A fresh framework for education in thermodynamics by field theory

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Abstract

Present article concludes a trilogy started with the work of Serpa & Fernandes [1] and motivated by the research of Serpa, Cathcart & Varison [2], the latter published in this journal. The main idea is to bring to the public of students, professors and researchers initiated in thermodynamics the potential for expansion and innovation of this discipline in domains ranging from technological applications that meet human needs to the formulation of cosmological theories in tune with the new astronomical discoveries that surprise us at everytime. The Second Law of Thermodynamics is reviewed in a realistic perspective with respect to the universe as it appears to us, seeking to eliminate misunderstandings about the concepts of entropy and reversibility. The theory presented expands the generalization of the field concept, assuming it as a non-massive heat scalar, the caloric field, whose diffusion leaves its own entropy registered. The work establishes the basic principles for the correct learning of thermodynamics, eliminating fictional notions that distort not only the meaning of Law II, but also the meaning of evolution in the cosmic sense. This study also emphasizes the creative character of entropy, unlike classical texts that only describe it as a kind of measure of degradation.

Keywords: Entropy, Thermodynamics, Caloric field, Second Law, Irreversible process, Innovation.

Resumen

El presente artículo concluye una trilogía iniciada con el trabajo de Serpa & Fernandes [1] y motivada por las investigaciones de Serpa, Cathcart & Varison [2], este último publicado en esta revista. La idea principal es acercar al público de estudiantes, profesores e investigadores iniciados en la termodinámica el potencial de expansión e innovación de esta disciplina en dominios que van desde las aplicaciones tecnológicas que satisfacen las necesidades humanas hasta la formulación de teorías cosmológicas a tono con los nuevos descubrimientos astronómicos que nos sorprenden en todo momento. Se revisa la Segunda Ley de la Termodinámica en una perspectiva realista con respecto al universo tal como se nos presenta, buscando eliminar malentendidos sobre los conceptos de entropía y reversibilidad. La teoría presentada amplía la generalización del concepto de campo, asumiéndolo como un escalar de calor no masivo, el campo calórico, cuya difusión deja registrada su propia entropía. El trabajo establece los principios básicos para el correcto aprendizaje de la termodinámica, eliminando nociones ficticias que distorsionan no solo el significado de la Ley II, sino también el significado de la evolución en el sentido cósmico. Este estudio también enfatiza el carácter creativo de la entropía, a diferencia de los textos clásicos que solo la describen como una especie de medida de degradación.

Palabras clave: Entropía, Termodinámica, Campo calórico, Segunda Ley, Proceso irreversible, Innovación.

I. INTRODUCTION

The way physics is taught has always bothered us. The boring and repetitive high school classes with their trains moving in opposite directions, the electromagnetism classes in higher education restricted to 19th century physics, the conventional exams without any stimulus to creative thinking, the tiresome lists of exercises just to make a hell the life of those who were in search of a true understanding of how things are in their essences, all this conspiring in the opposite direction of inquiring thought. About this, it would be difficult to speak more directly than Rovelli:

"*What attracted me to physics was the suspicion that behind the deadly tedium of high school physics, behind the stupidity of exercises with springs and levers and rolling balls, there lurked a genuine curiosity to understand the nature of reality*"[3].

Luckily, we had a few like-minded professors, so we took the space they gave us and went ahead. On the other hand, it was difficult to survive the thermodynamics classes. No one can doubt the essentiality of thermodynamics for the understanding of the universe, although the confusion created around the Second Law over decades has contributed to its relative stagnation. The one-sidedness expressed by Law II makes clear that reversibility is an appearance resulting from anthropic processes that emulate reversion. If we want to reach the real and full scope of the Second Law, it will be necessary to translate thermodynamics in terms of concepts that are more general to apply to the most diverse circumstances. Strictly speaking, this necessity stems from the fact that the laws of thermodynamics are expressed by primitive functions, and not by differential equations, a characteristic that makes them less general than the laws of motion and gives the impression that the strong empirical basis of thermodynamics makes it extremely restricted. The fact that such laws are expressed by primitive functions does not mean that thermodynamics is restricted to laboratory approaches as one might think at first.

One of those most general concepts is the so-called "caloric field", which intends to describe all processes of transformation and interchanging of thermal energy. Ultimately, the theory of caloric field is the axiomatization of certain initially tacit basic premises for the control of entropy in thermal systems of condensed matter transformation, with evident potential for application in solid waste recycling plants. Whilst it does not follow directly from the theory, the motto that entropy cannot decrease, only decelerate in its advance, is presumed as a fundamental principle. Subsequently, the system of hypotheses evolved for applications in cosmology (in practice, the applicability of the field concept is independent of scale). In summary, the theory states that any region of space confined by a given neighborhood retains an amount of heat featured by a complex non-massive scalar field — the caloric field — whose evolution equation includes the entropy trail of the field itself, being the flow of this entropy analyzed at the borders of the region. In the context of general relativity, instead of ordinary space, it is introduced the four-dimensional continuum, so that it becomes possible to theorize about time-like regions.

This article is an attempt to show how a fundamental theory can be taught in an innovative and generalizing way, bringing new aspects for reflection and improvement of learning.

II. WHAT IS THE CONTENT OF LAW II?

Entropy is associated with the Second Law of thermodynamics, commonly defined by the statement that in any ordered system (independently open or fictionally closed), there exists a propensity for decay to a state of disorder, being this propensity only anthropically “attenuated” under an external supply of energy directed to build order. An eloquent explanation, no doubt; but, the problem begins when one understands "propensity" as a kind of "breach" for something to happen contrary to what it should. In this case, we can replace "propensity" with "inescapableness", that is, a physical obduracy towards thermal inertia. In other words, there is no “going back”, although the inexorable final outcome can be postponed. In addition, although we ourselves have used the term "order", we believe that at this point of clarification it is convenient to abandon it, giving way to a more precise terminology, say "thermal-life span" (and “thermal extinction” in place of “disorder”). Anyway, here it is the true meaning of Law II: “there exists an inescapableness for the worldwide decay to a state of thermal extinction”. It follows that thermal systems engineering is the art and technique of slowing down the advance of entropy with maximum efficiency of the energy conversion cycles.

Of the countless authors who have tried definitions of entropy — most of them shrouded in confusion —, there are two who have done so in accordance with the content of Law II, namely

1)- Lecomte du Noüy — defined entropy as a function whose value depends on the current state of the system regardless of its generalized trajectory of evolution; moreover, we don't know its absolute value, only its variation [4];

2)- André Lalande — presented an objective definition: “Entropy is a function whose variations make it possible to give a quantitative expression to the Second Law of thermodynamics” [5].

Note that neither makes mention of probabilities. These definitions are straightforward and free from interpretations, being applicable in all discussions of reversibility and complexity. From an industrious pragmatic point of view, as Wang observed, classical thermodynamics emphasizes the degradation of isolated systems, while modern thermodynamics emphasizes the continuous evolution of non-equilibrium systems under a permanent energy supply [6]; that is, in contemporary perspective, the naturalness of open systems and the creative implications of their interactions are assumed.

A. Causation chains, thermal-life span and thermal extinction

Causation chains generate the configurations of matter and energy. They constitute the thermal-life spans of the sequences of events, and their wears accumulate until thermal extinction. They began with the Big-Bang, the very low entropy starting point. Some chains are more persistent than others, enduring despite the multiple interactions they experience. However, with time, these too will be broken.

This positioning summarizes causality seen through the prism of the flow of entropy, always present where there is cause and effect. From that perspective, it is absolutely timely to claim that reversibility is a fiction, at best a well-intentioned school attempt at simplification that, unfortunately, leads to nescience. Entropy does not go backwards, nor does the time that elapses between cause and effect. There is no true reversal, only episodes of transient equilibrium, which will evermore occur at different times in the temporal sequence[1]. In the precise saying of Norton [7],

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[1] The fact that they occur at different times is enough to understand why there is no reversibility; because there are no closed systems, the return to equilibrium requires systemic interactions that inevitably change neighborhoods and the system itself internally. On the implied topology, please see reference [1].

“The label ‘thermodynamically reversible process’ denotes a set of irreversible processes in a thermal system, delimited by the set of equilibrium states”[2].

Thus, the idea of reversibility expresses a rough and fanciful approximation focused in the extremes of equilibrium, which are only brief transient flaws of irreversibility.

B. Caloric field: just the essentials

The caloric field theory has its origins in the early 2000s, having been compiled in more recent works such as the publication of reference [1], in which the reader will find a complete approach and other specific references to the theory. For the purposes of this article, an overview of the main ideas plus some insights under discussion is sufficient. So let us take the field equation

$$\partial_q \partial^q \xi + \left(1-\gamma^2\right)\xi - \gamma^2 \xi \ln\left|\xi\right|^2 = 0\,,$$

or

$$\partial_q \partial^q \xi + \left(1-\gamma^2\right)\xi - 2\gamma^2 \xi \ln\left|\xi\right| = 0\,, \tag{1}$$

where ξ is a complex non-massive scalar field — the caloric field —, q is the generalized coordinate, and γ is one of the environment parameters of the theory [1]. The last term represents the entropy trail of the field left from its evolution.

It is easy to show that $\left|\xi\right|^2$ is invariant under phase transformations; thus, it can be included in a Lagrangian as

$$\mathrm{L} = \left(\partial_q \xi\right)^\dagger \left(\partial^q \xi\right) - \left|\xi\right|^2 + \gamma^2 \left|\xi\right|^2 \ln\left|\xi\right|^2\,, \tag{1a}$$

from which we derive equation (1) by means of Euler-Lagrange differential equation,

$$\frac{d}{dq}\left(\frac{\partial \mathrm{L}}{\partial \partial_q \xi^\dagger}\right) - \frac{\partial \mathrm{L}}{\partial \xi^\dagger} = 0\cdot \tag{1b}$$

From equation (1), we take the entropy S,

$$S = \int -2\gamma^2 \left|\xi\right|^2 \ln\left|\xi\right| dq\,. \tag{2}$$

which is sometimes hastily interpreted as a direct generalization of Gibbs entropy. By definition, the acceleration of entropy is given by

$$\frac{\partial^2 S}{\partial \tau^2} = -2\gamma^2 \frac{\partial^2}{\partial \tau^2} \int \left|\xi\right|^2 \ln\left|\xi\right| dq =$$

$$= -2\gamma^2 \frac{\partial^2}{\partial \tau^2} \int \xi\xi^\dagger \ln\sqrt{\xi\xi^\dagger}\, dq\,. \tag{3}$$

Now, we may take the generalized coordinate q as an arbitrary time function,

$$q = f\left(\tau\right),$$

so that the calculation sequence allows us to deduce

$$\frac{\partial^2 S}{\partial \tau^2} = -2\gamma^2 \int \Bigg\{ \Bigg[\left(\ddot{\xi}\xi^\dagger + 2\dot{\xi}\dot{\xi}^\dagger + \xi\ddot{\xi}^\dagger\right) \ln\left(\xi\xi^\dagger\right)^{1/2} +$$

$$+ \frac{\left(\dot{\xi}\xi^\dagger + \xi\dot{\xi}^\dagger\right)^2}{2\xi\xi^\dagger} + \frac{1}{2}\left(\ddot{\xi}\xi^\dagger + 2\dot{\xi}\dot{\xi}^\dagger + \xi\ddot{\xi}^\dagger\right) \Bigg] \dot{f}(\tau) d\tau +$$

$$+ \xi\xi^\dagger \ln\left(\xi\xi^\dagger\right)^{1/2} \frac{\partial^2 \dot{f}(\tau)}{\partial \tau^2} d\tau \Bigg\}. \tag{4}$$

But, from the work developed in reference [1], considering the entropy flow at the border of a given region,

$$\frac{\partial^2 S_{int}}{\partial \tau^2} = \beta \frac{\delta \dot{Q}_{ext}}{T \tau_{ref}}\,, \tag{5}$$

where τ_{ref} is the characteristic transition time interval of the system, called "reference time", and β is a Lagrangian parameter,

$$\beta = \left\{1, \frac{1}{2}, \frac{1}{3}, \ldots, \frac{1}{n}\right\},$$

remembering with Bejan that each heat transfer interaction $\dot{Q}_i$ which crosses the border of a temperature system T_i carries with it the entropy interaction $\dot{Q}_i / T_i$ [8]. Therefore, we may say that, at the border, the entropy acceleration is

$$\lambda = -2\gamma^2 \int \Bigg\{ \Bigg[\left(\ddot{\xi}\xi^\dagger + 2\dot{\xi}\dot{\xi}^\dagger + \xi\ddot{\xi}^\dagger\right) \ln\left(\xi\xi^\dagger\right)^{1/2} +$$

$$+ \frac{\left(\dot{\xi}\xi^\dagger + \xi\dot{\xi}^\dagger\right)^2}{2\xi\xi^\dagger} + \frac{1}{2}\left(\ddot{\xi}\xi^\dagger + 2\dot{\xi}\dot{\xi}^\dagger + \xi\ddot{\xi}^\dagger\right) \Bigg] \dot{f}(\tau) d\tau +$$

$$+ \xi\xi^\dagger \ln\left(\xi\xi^\dagger\right)^{1/2} \frac{\partial^2 \dot{f}(\tau)}{\partial \tau^2} d\tau \Bigg\}_{int} = \beta \frac{\delta \dot{Q}_{ext}}{T \tau_{ref}}. \tag{6}$$

Curiously, there are still those who don't see an inch ahead, criticizing Norton's approach based on 19th century thermodynamics, repeating the old roll of aberrations like isolated systems, negative entropy and other products of idealist thinking which hinder the advancement of understanding. This anachronistic attitude only serves to limit the scope of the heat exchange science. Unfortunately for these people, contemporary discourse only makes sense if we take into account the numerous discoveries of the 21st century about the behavior of the universe and the strangest celestial bodies that until recently were unthinkable. The field formalism opens horizons to thermodynamics for its objective and consistent application in the construction of comprehensible evolution models, both for systems on the scale of human devices and on the scale of cosmic natural devices, in this latter case, particularly, turning itself into a thermodynamics of the accelerated expansion of the space-time. But be careful! Probabilistic interpretations of Law II move thinking toward idealism and its usual absurdities, such as "be patient and wait long enough to see the heat flow from the cooler to the warmer body."

The physical meaning of quantities like γ depends on the context of application of the theory. Referring to solar power plants, γ is the opacity of the medium crossed by sunlight, and is related to the refractive index ϑ, both environmental parameters. To give no more than a simple example, to satisfy the proposed relation

$$\vartheta = \frac{\gamma^2 + \alpha^2 - 1}{2\gamma^2}, \tag{7}$$

a solution for field equation (1) is

$$\xi = e^{i\alpha q - \vartheta}, \tag{8}$$

with α = const.

Also, caloric fields at elevated temperatures can set up plasma induced pyrolysis in solid waste recycling chambers, while in cosmology they can express the thermal energy of space-time expansion.

Therefore, caloric field defines the shape of thermal energy diffusion. In addition, with arbitrary function $f(\tau)$, it defines the shape of the entropy flux at the border of the region in focus. Its evolution according to equation (1) reflects the way in which the environment parameters are related.

The Lagrangian formulation leads us to deduce a caloric conserved current J, the basis for the definition of what we call "entropic force". Since entropy is thought of as a flow between neighboring regions, it is natural to think of the entropy force as a result of the entropy acceleration times the conserved current (dynamic constant). So,

$$\Gamma = J\lambda, \tag{9}$$

where

$$\begin{gathered} \mathrm{L} - \partial_q \xi \frac{\partial \mathrm{L}}{\partial \partial_q \xi} = J = C^{te} \therefore \\ -\left(\partial_q \xi\right)^\dagger \left(\partial^q \xi\right) + \left(\partial_q \xi\right)^\dagger \left(\partial^q \xi\right) - |\xi|^2 + \gamma^2 |\xi|^2 \ln|\xi|^2 = \\ = \left(\gamma^2 \ln|\xi|^2 - 1\right)|\xi|^2 = J. \end{gathered} \tag{10}$$

The conserved current dynamically plays a similar role to that of mass in Newtonian theory. Since we don't know the absolute value of entropy, only its variation (see the arbitrary function $q = f(\tau)$), the entropy force gives us a measure of how strongly entropy happens in a given system.

III. THE SPIRIT OF THE PROPOSED FORMALISM

Physics students usually don't express much reflective ability. They had no philosophical facility of their own, so they need to be coached in this regard. It's not their fault; the elementary education system does not favor the training of this innate skill of the human being. In most orthodox courses, all that matters is doing the math and solving sterile exercises. There is no enthusiasm about positive questioning. A lot of time is wasted repeating old theories. With regard to thermodynamics, the matter of this article, the need for disruption is indisputable especially when the targets of caloric field theory conflict with the traditional interests of statistical mechanics. This is worth a quick discussion in order to understand the root of such conflict.

As is known, canonical statistical mechanics presupposes that systems can be truly isolated from any energetic interaction with the outside world, a hypothesis that is not fulfilled since even the weakest interactions can never be ruled out in a non-empty universe (verily, in the most accurate experiments, the usual macroscopic approximations to equilibrium seem to remain despite all possible isolation precautions). This means that, in the same way gravitational interaction subsists, however minimal it may be, the entropic force subsists in parallel, though very small. Therefore, reversibility is a fiction (as well as empty universes and other toys), as the most wise physicists recognize. Also, there is no necessary *a priori* reason to justify the probabilistic interpretation of the function that designates entropy. Sure, expression (2) suggests a generalization of Gibs entropy, but this is only a *prima facie* semantic suggestion, which does not hold up after a deep critique.

In the basic principles of quantum mechanics there is a philosophical content that applies to physics as a whole. How naive we were for so long to exaggerate the realism of representations! According to our way of seeing it, the mere practice of using the imaginary unit already places us in a phenomenological perspective of distance from immediate reality (this is something that is never discussed in scientific circles); something happens in physical systems in general (not just microphysical ones) that we do not have direct access to, or at least to a more intuitive primitive description along the lines of philosophical realism. We think we're on fairly firm ground in saying that the real mystery of the fact that the existence of physical objects depends on their relationships with other objects is inserted in the region of the imaginary.

A. The necessary disruption in General Physics

Teaching is first and foremost a call to reflection and critical thinking, not an invitation to sameness and repetition. There is a subtile passage from the illustrious Ernst Mach — who, as a physicist, has influenced us so much with his profound philosophy — which we like to remember whenever we reflect on education:

"El gato que busca su imagen detrás del espejo, instintiva e inconscientemente ha hecho uma hipótesis sobre la materialidad de esa imagen y busca verificarla. Pero, para él, el proceso se detiene ahí, mientras que em un caso análogo, el hombre se admira y reflexiona" [9].

Stuck in an educational pattern dimmed by monotony, we won't do much more than cats (without belittling them, as they are not only intelligent but also extremely sensitive).

In other words, the cat has to be the cat, and the man has to be the man. It is the ability to be surprised and to reflect on the reasons for this surprise that distinguish us.

So, reflecting on the nature of the world that surprises us, and remembering what we have already said, an object is only defined by its relations with other objects. In the quantum world, these relationships have to be though and established according to different rules than we are used to. The relations that characterize two so-called entangled photons "transit" freely in time, causing the impression of instantaneous action for whom interobjective relations can only transit from the past to the future. We therefore need a disruptive framework in which time plays a key role in the symmetry of quantum interactions, as discussed in reference [10][3] (let's keep this in mind when we set out to take thermodynamics to the quantum scale).

The fact that we live in a world whose spatio-temporal relations are constructed in a (3+1)-dimensional model — with three spatial and one temporal components — is, in principle, a fortuitous event, a haphazard effect (this being an unsatisfactory statement, no doubt!). There is no *a priori* reason why things are the way they are. Also, there is no *a priori* manner to eliminate possible scale effects on the mode objects are related.

IV. THE HUMAN DIMENSION OF THERMODYNAMICS

Furthermore, in thermobiology, or thermodynamical biology, it is possible to establish parameters to control physical performance and wear and tear in athletes in order to achieve the best individual training and nutrition condition. Recent works on individualization of training load and recuperation strategies based on the observation of the activated musculature temperature [11, 12] open a promising way for innovations in applied thermodynamics. Also here, caloric field theory, both formally and conceptually, proceeds to the extent that we can assume a scalar field internal to the athlete, however, in diffusion to the outside environment, with the entropic flow being analyzed at the human body-environment boundary. This internal field is metabolically generated from the ingestion of caloric nutrients according to the equivalence between mass and energy. Lastly, the possibility of a partial association between genomic DNA and individual thermobiological differences in wear and tear and inflammatory processes has raised encouraging discussions.

All these ideas can be transmitted in an accessible way from the first years of basic scientific school education, showing the direct relationship between the organic processing of food and the energy available for the exercise of our functions. And not only that: through early education, understanding the game between mass consumed and burning calories in the balance of the amount of energy stored in the form of fat would surely lead us to understand the reason for the arising of obesity and its morbid consequences, so that we could plan a healthier and less sedentary life in adulthood.

V. SIX ACTIONS TO LEARN BY HEART BEFORE STARTING STUDIES IN THERMODYNAMICS

It is imperative to deconstruct practically everything that traditional teaching has brought us about the foundations of thermodynamics. One of the first deconstructions to be made is on the myth of the association between entropy and probability. In fact, entropy is a very well-defined concept, as pressure, temperature, and volume; it would exist even if probability theory “had never been invented”, as Margenau already observed in the 1950s [13]. Therefore, stochastic association is not instructive, leading to confusion and conceptual extrapolations beyond thermodynamics itself. Furthermore, Law II is very clear regarding the irreversibility of natural processes, except for human interventions that artificialize reversibility in a partial way. Considering all this, to approach thermodynamics we must:

1. Banish from thought the old image of the two interconnected reservoirs with different contents, and the bags of mixed-up marbles.
2. Eliminate the fiction of isolated systems.
3. Eliminate idealism within thermodynamics (there is no negative entropy, remembering that positive entropy production principle is suitable for all systems, even the fictional ones — isolated systems, closed systems, etc.).
4. Recognize that reversibility refers to an anthropized process that emulates a fanciful natural return to certain initial state.
5. Recognize that entropy reduction is a fictional effect, unlike entropy deceleration, which is a real effect.
6. Keeping the concept of entropy within the limits of thermodynamics.

With this thought re-education, we will be able to understand thermodynamics from an entirely new perspective. Just as in modern astrophysical cosmology, Type I-A supernovae represent lethality and at the same time creation and diffusion of the elements necessary for life, we must recognize in entropy a measure not only of natural degradation, but also of creation and renewal. Even under the misleading excuse of preparing examples that simplify the understanding of the subject by the students, it is irrefutable truth that, acting like this, we create unreal representations at an age of civilization during which every day we reaffirm our beliefs in the multiple interconnections that move the universe.

VI. FINAL REMARKS

The world is going through a phase of depreciation of culture, which began decades ago under the banner of postmodernism. This process of degradation is due in part to the disbelief in social values that have been diluted with wars, genocides and the absence of a global peace solution

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[3] An example of a very impactful disruption to our ways of thinking is offered in this reference.

for the species. On the other hand, the excess of technology aimed at exaggerated comfort and promotion of the related illusion of quality of life has contributed to the rampant increase in consumerism. Like it or not, we always return to education as the main instrument of transformation. So, it is through education that one can expect the development of a new mentality capable of reversing or at least mitigating the deleterious effects of human action such as global warming, which is a typical thermodynamic problem. When we think about the energy needs of nations, we go back to thermodynamics, the science that allows us to avoid all kinds of waste. From the wildest fires to the almost unthinkable Dyson spheres, it's all about slowing entropy by anthropic means. That is why an energy management committee made up of functional illiterates in energy engineering and thermodynamics is unacceptable (also, for those who see the world only from the perspective of economics, it would be interesting to know the amplitude of thermodynamics as explained by Georgescu-Roegen [14]).

For all that, we have said, we hope this essay will inspire innovation in physics teaching, motivating professors and researchers, especially in Latin American countries, to take a new look at the current inefficient and sterile learning process.

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REFERENCES

[1] Serpa, N., Fernandes, G., *The way of entropy: From Lagrangian modeling to thermal engineering*, CALIBRE – Revista Brasiliense de Engenharia e Física Aplicada **5**, 1-16 (2020).

[2] Serpa, N., Cathcart, R. B., Varison, V., *New lessons on entropy: A matter of education in thermodynamics*, Latin American Journal of Physics Education **15**, 3306-1-3306-6 (2021).

[3] Rovelli, C., *O abismo vertiginoso* (Schwarcz, Rio de Janeiro, 2020), p. 198.

[4] Noüy, L. *du, L' homme devant la science* (Flammarion, Paris, 1969), p. 186.

[5] Lalande, A., *Vocabulaire technique et critique de la philosophie* (Presses Universitaires de France, Paris, 1969).

[6] Wang, J., *Modern thermodynamics based on the extended Carnot Theorem* (Springer-Verlag, UK, 2021), p. 315.

[7] Norton, J., *The impossible process: Thermodynamic reversibility*, History and Philosophy of Modern Physics **55**, 43-61 (2016).

[8] Bejan, A., *Entropy generation minimization* (CRC Press, Boca Raton, 1996), p. 400.

[9] Mach, E., *Conocimiento y error* (Espasa Calpe, Buenos Aires, 1905/1948), p. 309.

[10] Serpa, N., *Sur les rotations de Wick et les quaternions: Le jeu de symétrie entre l'espace et le temps*, (PhD lecture) CALIBRE – Revista Brasiliense de Engenharia e Física Aplicada **4**, 1-11 (2019).

[11] Junior, R., Duarte, J. L., Falqueto, W., Andrade, H., Morandi, A. G. P., Albuquerque, R. F., Gomes de Assis, M. R., Serpa, M., Mendonça T. K., Pimenta, E., *Correlation between strength and skin temperature asymmetries in the lower limbs of Brazilian elite soccer players before and after a competitive season,* Journal of Thermal Biology **99**, 102919: 1-8 (2021).

[12] Alburquerque Santana, P. V., Dutra Alvarez, P.; Costa Sena, A. F. da; Serpa, T. K.; Gomes de Assis, M., Mendonça Pimenta, E.; Araujo Costa, H., Sevilio de Oliveira Junior, M. N., Torres Cabido, C. E.; Veneroso, C. E., *Relationship between infrared thermography and muscle damage markers in physically active men after plyometric exercise*, Journal of Thermal Biology **104**,103187: 1-7 (2022).

[13] Margenau, H., *The nature of physical reality: A philosophy of modern physics,* (McGraw-Hill, Toronto, 1950), p. 479.

[14] Georgescu-Roegen, N., *The entropy law and the economic process* (Harvard University Press, Cambridge, 1971), p. 457

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