the natural and social sciences (Part 1)'.

Subject Areas:
statistical physics, thermodynamics, complexity, biophysics

Keywords:
atomism, entropy, free energy, holism, statistical physics, thermodynamics

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1. Introduction

In 1959, C. P. Snow coined the phrase 'two cultures' to call attention to scholarly compartmentalization that troubles tackling the world's problems [1]. The British novelist framed the barrier between humanities and sciences by likening the nescience of the second law of thermodynamics to the illiteracy of Shakespeare's plays. Since then, disciplines might just have divided further and distanced further away from a comprehensive worldview needed now more than ever to revise our way of life for sustainable living.

In the quest after the yearned-for unifying view of reality, thermodynamics is not only an apt exemplar of science curriculum but the crux of the matter. Not surprisingly, Eddington [2] raised the second law of

THE ROYAL SOCIETY
PUBLISHING

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thermodynamics to the supreme position among the laws of nature. Likewise, Einstein [3] ranked thermodynamics as the only one among the theories of physics with the universal content.

Undoubtedly, the law, 'heat always moves from hot to cold', words a universal truth, and its generalization, 'energy always flows downhill', opens an all-inclusive outlook on causes and consequences dictated by the arrow of time. However, as Snow wrote, 'there is, of course, no value in just knowing it by the rubric in an encyclopaedia', but by comprehending its meaning [1]. So, what is the universal substance embodying energy in irreversible motion toward thermodynamic balance? Since textbook physics does not address the ontology of *enérgeia* 'activity' (Greek), perhaps the import of thermodynamics is not so obvious even for physicists, let alone laymen.

A law of nature, however comprehensive, need not be comprehensible. By definition, it is a rote that recaps data. By contrast, it is a theory that explains data. *Theōria* is a 'view' of the world, i.e. a worldview, from *theatron* 'theatre' literally 'place for viewing' (Greek). Thus, comprehending the meaning of all-encompassing thermodynamics requires knowing its standpoint, i.e. foundations.

Thermodynamics, the canon of change, is considered a universal theory but not a foundational one because macroscopic quantities, e.g. entropy, free energy, have not been derived from microscopic entities [4], say, from the fundamental element, *atomos* 'the non-divisible [particle]' (Greek) [5]. The ancient logic is ironclad; how else could one thing transform into another unless both are made of the same elemental entities? Thus, in the Aristotelian sense, metaphysics, a branch of philosophy rooted in empiricism, just might provide the foundation for thermodynamics.

Indeed, Ludwig Boltzmann, an adamant proponent of the atomic view of matter, aimed to derive the second law of thermodynamics from statistics of the microscopic composition of macroscopic bodies [6]. His idea of all substances irresistibly evolving toward thermodynamic balance echoes Gottfried Leibniz's argument about the world being the best of all possible worlds. Moreover, Boltzmann recognized this maxim about natural processes in Charles Darwin's doctrine [7]. However, Boltzmann's ambition to derive the most probable distributions of atoms from first principles resulted in the renowned equilibrium velocity distribution of gas atoms in a thermostated container, not the equation of evolution to the balance. Likewise, Gibbs [8] derived the most probable partition of molecules at chemical equilibrium in a reaction vessel but not the equation of evolution to the equilibrium.

Evolution entails changes of state, but Boltzmann discounted dissipated quanta. Therefore, he could not formulate the probability of a state along an evolutionary path to the special state of balance. Thereby, the optimal path to the optimum remained obscure [9]. Lecturing in 1899 at the decennial celebration of Clark University in Worchester, Boltzmann himself admitted his failure in relating the second law of thermodynamics to the variational principle of least action disclosing paths to balance [10].

As thermodynamics lacked a firm foundation, also the object of optimization remained ambiguous. Consequently, various non-equilibrium variational principles were formulated. Onsager and co-workers [11] saw natural processes evolving into more and more efficient energy conversion by minimizing dissipation. Likewise, Ilya Prigogine saw ever more efficient systems emerging with new means in the quest of minimizing entropy production [12]. Then again, for the systems to attain thermodynamic balance in the least time, the rate of entropy production ought to be maximal [13]. Without foundations, even the basic correspondence between minimizing free energy and maximizing entropy became unclear, and entropy was erroneously associated with the disorder. This contemporary conceptual disarray only accentuates the need for deriving thermodynamics from the atomistic axiom.

2. Statistical physics

Katástasi ta physiká 'the state of natural things' (Greek) can be taken for the arrangement of atoms. Despite its all-inclusive logic, Democritus criticized Parmenidean monism by asking, how could the atoms rearrange unless immersed in the void free of atoms?

Still today, the quintessence of the void and the essence of matter remain at least contestable, if not obscure. Even so, let us adopt the ancient axiom, at least to make a case for deriving thermodynamics from statistical physics by assuming that everything comprises indivisible entities, expressly light quanta. The thesis convinced Galileo Galilei [14] and Newton [15] once, and later Gilbert Lewis, who renamed Einstein's interpretation [16] of Max Planck's discovery of light quantum [17] the photon [18]. Shortly after, Blackett & Occhialini [19] showed that photons transform into pairs of electrons and positrons, and, in turn, Heiting [20–22], Joliot [23] and Thibaud [24] demonstrated the reverse process, where matter and antimatter annihilate each other into photons. In line with the wealth of observations consistent with the photons constituting everything, the second law stipulates that no transformation from one state to another occurs without photon absorption or emission.

On the whole, it is not inconceivable that the photon, carrying energy, E, on its period of least time, t, *is* the indivisible basic building block of everything. Paradoxically, the photon invariance, cemented in Planck's constant, $h = Et$, is malleable for a reciprocal change in E and t, seen as red and blue shifts. So, after all, this mechanical monism does not present an impermeable obstacle to rearrangement of *atomos* [5] since the void of photons is not fixed but fluid [25]. In this light of empirical evidence and rational arguments, the photon could be the atom of all natural things. So, let us proceed with it to set up statistical physics, the many-body theory underlying thermodynamics [26].

(a) The probability of an entity

The probability of an out-of-balance aggregate of quanta can be deduced from an energy level diagram (figure 1). Consider, for example, abiogenesis as an evolutionary process and ask what it takes for a particular molecule to exist in a primordial warm little pond. For one thing, any one substrate, indexed with k, when nil, $N_k = 0$, in a mathematical product, $\prod_k N_k$, excludes the molecule's existence. For the other, the energy difference, $-\Delta G_{jk}$, between the k-substrate and the j-product and the energy influx, ΔQ_{jk}, coupling to the jk-transformation, contribute to the probability,

$$ {}_1P_j = \prod_k N_k \exp\left[\frac{(-\Delta G_{jk} + \mathrm{i}\Delta Q_{jk})}{k_B T}\right], \tag{2.1}$$

where the energy differences are given in the scale-free exponential form, $\mathrm{d}\exp(x)/\mathrm{d}x = \exp(x)$, relative to the average energy, $k_B T$ [8]. The $k_B T$ concept, familiar from the zeroth law, defines the system to which the j and k entities belong. Likewise, energy, familiar from the first law, is an attribute of any system, because energy is the attribute of any photon, i.e. the fundamental constituent. In the exponent, i distinguishes energy in radiation, Q_{jk}, covering the whole spectrum of light quanta that couple to the jk-transformations, from energy in matter, G_j, the source of thermodynamic potential driving the jk-transformations. This notation opens closed, or stationary, systems of textbook statistical mechanics [27] for evolution by endergonic. i.e. absorptive, and exergonic, i.e. emissive, transformations [26,28]. The indexing by unconventional characters, j and k, serves to distract from conventional lines of thought and aims to prevent mistaking the introduced formalism for established concepts.

(b) The probability of a population

Next, consider a population of j-molecules. Again, if any one of the N_j molecules were missing, then ${}_1P_j = 0$ (equation (2.1)), and the probability of a population,

$$ P_j = \frac{({}_1P_j)^{N_j}}{N_j!}, \tag{2.2}$$

would be zero. In this way, P_j counts all j-entities, and the division by the factorial $N_j!$ accounts for the inconsequential order of identical entities.

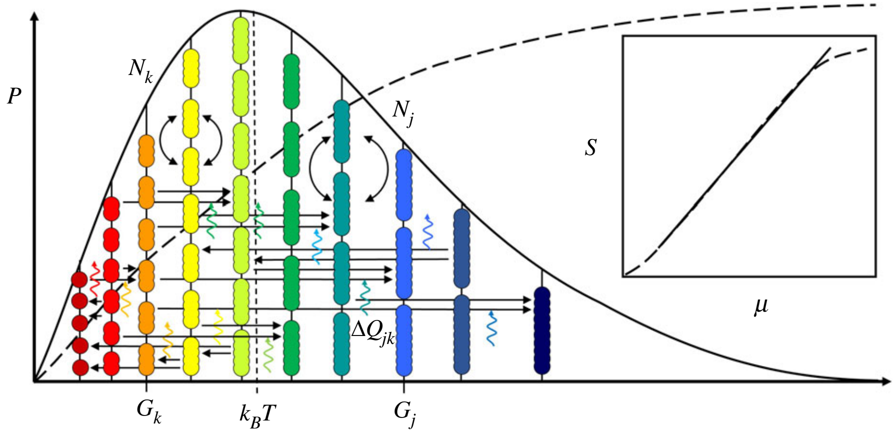

Figure 1. The general energy level diagram represents any system comprising quanta. Entities in numbers, N_k, of the same energy, G_k, relative to the average energy, k_BT, are on the same level. While their mutual exchange (bow arrows) causes no change, the system evolves toward balance with its surroundings through transformations (horizontal arrows) where quanta with energy, ΔQ_{jk} (wavy arrows), absorb into products, N_j, or emit from starting materials, N_k. The logarithm of the sigmoid, cumulative probability, P (dashed line), is entropy, $S = k_B \ln P$. On the logarithm–logarithm scale (inset), S versus potential energy, μ, mostly follows a power law, i.e. a straight line. (Online version in colour.)

(c) The probability of a system

Finally, the total probability of a whole system,

$$P = \prod_j P_j = \prod_j \frac{\left(\prod_k N_k \exp((-\Delta G_{jk} + \mathrm{i}\Delta Q_{jk})/k_BT)\right)^{N_j}}{N_j!}, \tag{2.3}$$

as the product, $\prod_j$, of P_j (equation (2.2)) over all populations ensures that if any one entity was missing, then $P = 0$. Since every entity can be expressed as a product of the elemental entities, the quanta, in numbers N_1, the probability, P, is the sought-after macroscopic measure of the state of a system deriving from microscopic elements. Consistently with atomism, also the state of the void comprising photons can be formulated accordingly to yield Bose–Einstein statistics underlying Planck's law of radiation [25,29].

The view of the world evolving irresistibly toward ever more probable partitions was Boltzmann's all-inclusive insight. Also, the contemporaries Francis Galton [30] and Peirce [31] understood evolution by natural selection to be a law of nature in a statistical sense. Since a law states a regularity, data are expected to display the same patterns over the scale the law applies. Indeed, irrespective of scale and scope, data are similar.

Already, Galileo Galilei knew allometry from the bones of mammals [32]. Later, the relationship of body size to shape, anatomy, physiology, metabolism and behaviour was realized by Snell [33], Thompson [34], Kleiber [35] and Huxley [36]. In turn, Pareto [37] noted the same relationship between population and wealth, Newcomb [38] and Benford [39] in the distribution of leading digits, Auerbach [40] in the populations of cities, Lotka [41] and Price [42] in publications, Gibrait [43] in the proportional growth rate of a firm and Zipf [44] in words.

Today, the wealth of data only speaks more conclusively for a universal law. Distributions are similar, skewed, nearly lognormal, rather than dissimilar, let alone arbitrary [45–51]. Cumulative curves of distributions are sigmoidal hence mostly following power laws [52]. These data patterns are on display from the cosmic microwave background to galactic jets, from mitochondrial to mammalian metabolism and from small purchases to world trade.

While mechanisms that generate scale-free, power law, lognormal and logistic distributions have been proposed [53–55], only recently has the regularity been ascribed to a natural law [56–58]. When the probability of statistical physics is transcribed into the entropy of thermodynamics, it is seen that the skewed distributions and their cumulative curves result from the probable motion toward thermodynamic balance. This analysis suggests that, indeed, all phenomena comply with the second law of thermodynamics.

3. Thermodynamics

Traditionally, thermodynamics describes the state of a system and its changes from one state to another in macroscopic terms. But now, the irreversible evolution toward thermodynamic balance, derived from the atomistic axiom using statistical physics, can be understood as a probable process in microscopic terms (equation (2.3)). This comprehension clarifies that free energy forces changes from one state to another.

(a) The equation of state

The statistical physics' probability, $P = \prod P_j$, the multiplicative gauge (equation (2.3)), translates, by taking logarithm and multiplying $\ln P$ with Boltzmann's constant, k_B, into an additive measure, $k_B \sum \ln P_j$, known as thermodynamic entropy,

$$\begin{aligned} S &= k_B \ln P = k_B \sum_j \ln P_j \\ &\approx k_B \sum_j N_j \left(\sum_k \ln N_k + \frac{-\Delta G_{jk} + \mathrm{i}\Delta Q_{jk}}{k_B T} - \ln N_j + 1 \right) \\ &= \frac{1}{T} \sum_{j,k} N_j(-\Delta\mu_{jk} + \mathrm{i}\Delta Q_{jk} + k_B T), \end{aligned} \tag{3.1}$$

where the approximation refers to $\ln N_j! \approx N_j(\ln N_j - 1)$. The total energy, TS, is bound in the populations, $\sum N_j k_B T$, and free in the differences, $\Delta\mu_{jk} = \mu_j - \mu_k$, between the potential, $\mu_j = k_B T \ln N_j + G_j$, of the j-product and $\mu_k = k_B T \ln N_k + G_k$ of the k-substrate as well as in the flux, ΔQ_{jk}, that couples from the surroundings to the jk-transformations. For example, absorbed insolation, ΔQ_{jk}, balancing differences in potentials $-\Delta\mu_{jk}$, sustains high-energy distributions of populations, so to say, dissipative structures [59]. For example, high insolation powers species richness in the tropics [60].

Entropy (equation (3.1)), as a mere logarithm of the probability (equation (2.3)), is a measure of energy per average energy, not of disorder. The common but erroneous association of entropy with disorder, by Boltzmann's tombstone equation, $S = k_B \log W$, originates from failing to derive S from first principles and ending up with a stationary-state condition for S. At a dynamical steady state, the system *exchanges* quanta, whereas when evolving, it *changes* in quanta. Thus, the dispersion in phase space among conceptual, yet empirically indistinguishable, microstates, counted in W [61], differs from the evolution from one state to another.

(b) The equation of evolution

Differentiation of the state equation (equation (3.1)) yields the equation of evolution [62],

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \sum_j \frac{\mathrm{d}S}{\mathrm{d}N_j}\frac{\mathrm{d}N_j}{\mathrm{d}t} = \frac{1}{T}\sum_{j,k} \frac{\mathrm{d}N_j}{\mathrm{d}t}(-\Delta\mu_{jk} + \mathrm{i}\Delta Q_{jk}). \tag{3.2}$$

As per textbook, $\mathrm{d}S = \bar{\mathrm{d}}Q/T$, the change in entropy, $\mathrm{d}S$, in a given temperature, T, is a path-dependent process, driven by free energy, $-\Delta\mu_{jk} + \mathrm{i}\Delta Q_{jk}$. So, the system evolves along the paths of jk-transformations until $\mathrm{d}S/\mathrm{d}t = 0$ (equation (3.2)). When all free energy is consumed, influx and efflux tally. Then, free energy is at minimum, $\sum_{j,k} N_j| - \Delta\mu_{jk} + \mathrm{i}\Delta Q_{jk}| = 0$, and entropy is at maximum, $S = k_B \sum N_j$ (equation (3.1)).

The free energy consumption along a path toward balance corresponds to the rate of irreversibly lost work, $\mathrm{d}W/\mathrm{d}t = T\,\mathrm{d}S/\mathrm{d}t$, as expressed by the Gouy–Stodola theorem [63–65]. However, the practical aspect of optimizing processes, e.g. photosynthesis or combustion, by minimizing irreversible losses should be understood so that systems evolve in efficiency to attain ever closer thermodynamic balance with their surroundings. Moreover, while dissipation, or in general emission or absorption of quanta, couples to the least-time free energy consumption, the thermodynamic objective is not to minimize dissipation *per se* [11] but *en masse* to attain balance where net dissipation vanishes. Likewise, the target is not minimizing entropy production [12] but to gain balance where entropy is at maximum. Also, the idea of maximizing entropy production [13] parallels gaining balance in the least time but, then again, is only implicit in the aim of attaining balance.

(c) The rate equation

The statistical physics-derived thermodynamics (equation (3.2)) by indexing *jk*-pathways is consistent with the least-time kinetics down along the gradients in free energy, never over barriers, when populations change at the rate,

$$\frac{\mathrm{d}N_j}{\mathrm{d}t} = \frac{1}{k_B T}\sum_k \sigma_{jk}(-\Delta\mu_{jk} + \mathrm{i}\Delta Q_{jk}), \tag{3.3}$$

proportional to the mechanisms, σ_{jk}, that transform free energy into the bound energy [52,66]. For example, catalysts speed up chemical reactions, not lowering fictional activation energy but enlarging factual flux. Thus, the more effective the mechanism, the faster the entropy increase and the faster the free energy decrease. This imperative drives the emergence of ever more efficient dissipative structures [59]. In biological lingo, the flows of energy *naturally select* paths with efficient mechanisms to attain balance in the least time. The fittest [mechanisms] survive, and conversely, other paths drain dry [67]. Paraphrasing Darwin, 'it is not the most intellectual of the species that survives; it is not the strongest that survives, but the species that survives is the one that is able best to adapt and adjust to the changing environment in which it finds itself' [68].

From the derived scale-free standpoint, a mechanism itself is a system of its own. For example, an enzyme is a system of atoms that evolves with time to become ever more effective in attaining balance. Such molecular evolution, like evolution in general, directs along the lines of force. The flows of energy *naturally select* those mechanisms that increase entropy in the least time. For example, genes, the 'aperiodic crystal' [69], surfaced to serve evolution, not to supervise it [70,71], as Waddington [72] understood. Also, the branching patterns of phylogenetic trees testify to the multiplicative nature (equation (2.3)), i.e. allometric law [73].

Inserting equation (3.3) into equation (3.2) and squaring proves the renowned inequality, $\mathrm{d}S/\mathrm{d}t \geq 0$. Conversely, its imaginary violation would conflict with the conservation of quanta. Energy differences can only diminish as the quanta move from the system to the surroundings or vice versa. Consequently, the system and its surrounding system coevolve in line with *panta rhei*, 'everything flows' (Heraclitus). Therefore, 'No man ever steps in the same river twice. For it's not the same river and he's not the same man.'

(d) The continuous equation of motion

Like flowing water, many motions appear continuous. So, it is useful to substitute the discrete scalar, μ_j, and vector, Q_j, potentials in equation (3.3) with differentials, $\mu_j = \partial U/\partial N_j$, and $Q_j = \partial Q/\partial N_j$, to obtain the continuous equation of motion [52]

$$T\frac{\mathrm{d}S}{\mathrm{d}t} = \sum_j \frac{\mathrm{d}N_j}{\mathrm{d}t}\left(-\frac{\partial U}{\partial N_j} + \mathrm{i}\frac{\partial Q}{\partial N_j}\right) = -\frac{\partial U}{\partial t} + \mathrm{i}\frac{\partial Q}{\partial t} = \frac{\mathrm{d}}{\mathrm{d}t}2K. \tag{3.4}$$

It says, for example, that an influx or efflux of photons, $\mathrm{d}Q$, causes changes in the potential, U, and kinetic, $2K$, energy. Consistently with the continuity approximation, the path dependence, $\bar{\mathrm{d}}Q$, inconsistent with paths that are infinitely close, is substituted with $\mathrm{d}Q$.

Eventually, when the system attains thermodynamic balance with its surroundings, influx and efflux tally. Then the steady state, $\mathrm{d}2K/\mathrm{d}t = 0$, integrates to the familiar virial theorem, $2K = -U$, where the energy in motion matches the energy in potential. In other words, the general equation of imbalance contains the special state of balance.

It is also insightful to see that Newton's second law of motion, force, $\mathbf{F}$, multiplied with velocity, $\mathbf{v}$,

$$\left.\begin{aligned} \mathbf{F} &= \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = m\mathbf{a} + \mathbf{v}\frac{\mathrm{d}m}{\mathrm{d}t} \\ \text{and} \qquad \mathbf{v}\cdot\mathbf{F} &= \mathbf{v}\cdot\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t}\cdot m\mathbf{a} + \mathbf{v}\cdot\mathbf{v}\frac{\mathrm{d}m}{\mathrm{d}t} = -\frac{\mathrm{d}U}{\mathrm{d}t} + \mathrm{i}\frac{v^2}{c^2}\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{\mathrm{d}U}{\mathrm{d}t} + \mathrm{i}\frac{\mathrm{d}Q}{\mathrm{d}t} \end{aligned}\right\} \tag{3.5}$$

yields the continuous equation of evolution (equation (3.4)). The change in mass, $\mathrm{d}m$, relates by mass-energy equivalence, $E = mc^2$, to the dissipated quanta, $\mathrm{d}Q$, to a medium, characterized by the index of refraction $n = c/v$. The surrounding void absorbs dissipated quanta in accordance with a complex-valued refractive index describing light propagation in absorbing medium [74]. Conversely, if the change in mass was neglected, the change of state would not be accurately accounted for [75].

Customarily, mass-energy equivalence is deemed as Einstein's relativistic formula, but it is just a special case of the general formula for kinetic energy, mv^2, where velocity, v, is the speed of light in the vacuum, c. The general relation, confirmed by Willem's Gravesande in the early eighteenth century, was only later halved into $\frac{1}{2}mv^2$ when the change in kinetic energy of the surroundings was omitted. For example, a stone rolling down a slope gains kinetic energy but concurrently also, the landscape changes. Initially, the stone was on the hilltop, finally at the valley bottom. Thus, by flattening, the landscape moved too.

In summary, the second law of thermodynamics maintains that regardless of complexity, all we witness are quanta in evolution along the lines of force. This simple principle of consuming free energy in the least time may nevertheless seem too simple, as if overlooking details and subtleties. However, data, undeniably similar across disciplines, speak for the offered holistic tenet.

4. Analyses

Customarily, a theory is evaluated against empirical evidence and contrasted with existing knowledge. To this end, the characteristics of the least-time free energy consumption are deduced from the equation of evolution (equation (3.2)) and rate equation (equation (3.3)).

(a) Non-determinism

The second law of thermodynamics, equivalent to the principle of increasing entropy, portrays all events as probable processes, i.e. irreversible motion downhill in free energy. While the equation of motion (equation (3.2)) can be written in exact terms, it cannot be solved exactly because the variables cannot be separated. Expressly, the change in a population, $\mathrm{d}N_j/\mathrm{d}t$ (equation (3.3)), driven by decreasing free energy, cannot be integrated into $N_j(t)$ because N_j is contained in the free energy component, $\mu_j = k_BT\ln N_j + G_j$. The non-integrability means that an initial state does not determine a future state, but any given state depends on the path taken.

Although the future is *non-determinate*, it is not all arbitrary, i.e. *indeterminate*, but bounded by free energy. Namely, indeterminism is excluded as a non-physical idea because only forces cause changes according to Newton's second law of motion (equation (3.5)). But so is also *determinism* excluded because, in reality, changes bring forth new forces causing changes, and so on. The future is predictable only as much as forces are present, not beyond. In other words, the least-time quest for thermodynamic balance is a teleological tenet, however, not a predestined paradigm.

So, non-determinism following from non-integrability does not put causality at stake; on the contrary, the atomistic axiom concretizes causality; the photon, propagating down along energy gradients, sets the arrow of time by carrying energy on its period of time [76,77]. Conversely, natural processes are reversible only as much as there is free energy and mechanisms to run reverse reactions.

Although the evolutionary trajectories cannot be calculated exactly, like stationary orbits, their law-like characteristics are still unambiguously discernible. Namely, throughout nature, we find data that follow sigmoid growth curves, approximately power laws, and display skewed, nearly lognormal distributions [46–48,52].

(b) Sigmoid cumulative curve

According to the rate equation, equation (3.3), the *s*-shaped cumulative curve shoots up initially, nearly exponentially, $N_j(t) \propto \exp(\sum_k \sigma_{jk} t)$, when the system is consuming seemingly unlimited reserves of free energy by elementary mechanisms, σ_{jk}. Conversely, in the end, the curve decays as $N_j(t) \propto \exp(-\sum_k \sigma_{jk} t)$ when matured mechanisms are exhausting resources. The intermediate growth, $\mathrm{d}N_j/\mathrm{d}t = j\alpha_j N_1^{j-1}\,\mathrm{d}N_1/\mathrm{d}t = j(N_j/N_1)(\mathrm{d}N_1/\mathrm{d}t)$, integrates into a power law, $\ln N_j = j \ln N_1 + \text{constant}$, since quanta, in numbers N_1, constitute all populations, $N_j = \prod_k N_k \exp[(-\Delta G_{jk} + \mathrm{i}\Delta Q_{jk})/k_B T] = \alpha_j N_1^j$, through *mn*-transformations, $\alpha_j = \prod_{mn} \exp[(-\Delta\mu_{mn} + \mathrm{i}\Delta Q_{mn})/k_B T]$. In other words, evolution is not gradual progress but advances through punctuations and stases [78].

In case the condition, $|-\Delta G_{jk} + \mathrm{i}\Delta Q_{jk}| \ll k_B T$, does not hold, but free energy is comparable with the average energy, the course of events becomes oscillatory or even chaotic [52,79]. Still, the resulting time series is not random but follows a power law [80–82].

Also, Newton's second law of motion, equation (3.5), divided by momentum, $p = mv$, and multiplied by $\mathrm{d}t$, yields $\mathrm{d}p/p = \mathrm{d}v/v + \mathrm{d}m/m$, which integrates to $\ln p = \ln v + \ln m$, i.e. a straight line on a log–log plot. For example, avian body mass, m, relates in this power-law manner to the metabolic power at cruising speed, v [83].

(c) Skewed distribution

The form of density in energy, equation (2.1), Gibbs [8] matches ubiquitous skewed distributions, which are nearly lognormal when the variation, n, is small, $n \ll j$, about the average, j. Then the logarithmic factors, $\ln \phi_{j-n\cdots j+n} = \ln \phi_j + \sum_n n \ln \phi_1$, distribute about the average density in energy, $\phi_j = N_j \exp(G_j/k_B T)$, given in terms, $\ln\phi_j = j \ln \phi_1$, of the elemental factor, ϕ_1, approximately in a normal manner according to the central limit theorem. In other words, a distribution optimal in energy is skewed. Conversely, the normal distribution is a misnomer. Such a symmetrical distribution implies that energy differences, i.e. forces, are vanishing. Such a random variation, despite a fundamentally flawed model, is a practical approximation near balance where the forces are small.

Since the least-time free energy consumption results in skewed distributions summing up along sigmoid curves, deviating at low and high ends from the power law [50,84], the logical conclusion is that the ubiquitous patterns in data display one and the same principle.

In summary, thermodynamics based on the atomistic axiom maintains that every system evolves toward balance with its surrounding systems through flows of quanta that even out energy differences in the least time. In general, the surroundings are superior to the system. Even then, also the habitat adjusts to the animal adapting to its habitat. Likewise, numerous communities acclimating to local climates amount to the anthroposphere affecting the atmosphere. But as we witness, the changing climate strikes back to human habitats. Thus, in the hierarchy of systems within systems, every system is eventually at the mercy of its surrounding system, ultimately the cold space, the vast void.

5. Discussion

Thermodynamics deriving from atomism is, by definition, an all-encompassing theory, even a philosophy addressing such questions as what the world is, how we know about it, what is the meaning of life and how we should live. In reference to C. P. Snow [1], the tenet roots the two cultures into one worldview.

(a) Ontology

The thought that everything comprises the same substance is found in the first philosophy of Thales and his students, Anaximenes and Anaximander. It developed into atomism by Parmenides and Leucippus and Democritus. However, only much later, during the sixteenth and seventeenth centuries, atomism regained interest among natural philosophers, most notably Isaac Beeckman, René Descartes, Baruch Spinoza, Gottfried Leibniz, Pierre Gassendi, Robert Boyle, Henry Percy, Francis Bacon, Giordano Bruno, Thomas Hobbes and Thomas Hariot. Specifically, Galilei [85] and Newton [15] considered that the corpuscle of light could be the basic building block. And explicitly, in 1926, Lewis [18] coined the photon as the atom.

However, the all-inclusive idea never really caught on [86]. Quantum mechanics turned the tables, and today the photon just stands for a quantum of the electromagnetic field [87]. As traditional theorizing, from ontological axioms to testable equations, gave way to mathematical modelling, hypothesized equations became the object of unnatural interpretations instead of nature remaining the subject of mathematization. This instrumental stance reproduces data successfully but leaves the data unexplained, even regarding the world as profoundly inexplicable.

However, persisting problems suggest that instrumentalism is not enough, perhaps even complicating matters with illogical concepts. For example, elementary particle reactions imply that the elementary particles are not genuinely elemental but compounds of common constituents. Namely, the electron and proton do transform into the neutron and neutrino [88,89]. Moreover, presumed dimensionless pricks, however handy mathematically, could hardly produce properties such as charge, magnetic moment and mass. For instance, the electron only appears as a point-like particle at experimentally accessible energies [90] but breaks into pieces, e.g. into the W^- boson and neutrino. Also, the quarks having fractional charges of the electron or positron suggest that the elementary particles are not elementary, but compounds—logically—of photons since all particles annihilate with their antiparticles into photons which are their own antiparticles.

Moreover, energy as the universal attribute implies that everything comprises the same fundamental element. By carrying energy on its period of time, the light quantum also renders time real. The flow of time *is* the flux of quanta. Thus, thinking that the photon is *atomos* concretizes metaphysics, the first principles of being.

The thought that the photon is the basic building block has both rational and empirical merits [91,92]. For one thing, the photon invariance, fixed in Planck constant, $h = Et$, is still flexible for a reciprocal change in energy, E, and time, t. Thereby the fundamental element itself adopts a change and adapts to changes. For the other, we can see and sense photons to know the photons by experience [93]. Thereby, we can trace thermodynamic inferences back to the atomistic axiom, falsifiable by our own senses. Conversely, the offered thought style would collapse if it were shown that there exists something that is not composed of photons or that the photon could be divided into pieces.

(b) Epistemology

Consistently with atomistic holism, the least-time free energy consumption itself describes the acquisition of information as a photon-mediated process. First, the obtained information is invariably subjective because the photon propagates from its source to only one receiver instead of many. Second, the same message can produce different, even opposite, meanings in different receivers because incorporating, i.e. interpreting, the received photon depends on how the receiver system consumes the free energy associated with information. In this sense, communication is meaningful only when it entails misunderstanding, for if there were perfect understanding, the sender and receiver systems would be identical, and no communication would make any difference.

As a theory of knowledge, thermodynamics only involves what exists. The substance emitting quanta is the source of information, and the absorbed information causes changes in the receiver characteristics [94,95]. This is the way how we come to know what we know. In other words, learning always takes place in a context. Broadly speaking, the context is all the history there is, or narrowly seen, the context is the past that produced an individual, cultural or social setting.

Importantly, the extracted quanta change not only the receiver but also the target of inquiry. For a large system, the loss of a few quanta hardly makes a difference, but the change of state is apparent, for example, when an atom emits a photon. In accordance with Heisenberg's uncertainty relation, no state can be known more precisely than by one quantum. The induced change can be dramatic. As Pascual Jordan put it, 'Observations not only disturb what is to be measured, they produce it'. [96] Of course, it is not only microscopic but also macroscopic systems, say social systems, that respond to investigations, just as they react to other influences, by changing their character and behaviour.

Furthermore, the least-time principle acknowledges that every piece of information comes with some subjective cost and that every piece of information is interpreted in some subjective way. In other words, also when acquiring information, the path along the steepest descent in free energy is different for different subjects. Consequently, while a piece of information is easy to absorb by one, another cannot fit it into the mindset and may even discard it at face value. As Fleck [97] put it, 'The individual within the collective is never, or hardly ever, conscious of the prevailing thought style, which almost always exerts an absolutely compulsive force upon his thinking and with which it is not possible to be at variance'.

(c) The meaning of life

The meaning of life may seem an elusive philosophical question but not at all obscure from the thermodynamic viewpoint.

First, thermodynamics does not recognize living as distinct from non-living but regards everything as quanta, thus eradicating any remnant of vitalism. For example, unveiling the origin of life is an ill-founded inquiry since we have no evidence of life [98]. Namely, the data do not distinguish the animate from the inanimate. Logically, all we witness are quanta in evolution down along the gradients in free energy. However, although not a proper concept, the thermodynamic tenet does not deny the value of a living being. On the contrary, thermodynamics puts everything on the same scale of energy.

Second, the meaning, as intent, motivation or purpose, relates to energy differences, forces that make things happen. Basically, the greater the meaning, the more consequential the forces are. While this stance may seem grossly simplifying, the summation over all forces (equation (3.2)) takes into account all subtleties that project the least-time path into the future. Thereby thermodynamics also explains that the meaning of life becomes an acute issue at times when forces are negligible. Expressly, motivation is a motive force. It aims at finding a way out, i.e. making a change of state [99]. Also, conflicting forces cause anxiety about how to move on.

Thermodynamics parallels pragmatic thinking, where outcomes measure meanings, but equally well, the tenet tallies correspondence theory, where the claimed state of affairs must hold true, with the factual state. Accordingly, thermodynamics recognizes that social processes produce meanings, like any other process, but demands substance backing up truths for the truths to be falsifiable.

Consistently with philosophizing meanings as subjective, thermodynamics sees the subject as a system. Basically, the more forces the subject takes into account, the more objective the course of events. Such cumulative relativism ultimately discloses irrefutable forces, absolute truths, those things that could not be otherwise. For example, free energy can only decrease in the least time, no matter what.

The thermodynamic take on the course of events as free energy consumption is a teleological tenet but not a deterministic stance because causes, i.e. forces, are inseparable from consequences, i.e. changes in motion. In other words, while destiny, the balance, is the goal, it cannot be known or predetermined in advance because the outcome depends on the path taken.

Indeed, path-dependent teleology is inherent in Charles Darwin's theory of evolution. The fittest are those means and mechanisms that forward the system toward thermodynamic balance with its surroundings in the least time, hence *naturally selected*. Kurt Goldstein worded this adaptation so that each organism is actualizing its subjective potentiality as it comes to terms with its environment [100]. In economics, Walras [101] expressed the same non-determinate search for the optimum by trial and error as *tâtonnement* (French). In behavioural sciences, the maximization of entropy subsumes the maximization of utility [102], offered by Morgenstern & von Neumann [103]. In turn, Nietzsche [104] put the thermodynamic drive in psychological terms as *the will to power*, where self-determination actualizes one's will onto one's self and one's surroundings.

The will to choose a path is free as much as one has energy free to make things happen. Accordingly, one has the power to do otherwise as much as one has forces to do so. And conversely, it is not realistic to attribute free will to acting free from circumstances because everything depends on everything else. For example, the surrounding forces curtailing free will are on display as explicit physical obstacles or implicit impediments subsumed in one's ethics and the community's morals.

By the same token, it is irrelevant to contrast free will with causal determinism because causality does not entail determinism but non-determinism, distinct from indeterminism, i.e. randomness. While, at times, the struggle between forces may resolve itself only by a hair's breadth, it still happens by some force, however, feeble and fleeting. Conversely, when only one force dominates, the course seems next to deterministic. For example, paths to other possible worlds are hardly open when a rock, instead of a feather, falls down.

Thermodynamics as a view of the world also translates into political philosophy. For example, when gauging progress by increasing energy, wealth disperses and its skewness diminishes, similar to changes in the distribution of radiation with increasing temperature. The political debate on how to distribute wealth in a society can be compared to collisions of gas molecules in a container or to interactions between and within species in an ecosystem to discover the optimal distribution. For example, along the lines of classical liberalism, pioneered by Chydenius [105] and Smith [106], entropy increases with increasing freedom as it invites more and more forces into the shaping of society [107]. For example, freedom of speech, freedom of assembly, freedom of the arts and sciences and freedom to choose an occupation engage people in entropy production instead of shutting them out. Similarly, transparency in actions exposes forces and mechanisms that might obstruct the most voluminous flows of energy.

Paradoxically, freedom requires restrictions. Regulations prohibit, among other things, monopolies, cartels and the misuse of insider information, to ensure that as much as could happen will happen. The laws protecting property, infrastructure and capital secure means and mechanisms that make things happen. Thus, a restriction for some is a construction for many. For example, a cell wall, just like a city wall, protects numerous transactions by preventing intrusions.

In essence, free energy consumption in the least time is the final cause in the Aristotelian sense. It motivates everything.

(d) Our way of life

C. P. Snow argued that the compartmentalization of intellectual life impeded solving the world's problems that, by now, half a century later, have become more acute and more global. Climate change, the loss of biodiversity and dwindling natural resources signal that we are not on the way to sustainable planetary subsistence, thermodynamically speaking, to a stationary state [108,109]. Instead, we are led astray by following the formidable forces contained in fossil fuels. Conversely, we would be on the right track by complying with the strongest force, i.e. insolation. The total global-scale human activity, the anthroposphere, ought to align parallel with the planetary forces. So too, did the biosphere that emerged eons ago from the geo-, hydro- and atmosphere. It diminished the energy difference between the insolation and matter on the Earth. This natural quest of biota for planetary balance accumulated high-energy oil, gas and peat deposits. Likewise, instead of reducing, our activities ought to raise the Earth's energy content.

No question we tackle the problems we cause. From the thermodynamics perspective, eradicating powerful carbon absorption mechanisms, most notably forests, is especially damaging now that carbon emission is increasing. In addition to the direct greenhouse effect, the uprooting carbon fixation mechanisms couples with decreasing heat transfer to the upper atmosphere due to declining rainfall and evaporation. Indeed, we have awakened to the consequences of our way of life. By consuming more and more, we leave less and less to many other forms of life. Colossal consumption of fossil fuels has detached us from the whole, but only for a while. In the end, the loss of biodiversity will cut our access to essential resources.

The existential question is whether the anthroposphere transforms from dissipating matter-bound quanta into absorbing insolation to align with the bio, geo-, hydro- and atmosphere. Even now, when such a goal has become crystal clear, the items in the pans of balance are hard to weigh in practice. While we have begun to rate ecosystem services and natural capital in terms of money, it would be genuinely commensurate to price all services and assets in terms of energy. Then the flows funnelling through our hands would be on the same universal scale as all other flows to guide our course away from consuming into sustaining.

Data accessibility. This article has no additional data.

Author's contributions. A.A.: conceptualization, formal analysis, visualization, writing—original draft, writing—review and editing.

Conflict of interest declaration. I declare I have no competing interests.

Funding. No funding has been received for this article.

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