EDVCATIO PHYSICORVM
QVO NON ASCENDAM?
ISSN 1870-9095

New lessons on entropy: a matter of education in thermodynamics

Nilo Serpa[1], Richard B. Cathcart[2], Vitor Varison[3]
[1]*NIP-Núcleo Interdisciplinar de Pesquisa, Centro Universitário ICESP, Águas Claras, Brasília, Brasil DF.*
[2]*Geographos, Burbank, California, USA.*
[3]*Centro Universitário ICESP, Águas Claras, Brasília, Brasil DF.*

E-mail: nilo.serpa@icesp.edu.br

(Received on July 16, 2021, accepted on August 27, 2021)

Abstract
This article aims to discuss the importance of the concept of entropy in teaching. The Second Law of Thermodynamics is revised in light of a new interpretation of entropy, emphasizing its significance in the evolution of the universe and in the comprehension of life. Present work also seeks to show thermodynamics as a more complete science than mechanics, promoting a paradigm shift in classical physics teaching. Lastly, the adoption of a disruptive teaching model is defended, reinforcing the need for a divergent way of thinking.

Keywords: Entropy, Thermodynamics, Teaching, Divergent thinking.

Resumen
Este artículo tiene como objetivo discutir la importancia del concepto de entropía en la enseñanza. La Segunda Ley de la Termodinámica se revisa a la luz de una nueva interpretación de la entropía, enfatizando su importancia en la evolución del universo y en la comprensión de la vida. El presente trabajo también busca mostrar la termodinámica como una ciencia más completa que la mecánica, promoviendo un cambio de paradigma en la enseñanza de la física clásica. Por último, se defiende la adopción de un modelo de enseñanza disruptivo, reforzando la necesidad de una forma de pensar divergente.

Palabras clave: Entropía, Termodinámica, Docencia, Pensamiento divergente.

I. INTRODUCTION

It is a pity that the concept of entropy has been so neglected since elementary school, being at the basis of the very evolution of the Universe and of all things. Certainly, in its origins at the 19th century it is unlikely that the concept was associated with any ideal of abstraction judging by the interests of the epoch focused on the development of machines with increasingly better performances. It was a civilization on the way to a significant industrialization advance. Therefore, the excuse of entropy being merely a concept too abstract to be addressed in youth's basic education is fallacious, not least because all the concepts of Physics are truly abstract; they are only representative verbal and mathematical symbols with which educated adults try to describe and understand the world as it operates, both naturally and otherwise.

With such an objective, that is, the construction of an industrious and progressive human society, it would be difficult for the world populace to accept a concept that contained the crypto-motto "everything should evanesce at some point", no matter the idea of anthropic progress we have embraced philosophically. This was the main reason why thermodynamics has remained, and still remains, overshadowed in teaching *vis-à-vis* mechanics, despite being a much more complete science. In mechanics, everything is reversible, and time appears only as a marker external to the observed phenomenon. On the contrary, in advanced thermodynamics, entropy — often distorted by idealistic approaches — and time are closely related.

Although currently associated with the degradation of the systems, entropy brings also a creative power along with time. This apparently paradoxical characteristic is revealed when, instead of assuming the idealistic image of inverted entropy, we introduce a dynamic of acceleration and deceleration of the entropy. It happens, therefore, that it is the deceleration of the advance of entropy that allows the emergence of new complexities, and not the decrease of entropy, which can only increase. The reasons for such a slowdown may or may not be of anthropogenic nature.

Obviously, the slowdown is due to very special circumstances of interaction between systems. Leaving aside fictions as "isolated systems" and "reversible processes" — since the idea of an isolated system does not apply to Nature, and nothing is truly perfectly reversible —, it would be interesting to start teaching the natural sciences by presenting the idea of material and energy evolution associated with the basic principles of thermodynamics, especially the content of the Second Law, which still seems to be poorly understood by most people.

II. THE SECOND LAW AND THE ENTROPY

The almost universal appeal to entropy, from thermodynamics to economics, through biology and information theory, reflects at least a feeling that the concept is fundamental, albeit poorly understood (postmodern sociologists and management theorists with systemic view tend to use "entropy" in a way that promotes obscurantism rather than enlightenment). There are two main facts that make up the misunderstandings around entropy: first, the most technical, refers to the distance from its thermodynamic origins; second, the most subjective, concerns the excesses of voluntarist and imaginationist idealism. In the first case, the issues are discussed by an unqualified quorum (this includes the attempt by physicists, as Planck recalled [1], to postulate a perfect analogy between the passage of heat from a warmer body to a cooler one, and the fall of a body from a certain height to a point below). In the second case, speculation does not come from scientific plausibility, but from free fiction. To confirm this fact, we may take the common approach of statistical mechanics. The main problem here — without forgetting the mechanical entail as the name implies — is that when we analyze macroscopically the observations of a dynamic system made up of numerous particles, including the characteristic error margins of the measurement process, it is always possible to say that, on average, the global trajectory state of the particle constellation is irreversible (although a single trajectory can, in principle and ignoring time, be "reversible"!). Thinking like that, it is easy to make the mistake of constructing a theory of ignorance rather than a physical theory, not to mention the nonsense of originating irreversibility from a cluster of reversible trajectories! As Francis Fer said,

"Il est à vrai dire surprenant qu'une telle idée ait pu trouver créance. Comment en effet, puisque toutes les trajectoires sont "réversibles", se pourrait-il qu'en les groupant on obtienne une irréversibilité, même en moyenne? Et d'autre part comment pourrait-il se faire que l'irréversibilité, qui semble bien être tout de même une propriété physique, découlât de l'imprécision de nos instruments de mesure, c'est-à-dire en définitive du degré de notre ignorance?" [2].

Then, if irreversibility is a product of our ignorance, so does entropy which is in the core of irreversible processes. That is pure absurd!

In any case, we believe that the problem in dealing with the notion of entropy stems mainly from the supremacy of the mechanistic educational model; it is more difficult to deal with the intrinsic thermal exchanges in complex systems. For example, it is unlikely that, looking at a steel structure in full oxidation [3], one thinks of the energy loss associated with the degeneration of the steel by the action of oxygen (there was a previous consumption of thermal energy to produce the steel, so that the oxidation equals wasted energy). Therefore, thermodynamics seems to us to be a more complete science[1] when it shows that every transformation process causes irreversible wear and loss, and qualitative changes. Until the end of the 20th century, some insistence on a primacy of mechanics was still seen in Brazilian schools, even though the most specialized scientific literature no longer pointed in that direction.

Except for a "neo-mechanistic" attempt, not much referenced due to Vogel [4], strongly based on functional analysis, little was discussed about new complex evolutionary models of mechanical nature. The supremacy of the mechanistic educational model is not entirely fortuitous. Ironically, thermodynamics had its origins in the observation of mechanical phenomena. According to Hiebert [5], we can say that thermodynamics was born from the discovery of an invariant correspondence between the macroscopic movement of a body and the heat dissipated by that movement; in other words, a correspondence between the amount of mechanical work that disappears and the amount of heat that appears. We have here a statement that, by the very nature of the world of external things, would lead to an analysis of the amount of energy that cannot be used in a complete cycle of mechanical work. It was precisely this analysis that led to the notion of entropy; it was at the heart of the postulation of the Second Law. To better understand the Second Law and the concept of entropy, let's think about the evolution of the Universe. The Big-Bang configured an instant of extremely low entropy, since it concentrated a very high amount of "usable" energy. As the Universe expanded, transformation and dissipation of energy started and continued in parallel, marking the beginning of the slow progress of degradation.

The homogeneity of the first moments the Universe gave way to inhomogeneity, with regions of accelerated and decelerated entropy. The slowing zones provided the formation of galaxies and everything in them, including life. Even the slowdown in these regions is not homogeneous, with variations here and there, giving rise to new complexities. Despite the created order, all forms of energy (gravitational, electromagnetic, thermal, etc.) continue to slowly dissipate in cosmic time. The reasons for such inhomogeneity are likely to remain unknown; they are the nature of the universe itself.

Based on what has been said, we can now say that the Second Law is responsible for a kind of random creativity of Nature guided within certain limits of plausibility characterized by the arrow of time associated with a non-homogeneous irreversible growth of entropy. What a relearning effort will be required to teach such a fundamental discipline to the understanding of the universe!

[1] When dealing with thermodynamics, it was Helmholz who recognized energy as the universal quantity conserved behind the interchangeable classical quantities, namely, work, heat and electricity [6]. Thus thermodynamics assumes the link that unites all the specializations of traditional physics, becoming the theory of energy balances par excellence.

III. LEARNING THERMODYNAMICS WITH A DIVERGENT MIND

Thinking about acquiring in-depth knowledge, conventional thermodynamics classes are rarely clear, as is the case with other areas of physics whenever it is presumptuously assumed that the fundamental concepts are completely mastered. This attitude is at the root of most learning problems, especially in undergraduate courses. This same attitude leads us to lose the line of reasoning that allows to glimpse in irreversibility the mark of natural processes, as well as the understanding of reversibility as the mark of anthropic control processes. For this reason, it is necessary to replace the convergent model supported by the excess of analogies by an essentially divergent model of articulation of ideas and facts.

A divergent mind seeks interdisciplinarity and diversity of answers to a given problem. No use trying to understand the Second Law with a convergent traditional mind; we will only find confusion. In an inviting environment for free and creative thinking, thermodynamics — more specifically the Second Law — can be taught at elementary school level in direct association with the natural aging of living beings and with the first notions about the origin and evolution of the Universe, showing that all natural phenomena or events, as well as human actions in the world, occur at the expense of differences between energy states. With the help of basic biology and organic chemistry, ideas such as energy (understood as the result of the interaction between two entities or systems), photosynthesis and metabolism are easily connected to the concept of entropy. Adding some interdisciplinarity, one can gradually extend this reasoning to all conceivable systems, organic or inorganic[2]. The teachings conveyed through this way of conducting teacher/student interaction generate questions and incite different plausible answers to a given problem.

We believe that there is a totally new perspective of glance and contemplation of life in the knowledge of thermodynamics applied in a generalized way to the world around us *via* entropy, well understood and demystified. Also, the environmental ethics tends to manifest with greater ease in citizens endowed with a dialectical view of the energy balances involved in their daily actions that produce waste and can lead to losses. In higher education, it will be easier to conduct formal approaches with disruptive significance if the exercise of divergent thinking initiated in primary education remains in vogue. That's what we can see immediately, looking at the concept of entropy we presented. As we hinted in the previous section, there is a strong randomness in the formation of accelerated and decelerated regions, as well as in the manifestation of their interactions; this means that perhaps life is indeed a rare phenomenon in its most complex forms (it seems to us that Occam's Razor was tailored to explain phenomena that could suggest intelligent alien life!). But it is equally possible that once the irreversible process of life begins, life will tend to spread far and wide, and unless it is supposed that at least in some other few regions it has arisen and evolved into intelligent forms, we will be again in trouble with the Anthropic Principle! Thus, given the little we know, it is more reasonable to think that inteligent life is very rare, but not a privilege of Earth. This is how divergent thinking drives us forward.

Anyway, the plausible spread of some intelligent life is an entropic process slowed down in the totality of the actions involved, since it is an exothropic (or anthropic) phenomenon. As for a fortuitous microbial spread, it also falls into a random sequence of events that characterize deceleration on a much smaller scale. What is most important is to understand that in all these processes there is energy dissipation, and it is the balance between dissipation and "effective use" of energy that tells us about the acceleration of entropy (we put "effective use" in quotation marks so that critics of finalism won't classify us as finalists).

In all systems, biological or not, it is necessary to verify to what extent these systems tend to remain in certain configurations by their "effective use" of energy. There is no finalism in this, only more or less entropic configurations. For instance, a main-sequence star will go through a long journey as a Red Giant before the imbalance among the forces that sustain it as such leads to its ultimate transformational ruin; the "effective use" of its proper energy kept it like a burning sphere for billions of years; the heat dissipated throughout its radiant life has been lost in the vacuum, and there is no way to reverse this history as if we were playing a movie backwards.

A. A brief note on disruptive thinking

In our universe (the only one we know), irreversibility is consistent with the growth of entropy, even though the latter advances not because of the arrow of time, but because it would be very different if it went backwards. Within our universe, we can move indifferently in any direction in space, but not in time, and all objects are related this way. However, at the quantum scale there are indications of different relationships between objects; two entangled particles, for instance, seem to communicate freely in time, a fact that leads us to see in quantum entanglement a proof of the supreme symmetry between space and time, and the necessary disruption we need to advance knowledge. Irreversibility: the fundamental and natural running condition of the things we see all around. This simple fact which every student must keep in mind was pointed out by the oldest recorded founders of thermodynamics, and the Second Law was expressed in many axiomatic ways, two of which are especially pertinent to our purposes because of their aphoristic qualities:

1. Clausius’s statement:

[2] Associations with morbid states in certain stressful occupations can be useful to exemplify the accelerating advance of entropy; it is the case of Burnout Syndrome, a name for what stopped working due to general exhaustion, expressed through a feeling of failure, fatigue and dejection, caused by an excessive consumption of energy and long periods of stay in alert status.

> "Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time."

2. Kelvin's statement:

> "It is impossible for a self-acting machine, unaided by any external agency, to convey heat from one body to another at a higher temperature."

The underlined highlights were inserted by us. Of course, these scientists understood perfectly the notion of irreversibility in the world of natural processes, and, therefore, the artificial character of the apparent reversibility forced by human devices. However, despite the progress of thermodynamics and its academic teaching, what is rarely explained is the general meaning of the equilibrium expression $\delta Q = TdS$, mistakenly associated with the entropic process itself, and not with the boundary process[3]. This subtlety makes all the difference when it comes to describe thermal exchanges between neighboring regions. In short, this expression characterizes border situations where heat flows take place across transition surfaces until the equilibrium state is reached. Indeed, as Bejan underlines [7], each heat transfer interaction $\dot{Q}_i$ which crosses a border of temperature T_i carries with it the entropy interaction $\dot{Q}_i / T_i$, given rise to an interaction vector $\dot{\mathcal{Q}}_i = \left(\dot{Q}_i, \dot{Q}_i / T_i\right)$[4].

It is clear that the notion of boundary between regions is the pivotal construct for understanding thermal interaction by heat flows. Moreover, this interaction is only fully described by vector $\dot{\mathcal{Q}}_i$.

About the theory that supports the disruptive approach discussed here, the reader can find a complete study in reference [8].

IV. THERMODYNAMICS PLUS ECONOMY: FOUNDATIONS OF A NECESSARY MANAGEMENT

On one hand, in a civilization based on profit and power there is naturally a tendency to disregard academic curricula among the options for decision-making positions; this is much more serious in socially underdeveloped countries (where many managers of companies avoid academics), so one cannot expect a great scientific competence taking a seat at the decision table. On the other hand, it is difficult to technically discuss strategies for optimization and management of energy sources in countries where there are no permanent State policies on the subject, but rather seasonal policies for seizing and exercising power. Such scenarios are often conducted by commissions of decision makers raised by convenience and personal interests, mostly illiterate in the basic sciences that they should dominate to give their opinions correctly.

It is not new to talk about a connection between thermodynamics and economics. Georgescu-Roegen, recognizing that mechanics does not allow for qualitative changes, and that any vital process is governed not by the laws of mechanics, but by the law of entropy, brought in his discourse the understanding that through this law it is precisely thermodynamics that recognizes the qualitative distinction in vital processes, including the economic process, also irreversible as any other [9].

Thermodynamics (science) and economics (semi-science) should go together, but we doubt that this is feasible in economically dependent countries with serious social problems and little investment in basic science, research and public education. In addition, the human population of the world is still anachronistically dependent on fossil fuels, certainly not because of a lack of options, but because of market imposition, the "oil dictatorship" so to speak.

Energy efficiency can only be discussed with the following theoretical premises in mind: I) the validity of the 2nd law of thermodynamics, II) the non-existence of isolated systems, III) the non-existence of negative entropy, and IV) the direct relationship between energy and cost, being cost understood not only financially, but also in a social and environmental sense.

In fact, what mobilizes the world's contents are the differences between energy states of its composition. As Lincoln rightly said, "what life needs is not energy, but difference of energy" [10]. Obtaining these differences is what demands construction and operating costs. Certainly, it follows that entropy differences, that is, the rates of its advance, are more important than the entropy itself, mainly when the subject is the loss of efficiency of the systems.

There is a lot of old-school economists who seems to have been frozen in time, but still with socially influential voices in government agencies. In addition, with regard particularly to Brazil, there has been no real renewal for a long time; the same obsolete figures dictating the rules for decades, the same incapable and unreliable politicians. Even among physicists there is a lot of prejudice against new ideas in thermodynamics. Recently, a reviewer disposed of his role — which should be ethically impartial — to harshly and unreasonably criticize Norton's innovative work [14] throughout the review he was conducting on another author! Using the act of proofreading — which does not constitute a forum for personal preferences — to disparage a serious work that has been referenced in the paper under review is a moral outrage for both authors, who submitted the article and who was cited. People who act like this are not properly qualified, therefore they cannot be called upon either to participate in educational projects or to express opinions in advanced energy matrix projects because they are incapable of listening and welcoming new ideas. So, a good background in thermodynamics and economics among technocrats and bureaucrats would modify remarkably the current scenario of technological

[3] There is no way to understand the full meaning of a mathematical expression without the necessary and correct additional semantic content.

[4] The over dot means time derivative.

weakness in Brazil and other Latin American countries, with extensive investments in the use of solar energy focusing on ecological economy and quality of life. European countries with much less insolation are already at an enormous lead in research and implementation of thermosolar systems for large-scale use.

V. THE ENTROPY IN LARGE CITIES: WASTE AND DECLINE OF CIVILIZATION?

In some circumstances, unofficial environment-managers are better able to judge risk affecting humans that so-called expert reality-modelers employed by government and corporate organizations. According to Fiorino [11], non-expert, even the inexpert may have a better capability for "accommodating uncertainty and correcting errors over time through deliberation and debate". There is no country without an urban system. The world's cities are large, novel, unique and presently controversial projects changing the distribution and energy levels of Earth's contents. So, we assert that such persons would be even more effective if fully informed about the implications and everyday usefulness of the Second Law of thermodynamics.

All cities, eventually, will disappear so that, perhaps, the last relics of humankind's vision and vanity will be the two Voyager spacecraft moving out of our Solar System and into the greater Universe. In Japan, geoscientists separate the natural Earth-mass from that affected by humans with the term "Jinji Unconformity"—that is, a discontinuity of geological strata which is distinct by its composition and structuring. Residents of Tokyo are trained to notice this separation via public Art displays such as the scrap-metal mural in the Kiyosumi-Shirakawa Station of the Toei Oedo subway line installed by contemporary artist Shoichiro Higuchi in AD 2000. The mural reprises the development of Tokyo from the Big Bang until the late-20th century. In fact, Higuchi's artwork is a visible demonstration to the commuting Japanese public of the "The Urk World: Hibernating Infrastructures & the Quest for Urban Mining" (2015) described by Bjorn Wallsten.

In Brazil, with it long-established and growing cities, new opportunities have arisen to demonstrate the efficacy of thermodynamics' Second Law: by thinking of urban places as "alternative landforms", educators can draw people's attention to it. No society anywhere in the world can afford the ignorance and stupidity of poet P.B. Shelly's "Ozymandias". Let's suppose Brazilian geoscientists and teachers examine the effect upon soil of Nature and culture across many biomes [12][13], ultimately by outlining a projected future based on the Second Law, with some artists rendering their judgements in artworks placed strategically in every locale so as inform the nation's public. So, we call on artists, collaborating with thermodynamicists to create such edificatory public artworks that may help propel Brazilians into a better, more realistic future!

VI. FINAL REMARKS

The correct understanding of the Second Law and entropy has positive consequences for science and education in general, as well as for energy and solid waste management. However, reaching this vision requires early teaching and eradication of the distortions caused by the idealism of the industrial progress. Paraphrasing Norton [14], we would say that incantations of "isolated systems" and "reversible processes" have no magical powers that overturn the advance of entropy. We defend, therefore, a modern and realistic approach to thermodynamics in direct connection with the human experience of survival, occupying more space in syllabus. Following this way, we can expect qualified people in the right positions, making the right decisions in environmental comfort and urban planning, optimizing the use of renewable sources.

These ideas involve so many socio-political reversals and transformations that we fear there is no hope of change in the mid-term. Brazil's political management oscillates a lot between power groups with terribly inefficient and ignorant staffs, sometimes practically semi-illiterate in skill-sets, sometimes ideological radicals with myopic vision forward in time and space. In both cases, public education in formal schools is unimportant, being handled with unbelievably pernicious incompetence. If there is a continental geographic example of accelerated entropy, this is Brazil!

ACKNOWLEDGEMENTS

The authors thank the support of the Centro Universitário ICESP to this publication. The authors declare that they have no competing financial interests.

REFERENCES

[1] Planck, M., *Autobiographie scientifique*, (Flammarion, Paris, 1960), p. 220.
[2] Fer, F., *L'Irreversibilité, fondement de la stabilité du monde physique*, (Gauthier-Villars, Paris, 1977), p. 135.
[3] Wildman, J., *Rust: The longest war. New York:Simon & Schuster,* SEE also: Rabate, J-M, Schaberg, C. and Bogost, I. (Eds.) Rust (Object Lessons). (Bloomsbury Academic, New York, 2016), p. 152.
[4] Vogel, T., *Pour une théorie mécaniste renouvelée*, (Gauthier-Villars, Paris, 1973), p. 142.
[5] Hiebert, E., *Historical roots of the principle of conservation of energy*, (Arno Press, New York, 1981), p. 118.
[6] Rousseau, P., *Histoire de la science*, (Fayard, Paris, 1945).
[7] Bejan, A., *Entropy generation minimization*, (CRC Press, Boca Raton, 1996).
[8] 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).

[9] Georgescu-Roegen, N., The Entropy Law and the economic process, (Harvard University Press, Cambridge, Mass., 1971), pp. 450.

[10] Lincoln, D., *Universo Alien.* (Cultrix, São Paulo, 2017), p. 317.

[11] Fiorino, D., *Citizen participation and environmental risk: A survey of institutional mechanisms*, Science, Technology & Human Values **15**, 226-243 (1990).

[12] Ribeiro, F. *et al*. (2021), *The impact of drought on soil moisture trends across Brazilian biomes*, Natural Hazards and Earth System Sciences **21**, 879-892 (2021).

[13] Santos, R. *et al*., *Consequences of land-use change in Brazil's new agricultural frontier: A soil physical health assessment" Geoderma* **400**, 115-149 (2021).

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