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# Irreversibility and time: historicizing the second law of thermodynamics for science education[+][*]

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*Louise Trivizol*[1]
Master in Science and Mathematics Teaching
State University of Campinas
*Silvia F. de M. Figueirôa*[1]
State University of Campinas
Campinas – SP

## Abstract

*This article presents thermodynamic concepts linked to the second law of thermodynamics which reveal the inherently historical nature of the sciences and the philosophy of the accompanying physics. These concepts also play a role in complex thinking, according to Edgar Morin, and are valuable for science education in this century. In order to contextualize the relevance of this approach, we consider mechanistic and extractivist mentalities that shift responsibility away from humanity for its actions on the planet and instead view humans as mere spectators. We propose a historical and philosophical approach to the second law of thermodynamics in science teaching to overcome this detachment from reality through education; the goal is to emphasize meta-scientific aspects that arise from debates involved in the nature of science approach in order to meet the objectives of scientific literacy.*

**Keywords:** *Irreversibility; Entropy; History of Science; Physics Teaching; Uncertainty; Complexity.*

## I. Introduction

This article focuses mainly on teacher training, both initial and ongoing. An approach to the second law of thermodynamics that passes through the history, philosophy,

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[+] Irreversibilidade e tempo: historicizando a segunda lei da termodinâmica para o ensino de ciências

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[1] E-mails: lui.t.assis@gmail.com; silviamf@unicamp.br

and sociology of science can serve basic education through the mediation of teachers, and higher education in undergraduate programs related to physics. The objective is consequently to gather and systematize historical and philosophical aspects of science that may be useful for an in-depth approach to the second law of thermodynamics and the meta-scientific characteristics of the sciences: in other words, to tell a story of the transition from determinism to uncertainty, considering that the conceptual structures of the physical sciences require more complex descriptions that incorporate history, philosophy, and social aspects of scientific production. Here we present a potential history of thermodynamics based on readings of primary and secondary materials, selecting content deemed relevant to socio-scientific debates in science education.

Classical thermodynamics was substantially developed from the nineteenth century onwards, and by the turn of the twentieth century its fundamentals had been expanded, new applications developed, and microscopic formulation via statistical mechanics incorporated. Today, classical thermodynamics content is widespread throughout contemporary science, information theory, dynamic and biological systems, and so on, mainly through the concept of entropy. The theory of this notion was approached in greater depth and gained ground in other areas of application; for example, Shannon’s article “A Mathematical Theory of Communication” (1948) is considered the theoretical landmark for the founding of information theory, and was essential to the development of communication systems and data storage technology. Here we emphasize how the fundamentals of classical thermodynamics have the potential to establish bridges with the present. *Information* is held very dear by contemporary society: a discussion that is solidly grounded in historical and philosophical aspects of the concept of entropy and its relation with information and uncertainty makes it possible to bring highly relevant socio-scientific debates into the classroom. We accordingly consider that the history, philosophy, and sociology of science contribute to current debates and are not relegated to the past. The approach we have chosen adopts strategies that help avoid anachronisms when discussing theories in centuries past while remaining faithful to the topics that are relevant to physics education, such as the basics of physics and contemporary applications.

This article is organized as a “thematic approach” (Silva *et al*., 2013). By opting for a broad historical period in our research, we present an overview of how the concepts developed, rather than a microhistory. Considering the premises of historiographic writing (Pestre, 1996; Videira, 2007), we took several precautions to appropriately present the selected content, always keeping sight of the necessary simplifications and recommending in-depth readings when relevant, since this article is not strictly limited to the history of science but rather focuses primarily on education. Our objective is to present a history of the concepts in order to show how scientific knowledge developed in the context of contemporary debates.

Our research began with an initial search in the Brazilian Digital Library of Dissertations and Theses (BDTD) for the keywords “teaching thermodynamics” and refined the results to obtain works that explicitly focused on physics teaching in basic and/or higher education. Our goal was to gather references and verify works with a similar theme to ours in an attempt to identify potential gaps. For the period 2009-2022, we identified a total of 47 theses and dissertations: 11 addressed the development of didactic units or sequences for teaching thermodynamics, nine of which were based on potentially significant teaching units (UEPS), one based on problem-based learning (ABP), and another based on Bloom's revised taxonomy. Three studies analyzed textbooks on the subject, five explicitly addressed the history of science in physics education, 11 proposed approaches using investigation and/or experimentation with thermal machines, and two analyzed previous educational experiments.

The broadest and most widely researched subject was didactic strategies. Seventeen studies proposed a variety of strategies to improve the understanding of students in basic and higher education with regard to certain specific concepts in thermodynamics such as temperature, heat, and the second law. Some of the studies we identified in this category overlapped with topics from other research items, but they mainly focused on presenting didactic strategies for teacher training. For example, the history and philosophy of science feature among the strategies presented in five of the 17 studies. They mainly center around the difficulties faced by basic and/or higher education students in understanding and/or incipient understanding of thermodynamic concepts. We noted the predominance of themes related to the first law of thermodynamics, the Carnot cycle, and the concept of heat. For this reason, historical-philosophical exploration of the second law is still relevant, as it remains a topic that has not been widely addressed and offers the possibility of more in-depth approaches and the development of educational products to mitigate the problems mentioned above.

The present article has an "emphasis on entropy" and is located within the epistemological dimension of including complexity in scholastic science education, as discussed by Watanabe & Kawamura (2020): "The emphasis on entropy within the context of complexity implies specifying that everything has a history and that this history is irreversible" (p. 438, free translation). We present the concepts of irreversibility and entropy in order to develop material that can (a) improve the understanding of thermodynamic concepts that are considered problematic in physics education, (b) introduce and disseminate these concepts as foundations of complex thinking, and (c) show aspects of the nature of science against the backdrop of the history of thermodynamics. By building correlations between scientific knowledge based on its history and contemporary philosophy, we believe we are providing material that is substantial from the viewpoint of scientific content and connected to a new worldview.

## II. Brief review of the history, philosophy, and sociology of science in education

The perspective associated with outdated notions of how science functions (which in the specialized fields of this debate has already been widely overcome) persists in science education as the "hidden curriculum," namely implicit assumptions within programs and manuals that influence the construction of knowledge about the sciences (Hodson, 1985; Cachapuz *et al.*, 2004). These assumptions generally lead to superficial understanding, influenced by years of investment in the ideology of technological determinism during the wartime periods in the last century (Auler; Delizoicov, 2001). Common sense consequently considers science to be an enterprise detached from cultural realities, focused on the accumulation of finished and ahistorical products, and carried out by isolated scientists.

Such belief in technological determinism and the supposed superiority of "Science" is based on the theses of scientific neutrality and the linear progress of science. In this case, scientists would not share social values in their practices and would be exempt from responsibility, since the knowledge produced itself would have a beneficial purpose (Oliveira, 2008). These and other "myths," like the uniqueness of the scientific method (Woodcock, 2014), characterize the empirical-inductivist view which still predominates in the public understanding of science and common sense (Gil-Pérez *et al.*, 2001; Pereira; Gurgel, 2020). Such views are considered distorted, and are inconsistent with the past sixty years of studies in the fields that research the history, social aspects, and epistemic characteristics of science.

The review by Sasseron e Carvalho (2011) demonstrates that theorists of scientific literacy converge towards criteria that can determine whether an individual has a good understanding of the sciences: in other words, whether they are scientifically literate. These criteria are understanding the relations between science and society, knowing how to differentiate science from technology, knowing that there is a commonly agreed ethics that is essential in supervising scientific activity, knowing the characteristics of science or the "nature of science," observing the relationship between the sciences and other spheres of knowledge, and last but not least, having knowledge about the basic concepts of scientific content. Science is clearly more than just production, and knowing the social characteristics, processes of historical legitimation of practices and practitioners, characteristics internal to its function, and the structure and relationship between its objects of study, for example, is indispensable.

With these indicators as educational objectives for science education, there is a wide variety of possible methodologies and approaches to mobilize the debates that surround them. In our case, we followed the path of the history, philosophy, and sociology of science, based on the vast literature that addresses the benefits of explicitly including the historical, philosophical, and social dimensions of knowledge in education (to include only a few examples: Abd-El-Khalick; Lederman, 2000; El-Hani, 2006; Teixeira *et al.*, 2009; Praia *et al.*, 2007; Forato *et al.*, 2011; Moura, 2014; Clough, 2017; Peduzzi; Raicik, 2020). This literature is consistent with the summary by Mathews (1992), detailed below, that including the history, philosophy, and sociology of science in education helps to:

- Humanize scientific work and contextualize it in amid the historical era, places of production, and subjects of the theories and experiments expressed. These factors (social, geographical, cultural, etc.) mix with the knowledge produced and often play decisive roles in the acceptance or rejection of theories/experiments.

- Teach about the structures that comprise and organize the content of scientific theories. For example, how to discern between concepts, observations, experiments, models, postulates, laws, and scientific theories, for instance.
- Debunk myths around isolated genius scientists and gender/ethnic/etc. stereotypes, showing that science is a highly collaborative activity carried out by people from diverse cultures.
- Refute the myth of a univocal, algorithmic, and infallible "scientific method." Throughout history, it is possible to show various methods used in different sciences (and even within the same science), along with the fallibility and limitations of each method.
- Demonstrate that knowledge does not accumulate in only linear and cumulative processes. Errors and successes need to be historically positioned; something once believed to be a scientific fact can be proven wrong, just as an "error" may eventually be harnessed in future theories and become a fundamental concept for a new scientific theory or model.
- Assist in developing critical thinking by showing open-ended questions with philosophical and social implications. Historically, observe issues that had different possible solutions, where the scientific community needed intersubjective means to resolve conflicts between theories, which can shed light on how the scientific community requires moral values in contact with society and the environment, in addition to "objective" values to agree on a better theory.

Discussions that can be evoked from the above topics contain *meta-scientific* elements. This is a scientific approach that seeks to systematize unique characteristics common to the varied practices, methods, and criteria established in responsible institutions for what is intrinsic to "doing science." The field known as the "nature of science" emerged in education at the intersections between the history of science and philosophy of science (and social studies of sciences, in general), bringing together such elements; it is considered meta-scientific from its formation, since it is a scientific investigation focusing on the sciences and their structures. This field of investigation is intensely nourished by debates in the philosophy of sciences about the epistemological and ontological criteria that organize and structure scientific knowledge. However, it differs by focusing on retaining what is indispensable to the science which is *taught*. The nature of science (NOS) approach debates whether the processes of accepting a new scientific consensus depend on internal epistemic factors (such as method used and relationships between theory and experiment), factors related to the social organization of the scientific community (academic credibility of the researchers involved), or aspects external to the community (culture, economy, politics, religion). Note that all these factors are connected to socially and historically situated projects. We consequently maintain that the nature of science as a field of study via the history, philosophy, and sociology of science approach helps us understand what science is and how it differs from nonscientific knowledge as well as from pseudoscience (Moura, 2014; Peduzzi; Raicik, 2020; Pereira; Gurgel, 2020), thus contributing to a better-informed debate on the conditions in which science is produced. Science education is currently an interdisciplinary field that not only gathers contributions from different fields but also produces new knowledge with its own characteristics. The ability to incorporate “interdisciplinary approaches [is] what should be at the center of promoting a citizen science culture” (Fourez, 1995, *apud* Cachapuz, 2004, p. 365, free translation).

In this article we argue that the episteme of modern science (developed post-Renaissance) cannot solve all contemporary socio-scientific problems or even some from its own time, since it operates with subdivisions of the whole and analysis of the parts, similar to mathematical operations in differential calculus (Latour, 2020). Education consistent with such a worldview, which separates knowledge to benefit specialization and accumulate its production, will also be unable to encompass the complex web of real dynamics. Given the increasing complexity of human relations *per se* and how they relate to the planet, one of the main challenges of education in the twenty-first century is to present historically constructed knowledge to individuals in order to show that the boundaries created between knowledge are artificial and operational (Gallo, 1995; Morin, 2005).

Despite recent curricular reforms and advances in research on science education, school knowledge is still fragmented into disciplines and compartmentalized. Reintegrating knowledge, promoting interdisciplinarity, and proposing initiatives that support connections between school knowledge and daily life are recurring challenges. Everyday life requires students to be able to identify within the segments of the discipline which knowledge can assist them in decision-making and constructing citizenship. This task is not trivial since the way knowledge is presented in “boxes”, and the traditional class structure make it difficult to reconstitute the meaning of real-world phenomena. Globally, the most urgent contemporary problems have been characterized by their increasing *complexity*, that is, the way they integrate different knowledge that mutually affects one another. Some subjects cannot be reduced to the fragmented approach present in school culture. Complex thinking has been indicated as a strategy for more open curricula, suitable for building a broad and multidimensional view that can provide real solutions to real problems (Angotti, 1999; Almeida, 2005; Watanabe; Kawamura, 2020). For this reason, didactic strategies and curricular models that favor a “reconnection of knowledge” seem highly relevant in the current context (Morin, 2000; Gallo, 2015).

There is expansive literature presenting the fruitful collaboration between history, philosophy, and sociology and how debates in metatheoretical fields such as the history of science and philosophy of science can help address the challenges of contemporary education (for example, Forato *et al*., 2011; Damasio; Peduzzi, 2017; Moura, 2021; Lima; Guerra, 2022). However, use of the history of science for education should not be ancillary: we reiterate that the sciences *are* historical, socially built, and permeated by the beliefs of their practitioners. Therefore, the history of science does not function as a “supporting discipline” for *a posteriori* justification of the rational paths taken by the Sciences (Videira, 2007). Teachers mediate a critical process in which they provide inputs so students can obtain insights into the extra- and meta-scientific dimensions, such as “the epistemological, historical, political, and axiological foundations on which historical discourses are built" (*ibid*., p. 122).

The theoretical and methodological frameworks used in the research that led to this article justify the relevance of historical research and the choice of this modality to understand the object of study. The methodology employed to reach the conclusions presented herein was a bibliographic review of primary and secondary sources in the history of science during the period of study (mid-nineteenth century and twentieth century), in dialog with the bibliography on the history, philosophy, and sociology of science in science education. We present a possible historical narrative on thermodynamics based on critical readings, research group discussions, and reflections on the adopted references. Methodologically, we opted to emphasize the concepts that inform the narrative in order to include the history, philosophy, and sociology of science in science education (namely uncertainty, irreversibility, history, and complexity). All these terms, which are common to the references used in various fields of research, intersect to produce meanings for science education.

In theoretical terms, we also employ complex thinking, disseminated by Edgar Morin (1921- ), and the philosophy of physics defined by Ilya Prigogine (1917-2003). We believe that such theoretical lines are essential for contemporary society, which faces an uncertain future permeated by socioenvironmental crises of unprecedented scales (Guerra *et al*., 2020). Complex thinking is highly relevant to school culture in order to educate citizens equipped with cognitive strategies to handle the challenges of this century. Similarly, the epistemological framework developed by Prigogine and Stengers (1991) proposes a look into and about the sciences that inspire life and creativity to solve these challenges. Below we present some conceptual foundations for these concepts.

## III. The automaton world of the Newtonian paradigm

In the previous section, we traced a path for science education in Brazil and indicated that a particular perspective of science continues to inform and coordinate educational objectives: modern science. As we shall see, this perspective is founded on the mechanistic rationalism of classical physics, epitomized in the Newtonian paradigm. In order to illustrate aspects of this paradigm, we begin with an idealized object of the history of thinking that we denote (among other characteristics) as an *extractivist* paradigm. This object of analysis is the perpetual motion machine: observing the idea behind these machines provides a starting point to reconstruct the path that led to the formulation of the second law of thermodynamics, and makes it possible to illustrate the scientific, cultural, economic, and political impacts of classical mechanics on the science produced in Europe in the eighteenth century.

These idealized machines appear as an ancient curiosity or even an obsession with creating an object capable of sustaining movement *ad aeternum*. Simon Schaffer, in an article entitled "The show that never ends: Perpetual motion in the early eighteenth century" (1995), narrates an episode in 1720s England that signals the ideological proximity between the eighteenth-century English political and economic moment and perpetual motion machines. A Saxon clockmaker claimed to have built a spinning machine that would maintain its movement indefinitely, without the need for external propulsion, attracting attention from members of the British Royal Academy. Note the figure of the clockmaker, since clocks had been the subject of constant refinement since the fourteenth century and had a major impact in regulating social and economic dynamics. The appeal of counting and standardizing time during the establishment of industrial capitalism in Europe in the seventeenth and eighteenth centuries positioned clocks as literal monuments in public squares. Not incidentally, clocks are often considered in the historiography of science as model objects that synthesize the worldview produced by the glorification of Newtonian theories in European society (Prigogine; Stengers, 1991; Prigogine, 1996; Rosa, 2006; Paty, 2004a). It is important to note the excitement in the economic world of that time which encouraged the pursuit of such machines that could replicate movement forever (Hobsbawn, 2009). The potential of a perpetual motion machine was expected to be converted into work and generate even more profits, within the logic of investment in the financial market which was already established in eighteenth-century England. Still, more abstractly, verifying the existence of a perpetual motion set a new milestone for measuring the value of work for other machines. According to Schaffer:

> *The traumas of new monetary systems and credit mechanisms, very intense during the collapses of the exchanges of Paris and London in the early 1720s, only dramatized the puzzle of fixing secure values in a market society. In this period, terms such as "credit," "calculation," and "speculation" shifted their senses rapidly between problems of knowledge and of finance* (1995, p. 161).

Such inventions were consequently seen with a fair amount of distrust and some social concern. In 1775, the publication of alleged perpetual motion inventions was finally banned when the Paris Academy of Sciences recognized that constructing a perpetual motion machine would be impossible (Schaffer, 1995). The ban was based on moral arguments that sought to unite the principles of classical mechanics with those of society. The pursuit of perpetual movement generated excitement that could disrupt order and destabilize systems of credit, trust, and social security, since it was directly related to the notion of work. Pragmatically, if perpetual movement were achieved, this technique could be used to replace the blue-collar labor of men and women, reducing production costs and dramatically increasing profits while consequently producing tremendous social impacts. It could also drive waterwheels, draw water from flooded mines (in the case of coal, for example), and represent the ordered and infinite cosmological model: the clock world that maintained its movement forever after the primordial impulse.

Perpetual motion machines were therefore objects of dispute over ideological and economic matters and the limits of knowledge. Wise men, engineers, investors, and politicians were involved in the enigmatic apparent impossibility of an eternal movement driven by diverse desires: the pure pleasure of experimentation and discovery, expanding frontiers of knowledge, and the possibility of new ways of working and measuring value, the promise of inexhaustible profit, or reaffirmation of the divine order. The close personal relations between scientists and relevant figures of the absolutist states were also involved in the circulation of knowledge. Scientific practice was fostered and funded by members of royal courts, and when they were successful, scientific artifacts were used to make explicit references to the power of these patrons[2].

Newton's synthesis between theory (mathematics) and practice (experiment) and the successful strategy of proposing questions and answers to nature resulted in the understanding of the world as a clock, an *automaton* world (Prigogine; Stengers, 1991; Prigogine, 1996). An automaton is a machine that produces movements that appear to be its own due to the intricate organization of components (which are sometimes hidden). The *machine worldview* is a characteristic that arose from the Cartesian world scheme and profoundly inspired the Newtonian paradigm. Determinism, as we shall see, results from causality as a series of connected gears. Knowing the initial conditions of motion, it would be possible to determine the future path and reconstruct the past from any material point subject to the universal laws of motion. This was a new experimental methodology. The mechanical laws of motion elaborated by Isaac Newton (1642-1727) were in line with the philosophy of René Descartes,[3] whose philosophical bases permitted the development of mechanism. Such events were simultaneously products and reproducers of the mentality that presumed to understand the universe by capturing it in static frames, an operation that consisted of selecting inanimate objects and examining them in parts. Moreover, it was with great success that the analysis of the world over absolute time and space became descriptive: drawn by curves in Cartesian space (trajectories), intersected by abstract points concentrating the mass of extensive rigid bodies (center of mass), moved by the action of central forces acting at a distance (universal gravitation).

However, for the clock to start counting time or for the automaton to move, a "primary mover" was required outside or "above" the system that could be described by Newton's theory. Newtonian physics then combines with the Christian narrative of the life-giving creator who animated the machine world and wound the clock. The Catholic church remained a strong religious influence in Europe from the High Middle Ages, and the lack of explanations about the origin of life within the framework of rational mechanics could be conveniently filled by the idea of the Christian creator god, producing a coupling that

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[2] For example, in 1678 Gottfried Leibniz (1646-1716) proposed erecting an obelisk with a perpetual motion clock as a tribute to the power of his protector, Sophia of Hanover (Schaffer, 1995).

[3] René Descartes (1596-1650) and rationalism: the excellence of *reason* to achieve truth and the detachment of the spirit (reason, *res cogitans*) from the body (experience, *res extensa*). "According to Descartes, *cogito ergo sum* ("I think therefore I am") is the first principle of philosophy, ushering in a revolution that consists of starting from the presence of thought and not from the presence of the world." (Japiassú; Marcondes, 2008, p. 65, free translation)

amplified mutual acceptance of discourses: Christian discourse and the discourse of classical mechanics. We will not delve into this relationship between science and religion, but we would like to highlight it as another indication of the permeability between current beliefs and scientific theories.

Isabelle Stengers and Ilya Prigogine (1991) state: “[Modern] science is the product of the vital requirement of taking advantage of the world, and its concepts are determined by the need to manufacture and manipulate objects, to predict and act on natural bodies.” (p. 74, free translation). This need for manipulation and prediction about natural bodies lies at the foundation of rational mechanics and subsequent works influenced by it. Not incidentally, one of the most significant features of mechanistic epistemology is *determinism*, which appears in the Newtonian paradigm with the development of mechanics by figures such as Pierre Laplace (1749-1827).

In the preceding paragraphs, we used the example of perpetual motion machines to illustrate the human desire to extract labor at no cost; in other words, to obtain *resources* from the environment and reduce the effort required toward zero. We call this posture an *extractivist mentality* present in the modern ideal. Lima and Guerra (2022) argue, using the same terms, that there is an extractivist conception present in the official discourse of modern science, “which perceives nature as a source of *natural resources*” (p. 389, free translation). Humans would have the right to exploit and accumulate natural assets by coupling them with the Judeo-Christian discourse mentioned above. In this way, economic systems are founded that enable the emergence of a narcissistic and hedonistic consumer society that objectifies nature and sees itself above and especially *outside* it (Latour, 2020; Lima; Guerra, 2022).

What are the implications of the deterministic view of human forms of inquiry for the world? Historical observation of the limitations of mechanistic epistemology is required, noting its inability to accurately describe nonlinear relationships or solve problems with interdependent variables, even those of its own time. It is an epistemology that mainly values accumulation, linear growth, separation into parts, and the search for invariants. It consequently seems an inadequate approach for the problems of the contemporary world, which are increasingly complex, nonlinear, highly interdependent, and constantly changing.

Determinism is one of the categories we can consider, in the light of philosophy and the history of science, as foundational for modern scientific thought. Although the initial meaning of *determinism* has been positioned almost inseparably next to the concept of *causality*, it is possible and useful to distinguish them. According to Michel Paty (2004a), these *meta-concepts* are so strongly linked to each other and to the history of physics that to this day they are confused with the ideal of scientificity, reinforcing a static and cumulative image of science. However, such categories are historically situated and consequently present a context of validity and limitations. In explaining them, it is possible to show that the sciences are not exclusively characterized by causality and determinism, as we shall see in the case of deterministic chaos.

*Newtonian causality* stems from the understanding that relates *causes* and *effects* of the dynamics of the movement of bodies, as postulated by Newton: in other words, describing the change in a body's motion, explicitly assuming time as a continuous and absolute variable, and formulating differential and integral calculus. Within the scope of this article, we selected the notions of determinism and causality to talk about *initial conditions*. According to the epistemological framework of rational mechanics, if the initial conditions of any dynamic system at a given instant $t$ are known, Newtonian causality and knowledge of the natural laws to which the body is subjected make it possible to *determine* the posterior state from differential and uniform increments ($t + dt$). Causality is then a category (or meta-concept) that precedes the notion of determinism. Furthermore, the meaning of the word "cause" has a legal origin, related to the idea of law; that is, causality assumes it is possible to determine how all things move based on a *global law*.

The principle of *universal determinism* assumes that invariable relationships or laws bind all natural phenomena. It defines that if the state of the universe at a given time (initial conditions) and the laws of mechanics are known, all future states may be rigorously predicted because they cannot be independent from the series of causes (Paty, 2004a):

> *We may regard the present state of the universe as the effect of its previous state and the cause of what will follow. An intellect which, at a given moment, would know all the forces that set nature in motion and all positions of the beings that comprise it. If this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movement of the biggest bodies of the universe and those of the tiniest atom; for such an intellect, nothing would be uncertain, and the future just like the past would be present before its eyes* (Laplace, 1990 *apud* Japiassú; Marcondes, 2008).

This passage contains a philosophical implication of the worldview we have just described. Combining the causal laws of motion with absolute and continuous time leads to the conclusion that all of reality would already be in place for an observer who had a point of view of objective and finished knowledge (Paty, 2004b). In this way, the mathematical modeling that approaches problems through probabilities would only be a palliative to ignorance and the limitations of human perception (*ibid.*). This hypothetical intellect with infinite reasoning capacity became known as "Laplace's demon," and raised serious questions about the epistemological limits and philosophical implications of universal determinism such as free will. Laplace's demon was further refined by James C. Maxwell and used as a thought experiment to explore the meanings of thermodynamic concept consequently known as "Maxwell's demon"[4].

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[4] This thought experiment can be useful for physics education because it bears meta-scientific characteristics, such as research on the limits of knowledge, measurement, and information, the meaning of entropy, and philosophical implications of knowledge. For further details, see Mattos and Hamburguer (2004).

We argue that the cracks in the Newtonian paradigm and instability of the certainties and needs assumed by determinism are best seen in classical thermodynamics. In the early twentieth century, with the development of quantum mechanics and Heisenberg's uncertainty principle, the scientific community was more willing to accept uncertainty as an indelible characteristic of nature and the probabilistic structure of reality. However, as early as the nineteenth century the law of entropy imposed new limits on physical phenomena which would have otherwise been impossible based on mechanistic thought. It was Laplace's three-body problem that laid the first foundations for chaos theory and opened the door to concepts that begin to escape the conceptual framework of classical mechanics, such as unpredictability, as we shall see.

Laplacian determinism results from the mathematization and sophistication of Newtonian causality in Laplace's algebraic treatment of the equations of motion. This sophistication reached such a level that Laplace was able to describe the dynamics of three bodies affected by gravitational attraction (the Sun, Earth, and Moon, for instance), a very refined problem. But Laplace found no general, closed analytical solution to the three-body problem, because for this problem there are only numerical solutions.[5] It should be noted that no solution would have been possible without adopting conventions according to categories of similarity (like assumptions about the mass of bodies). Scientific practice requires the elaboration of hypotheses, conscious or unconscious; in this process, scientists imprint personal characteristics and the thinking style of their scientific community on the problem, thus demarcating the results. This characteristic of science can be called "*theory-ladenness*" or the nonexistence of neutral observations (Peduzzi; Raicik, 2020). The 1889 King of Sweden award was given to Henri Poincaré (1854-1912) for demonstrating that the stability of the solar system cannot be rigorously obtained without such approximations (Paty, 2004b). This is just one simple example of demarcating the problem through theoretical hypotheses to make meaningful observations, but we emphasize that there are assumptions underlying any and all scientific observations, even if they are not always conscious (Peduzzi; Raicik, 2020).

Any slight variations in the *initial conditions* of problems of this nature can amplify upheavals in arbitrary and indeterminate values, leading to uncontrollable and unpredictable outcomes. In other words, the three-body problem is that relationships between the bodies are well determined by universal gravitation, but it is impossible to predict their trajectories because of the high sensitivity to the initial conditions. The three-body problem is consequently the first example studied of *deterministic chaos*, and represents a time when the *predictive ability* of classical mechanics fails within its own scope of application. Newtonian mechanics is not incorrect, however; on the contrary, it is very robust and remains relevant in contemporary physics. It is the nonlinear (complex) nature of the interaction between bodies

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[5] A numerical solution is obtained through tables of values estimated by means of computational algorithms and approximations. In contrast, an analytical solution is an exact solution, obtained by means of mathematical equations defined by theory.

that produces the unpredictable effects. In such situations, any minuscule fluctuation or difference is amplified over time, resulting in a trajectory that differs significantly from that of another system that began in a practically identical state. The combination of nonlinearity and fluctuations is precisely what may produce *difference*, the unexpected and the new, contrary to the expectations of a world whose movements would all be revealed by Newton. The three-body problem is still unsolved in contemporary physics, and is the object of simulations to obtain numerical solutions.

In the next section we address the second law of thermodynamics via a historical and epistemological approach, offering an interpretation of the law for application in science education in order to construct more complex and integrated thinking. The principles presented can enrich the debate on climate change and energy transition, as well as in other subjects. Burning fossil fuels is known to be an irreversible process that increases entropy by releasing gases with strong heat-trapping capacity into the atmosphere, intensifying the greenhouse effect. The urgent transition to more renewable sources in our energy grids can be based on open systems that decrease entropy locally, producing a balance with more equilibrium in the (inevitable) production of entropy during energy transformation.

## IV. The second law of thermodynamics

The physics theory that first revealed the cracks in mechanism is classical thermodynamics, especially the second law of thermodynamics, because it addresses transformations (Prigogine; Stengers, 1991). Work on the second law sheds light on new scientific concepts related to experience and intuition: time runs in only one direction. Recall that in classical mechanics, time is an absolute variable and independent of space, and the laws of motion are reversible for precisely this reason. In other words, the mathematical description for a “backward” movement would be equivalent, just with a different sign for the variable. But if time is reversible for the universal laws of mechanics, why is it irreversible for all living things? What is the relation between life and decay, irreversibility and history? We will present the concepts of irreversibility and entropy through the notions of transformation and uncertainty to show the historical factor incorporated into scientific laws.

The second law of thermodynamics is a *phenomenological law*. That is, any statement that correctly describes a phenomenon resulting from the relationship between heat and work (which the second law imposes) is considered valid. We find different formulations of the second law throughout history, but the most common version in science books is the Kelvin-Planck formulation: “It is impossible to construct a device that operates on a cycle and produces no other effect than the transfer of heat from a single body for the production of work” (Planck, 1945, p. 89, *apud* Nóbrega *et al*., 2009). In other words, it is not possible to transform all the heat from a body into mechanical work or promote the passage of heat from a hot source to a cold source without another associated effect: in this case, heat dissipation. Max Planck (1858-1947), in his *Treatise on Thermodynamics* (1945), writes: “Clausius’s principle states that *heat cannot of itself pass from a cold to a hot body*." He adds: "[…] Heat can in no way and by no process be transported from a colder to a warmer body without leaving further changes, i.e. without *compensation*" (p. 85). The emphasis on "compensation" in the original indicates that its meaning is essential in exploring the concept of entropy. Even if textbooks and teaching manuals have gradually abandoned this meaning, the notion of compensation remains valid for understanding what entropy is within the context of applying classical thermodynamics (Aurani, 2018). For this reason we have chosen to underscore the interpretation by Rudolf Clausius (1822-1888), because of his contributions to the field and the set of assumptions available to him when this concept was developed. Teaching entropy according to Clausius can be useful in basic education, because it does not require an in-depth exploration of more sophisticated theories about the composition of matter and statistical physics.

Rudolf Clausius began his investigations into the implications of the Carnot cycle with the discoveries of conservation of energy. It was Clausius who established the nomenclature for *entropy* (*en* + *tropos*) as a variable, with an etymology that intentionally granted it the same status as *energy* (Clausius, 1865 *apud* Magossi; Paviotti, 2019). The term *tropos* (*τρόπος*) is a polysemic word of Greek origin that comes from *trepo* (*τρέπω*), which means to turn or spin. In modern Greek and philosophy, *tropos* has taken on the meaning of "mode" or "manner," but because of its roots implying turning or spinning, it also implies *transformation*. This was precisely the meaning Clausius wanted to invoke for the new variable (*ibidem*). Throughout his works published between 1854 and 1867, this author demonstrated that there is an amount associated with an essential transformation of systems that involve the processes of (a) converting heat into work, (b) converting heat at one temperature into heat at another temperature, and (c) changes in the internal arrangement (modes of organization) of the parts that comprise the system. For this last possibility of transformation, Clausius associated the word "disaggregation,"[6] which also remains as a valid understanding for the concept of entropy with the potential for application in teacher training and basic education (Aurani, 2018).

Although he did not explicitly formulate a theory of matter, Clausius made atomistic assumptions during the process.[7] The idea that there is something indivisible comprising the other objects in the universe – the atom – is repeated and adapted in various cultures throughout the history of thought, and can be considered an example of a *protoidea*[8]. Assumptions about the nature of matter are not necessary for the results of classical

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[6] "[…] a new concept, that of disaggregation, which concerns the arrangement of the constituents of substances, and which grows by the effect of heat, as dispersion in the body increases" (Aurani, 2018, p. 159, free translation).

[7] We will not explore this point further due to the limitations of space; this statement is based on a reading of Clausius' article translated into English, *On the Nature of the Motion which we call Heat* (1857).

[8] "Protoideas should be considered historical-evolutionary pre-dispositions of modern theories and their genesis should be founded on the sociology of thought" (Fleck, 2010 [1935], p. 66, free translation).

thermodynamics, which makes it a phenomenological rather than explanatory theory. However, the atomistic hypothesis is very useful for deeper exploration of the notion of entropy and is essential in statistical description of thermodynamic variables[9]. Clausius accepted the validity of the experiments by James Joule (1818-1889) on the principle of mechanical equivalence between work and heat, and rejected the idea of "conservation of the caloric fluid;" namely, Clausius assumed that heat was associated with the movement of particles. Both theories, heat as a fluid (caloric) or as particle movement, coexisted and produced errors and successes (Silva *et al*., 2013). But we can state that the pro-caloric scientists gradually died out, and the theory failed to gain new followers compared to the competing theory. The evidence that accumulated observing the relationship between heat and work generated new believers in the notion of heat as the movement of particles, bolstering this viewpoint. It should be noted that assumptions about the nature of heat were also not required to successfully demonstrate the efficiency of thermal machines, since Sadi Carnot (1796-1832) himself assumed that heat was a fluid (Santos, 2009; Silva *et al*., 2013).

The original article *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*[10] was published in 1824. Even though it was not widely disseminated or recognized at that time, the modern literature considers it a milestone of classical thermodynamics. We note the date to emphasize the time elapsed between investigations into perpetual motion and the theoretical formalization on thermal machines published by Carnot. According to this author, a thermal machine cannot obtain 100% yield, even if it operates in frictionless and reversible transformations (idealized processes). It thus follows that no technical limitations impede the production of work entirely from a heat source. In nature, through observation or controlled experiments, there has never been a record of a phenomenon in which thermal energy (heat) was totally converted into useful mechanical energy (work). Carnot's formalization supported this observation in the theoretical domain, where hypotheses are tested and experiments conducted under conditions that are ideally controlled. Therefore, *even in an ideal situation*, the relationship between the types of energy described does not allow a complete transformation from one type to another to take place: some portion of energy is always dissipated or lost. This reinforced suspicions among scholars of science for nearly a century that perpetual motion was in fact impossible.

The result of Carnot's work impacts the extractivist mindset we described in the previous section by confirming the impossibility of obtaining work from nature in a spontaneous, unrestricted manner without external action or production of entropy, in other

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[9] For a more detailed presentation of the atomistic hypothesis of matter and how the scientific community received the ideas about atomism disseminated by Ludwig Boltzmann (1844-1906), see Videira (2006).

[10] We should note that Carnot was motivated to study the efficiency of thermal machines in order to find ways to strengthen France in the face of England's overwhelmingly powerful steam engines (Santos, 2009). The belligerence between France and England drove the young scientist to seek a way to serve his nation through science. He adopted the theoretical approach, running counter to most works that focused on refining techniques that would reduce losses from dissipation.

words, without *compensation*. It also added subtlety: it is possible to consider perpetual motion machines that do not violate the principle of energy conservation but violate the law of entropy. These are known as “perpetual motion machines of the second kind,” and are precisely full-yield thermal machines. This reasoning demonstrates that the law of conservation of energy alone is not sufficient to describe the totality of phenomena which are prohibited in nature (Santos, 2009), reinforcing the relevance of the second law for understanding the physical world. The *dissipation* and *degradation* of part of the energy is inevitable and necessary, as “the production of heat alone is not sufficient to generate to the impelling power of fire: there must also be cold, without it heat would be useless” (Carnot, 1824 *apud* Aurani, 2018, p. 156).

To better understand the unique nature of the Carnot cycle, comprising only reversible processes, presenting reversibility and irreversibility in light of the references employed is useful. According to Clausius, in a *reversible* transformation the final and initial states are in *equivalent* internal arrangements, in such a way that the nature of the system is not transformed, since there was no disaggregation. The transformations (isothermal and adiabatic compressions and expansions) occur so that the compensations of each one total zero. The second law can be described in modern language as follows: *in reversible processes, the variation of entropy equals zero*. In cyclic processes, the initial arrangement is recuperated, with an equivalent final arrangement. However, the empirical law tends to favor a certain direction in some transformations, such as the passage of heat from higher to lower temperatures (the Clausius principle). In this case, the process occurs *spontaneously*, with no need for transformation elsewhere in nature, and compensation has a positive value. In other words, *the variation of entropy in spontaneous (and therefore irreversible) processes is always positive*. Notable examples of irreversible processes are free expansion of a gas, dissolution of substances, burning of fuels, and heat dissipation via friction.

One requirement for an irreversible process is that it is impossible to recover the previous state of the system *by any natural means* (Planck, 1945). In other words, it is an essential transformation of the internal arrangement[11], a disaggregation produced by the degradation of part of the usable energy. The initial state cannot be fully reconstructed from the final state to an equivalent arrangement *without an external agent*. In this way, even if the system can be returned to a state equivalent to the initial one, the energy expenditure to perform the action (work) will produce an irreversible transformation elsewhere (by heat dissipation, for example), adding a positive value to the total compensation. That is, although the entropy value can be reduced in an open system (which exchanges matter and energy with the external environment) it is always possible to find a closed system nearby in which

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[11] The internal arrangement is the mode of organization for the basic constituents of the system relative to the variables of position, time, energy, etc. Within the context of statistical physics, it is called a *microstate*. A microstate corresponds to a particular macrostate (pressure, volume, temperature), and the same macrostate can be obtained by different microstates.

entropy is positive and higher than negative entropy, maintaining the inequality of the second law.

We emphasize that the cornerstone of the second law of thermodynamics is that certain directions are favored for some natural phenomena. “The second law, therefore, furnishes a relation between the quantities connected with the initial and final states of any natural process” (Planck, 1945, p. 87). This statement allows us to say that the second law can create a distinction between time intervals, based on scientific terms, a notion of “before” and “after.” Considering the expressiveness of irreversible processes, we can question whether reversible processes even occur in nature. Max Planck argued that it is possible to consider reversibility if friction can be avoided. However,

> *Since there exists in nature no process entirely free from friction or heat-conduction, all processes which actually take place in nature, if the second law be correct, are in reality irreversible. Reversible processes form only an ideal limiting case. They are, however, of considerable importance for theoretical demonstration and for application to states of equilibrium* (Planck, 1945, p. 88).

We can then conclude that the real phenomena present in our daily lives are irreversible. This is one of the contrasts posited by thermodynamics with regard to Newtonian time, which is supposedly reversible and absolute. Irreversibility therefore permits the distinction between an initial state (before) and a final state (after), as a result of an essential transformation of nature. We should note that the laws of classical thermodynamics can only be applied to the *thermodynamic limit*. Although microscopic laws are deterministic, the individual trajectory of a particle cannot be precisely traced, similar to the aforementioned three-body problem.

Finally, how do we define entropy? In addition to a measure of compensation for transformations and disaggregation of constituents, one word that spans such meanings is *uncertainty*. If we make atomistic assumptions like Clausius did, entropy measures how much *we do not know* about the internal configuration of a system. Therefore, a system with high entropy can exist in a variety of modes (microstates) that present as the same macroscopic state (macrostate). Meanwhile, a system with low entropy has fewer modes of organization that correspond to the same macrostate they define. A piece of coal is what it is because it has a defined molecular configuration. As coal burns (an irreversible transformation), the atoms, which are confined in specific positions, are released into the atmosphere and can occupy a greater variety of positions in the form of gases that result from this combustion. In this way, the entropy of a volume of coal is less than the entropy of the volume of gases produced after the coal is burned. This is because there is more information and, consequently, less uncertainty about atoms when they are organized in molecules than when they are diffused in the atmosphere in the form of gases.

We emphasize that *uncertainty* is not only a word that comprises the scientific vocabulary but also a watchword in the paradigms derived from the irreversibility we have presented in this article. For example, unpredictability, openness to chance, and the possibility of error are essential in constructing complex thinking (Morin, 2005). The literature on the nature of science contains many statements about the conjectural character of scientific thinking, the mutability of the sciences, and the presence of intersubjectivities in the creation and choice of theories, among other characteristics that impose a degree of uncertainty required for scientific enterprise (among others, Forato *et al*., 2011; Moura, 2014; Peduzzi; Raicik, 2020).

The concept of entropy is commonly associated with "disorder" and progressive chaos, given that the second law imposes a spontaneous tendency toward the dissipation of energy and decay. However, the order/disorder binary is a highly subjective and ambiguous classification and needs to be considered in context, without triviality. "*Disorder is simply the order we are not looking for*" (Bergson *apud* Japiassú; Marcondes, 2008). This is because if there is a natural trend toward "disorder," how can we explain the appearance of organic molecules with increasingly intricate organizations over time? Life remains intangible within a conceptual framework that understands the law of entropy only as increasing disorder.

For this reason, we propose an interpretation for entropy that shifts the focus from disorder to the possibility of *other orders* and *self-organization* (Prigogine, 1996). From the latter half of the 1900s, Ilya Prigogine published research on the physical chemistry of open systems far from equilibrium, obtaining results on the behavior of matter he called *dissipative structures*. The order of these structures depends on the relation between the dissipation of energy and matter and their surroundings, oscillating between various dynamic configurations. Among the various scientific and philosophical potentialities, we emphasize the *historicity* present in the behavior of these structures. The succession of transformations traversed by the system makes it possible to observe an actual "historical element," with breaks in temporal symmetry and self-organized structures. Fluctuations play a crucial role in self-organization in regions of instability and force us to abandon the deterministic regime, similar to what we described with the three-body problem, in which any fluctuation in initial conditions leads to radically different trajectories. For example, when critical parameters are exceeded, in order to recover dynamic equilibrium a system which is far from equilibrium "chooses" more stable solutions, giving rise to bifurcations that express a history of how the system evolved (Prigogine, 1996, p. 71-73).

Given these characteristics, dissipative structures are useful for various chaotic, biological, and climatic systems, as well as other applications. But life, even in its simplest forms, reaches even more complex levels of organization and functions than the physicochemical systems studied. In his book *The End of Certainty* (1996), Prigogine details both the scientific content of his studies and the philosophy of physics that emerges from the paradigm of irreversibility and uncertainty. Without diminishing the relevance of description by trajectories, he expands the panorama of the sciences to encompass regions that are out of equilibrium, nonlinearity, and uncertainty as creative forces. He also states that the interest in systems which are far from equilibrium was not well received by the community at the time, which considered the study of such unpredictable objects fruitless. The mechanistic paradigm consequently continues to inform the choice of objects of study and the practices considered legitimate. Still, Prigogine's interest is precisely the matter of one of life's most glaring characteristics: impermanence.

We hope we have outlined the power of irreversibility and dissipation for a more historical notion of the sciences.

## V. Establishing connections with science education

Classical thermodynamics provides a scientific foundation for everyday intuition: the distinction between before and now is not a limitation of perception, but instead a fundamental law that governs transformations between matter and energy (at least at the level of human experience, at nonrelativistic speeds, and in macroscopic systems). Unidirectional time has finally been scientificized, and the sciences are historical in their very nature.

For the purposes of science education, we believe in irreversibility as an invitation to more critically reposition human actions amid the web of relations with the world. When teaching thermodynamics, it is important to note the difference between idealized systems (reversible, isolated) and real systems (irreversible, open), and the strong presence of the latter in everyday life, valuing the study of irreversible transformations, which result in increased entropy, degradation of usable energy, and greater uncertainty. We should also explain that even though there is always global growth of entropy, there are a variety of open systems in nature that can decrease entropy locally, creating other orders. One example is the photosynthesis process, which fixes a volume of carbon dioxide diluted in the atmosphere into organic molecules that fulfill vital functions in plants. Dissipation is an essential part of maintaining life, since living beings are open systems that consume energy.

Addressing this subject according to different themes, for example, considers the interdisciplinarity that indicates the interdependent and complex character of socio-scientific issues and the nature of science. Watanabe and Kawamura (2017), in an attempt to circumvent potential difficulties when introducing organization by themes into school culture, propose "open paths" which mix elements of traditional and thematic approaches. Both paths can be described as being in contact with the paradigm of uncertainty when they assume openness to teacher choice in response to the reality of classroom practice. Additionally, the framework they suggest allows adaptation of scientific content during the process of learning, with inevitable input from students and corresponding readjustments to educational objectives; in other words, they assume the importance of *unpredictability* and uncertainty in creating new knowledge.

Along with the historical perspective of how science functions, the paradigm of irreversibility can contribute to more complex thinking because it unveils the web of relationships between each action that takes place on Earth. The Intergovernmental Panel on

Climate Change (IPCC) reports that since 1970, the planet's average temperature has climbed faster than in any previous 50-year period. The concentration of carbon dioxide in the atmosphere is the highest it has been during the last two million years. The human contribution to the elevated concentration of greenhouse gases that in turn leads to higher average temperatures on Earth is considered undeniable (IPCC, 2023). Consumption patterns supported by a worldview that considers the planet an open source of resources and assumes progressive growth are unsustainable from a social and environmental point of view.

Besides being essential to the concepts presented herein, the mention of thermal machines is a conscious choice to combine them with the topics of climate change and energy transition. After all, steam engines were the main driver of the First European Industrial Revolution, a period of substantial change in capitalist modes of production. Thermal machines are the classic example of a technique that arose before theory, and can serve to foster rich debates about the uses of technical knowledge and the uncalculated impacts of this use. For example, Newcomen steam engines (which were most common prior to Watt's steam engine) had an efficiency of approximately 1%. This means that only 1% of the energy contained in a mass of coal was used to generate work; the remaining 99% was lost in the form of dissipated heat and gases released into the atmosphere (Santos, 2009).

## VI. Conclusion

We have seen that the mechanistic man is an individual who observes the world "from above" in an attempt to achieve a general law that is applicable everywhere (Latour, 2020). This uninvolved perspective simultaneously "reveals" nature's secrets and makes it appear suddenly inert, since it is entirely determined by an outside observer. As we have noted, science would be more successful if it was more susceptible to the immobilization and dissection of the objects of study and quantification "in the form of manipulable and calculable elements" (Prigogine; Stengers, 1991, p. 75, free translation). Modern science marks the passage from Aristotelian *contemplation* and *meditation* to the *manipulation* and *domination* of rational mechanics (Rosa, 2006; Oliveira, 2008).

"Science," in general, is referred to in the literature as a source of narcissistic injury to modern humans when it forced them to reposition themselves in three situations: within the universe, as a species, and before themselves, with the Copernican revolution, Darwinian evolution, and Freudian unconscious, respectively (Prigogine, 1996; Rosa, 2006; Latour, 2020). Nathan Lima and Andreia Guerra (2022) propose a less narcissistic science that can identify itself *as* the world, not something separate from it. In their article entitled "Overcoming Narcissus: history, philosophy, and sociology of science to postpone the end of the world," these authors suggest that the "end of the world," namely the set of collapses and crises we are currently experiencing, is the result of extractivist discourse like that described in this article, which took place as different forms of exploiting nature for centuries" (Oliveira, 2008; Lima; Guerra, 2022).

In the introduction to their book *A Nova Aliança* (1991), portuguese translation of the original *La Nouvelle Alliance: métamorphose des sciences* (1984), Prigogine and Stengers refer to a *disenchantment of the world* that would supposedly have been produced due to the successes of experimental dialogue. Together, control of nature's secrets and technical triumph would justify the extractivist posture we presented in the first section:

> *Disenchanted science, in this sense, doubly affects man's relations with nature: it not only legitimizes the posture of domination, but through technology provides the means to expand this domination and make it more efficient* (Oliveira, 2008, p. 99, free translation).

We suggest Oliveira (2008) for more details on the terms "disenchantment of nature," "domination," and "manipulation," which merit caution. Prigogine and Stengers as well as Oliveira do not simply and directly associate the "disenchanted world" with modern science, arguing that they are neither synonymous nor inevitably interconnected. The superiority of humans over nature was fostered by a series of factors in areas such as culture, economy, politics, and religion, which science cannot be held exclusively responsible for. A coupling occurred between the Newtonian cosmological model, Judeo-Christian discourse, and the capitalist mode of production and accumulation that could be widely applied to a nature immobilized by experimental strategies and the predictive success of theories (Oliveira, 2008; Lima; Guerra, 2022). However, the extractivist notion that emerged from this particular arrangement of modern European science is not the only way we can relate to the world; today, this way involves great cost, perhaps too great.

As we delved into the history of science, we found several episodes where scientific practice was not supported exclusively by the modern paradigm (Lima; Guerra, 2022). We used the example of the three-body problem and the second law of thermodynamics. We have seen that even in systems governed by Newton's laws, deterministic chaos and unpredictability are possible due to the nonlinear nature of interactions. We discussed the law of entropy from the point of view of irreversibility, transformations of nature, compensation, and uncertainty. Based on these fundamentals, we contemplated new directions for the sciences as posited by Ilya Prigogine, with systems far from equilibrium, which reiterate the importance of irreversibility, fluctuations, and the unpredictable as forces that create new orders. Irreversibility consists of being unable to restore a final state to a previous state without leaving an equivalent change elsewhere. This does not mean only being unable to restore the system to a previous state, but rather being unable to do so without something being transformed. In this way, a transformation in one portion of the universe entails a transformation in the neighboring portion, creating a chain of events and a direction that has been defined as an arrow of time. It then constitutes a sense of historicity, of becoming, which is inherent to nature.

Because of the uncertainty intrinsic to matter, events are possible but not necessarily determined to a complete extent. There is a quality called *contingency* which arises as a counterpoint to determinism, highlighting *non-necessity*. There may be gradations between contingency and necessity, however. The presence of probabilities introduces a measure of predictability, indicating that even though we are not totally restricted to determination, there is a particular propensity or regularity in events that can influence their course. We are inspired by the idea of contingency to propose that even if humanity's transformations of nature are irreversible, the way they have occurred thus far is not the only one possible. Contingency is a characteristic of the sciences (Peduzzi; Raicik, 2020) and can help us reject scientific and technological determinism.

As for the supposed disenchantment of the world, the sciences can rediscover enchantment in their own objects of study. While classical mechanics retains immutable characteristics, symmetrical qualities, and invariants from phenomena, thermodynamics deals with change, difference, flow, and breaks of symmetry. Even in dissipation (and because of it) and far from equilibrium, self-organized structures emerge, reconfiguring themselves into more stable arrangements to persist through destabilizing stimuli, similar to the logic of life. We emphasize historicity as a factor in systems far from equilibrium and how they incorporate more creative development into the sciences, one that is open to chance and to continuous reorganization that seeks stability, characteristics that have been attributed to science by countless historians and philosophers of this field.

We have presented a critique of the view of the world as a resource, subject to domination and extraction without consequences. We questioned the discourse of reductionist epistemologies that ignore the complexity of nature, and noted some of their limitations. We proposed overcoming mindsets that, in their fascination with abstraction and amid the search for the absolute and universal, end up losing sight of the beauty of a reality filled with uncertainty and unpredictability. The Cartesian human/nature, subject/object schism that is so typical of modern thought hinders our apprehension of the web of real events. We are not just in the world, we also are the world. We participate in it as both products and reproducers of irreversible transformations that write a planetary history, a common becoming of humanity (Morin, 2000). Complex thinking advocates a reconnection of knowledge until a less narcissistic and more ecological identity can be recovered that can reconstitute more critical meanings in human participation in the environment and society.

Clearly, our critique is based on our worldview and understandings, which are inescapable. From this worldview regarding science education, we took the relevance of complex thinking in developing didactic strategies, curricula, and reforming in school culture. Scientific literacy for citizen action must include teaching how epistemological and scientific understandings influence thinking in the current global context. It is not a matter of blaming science, but rather questioning a discourse that assumes science to be neutral and disconnected from socioenvironmental responsibilities. The main challenges of the contemporary world require ethical and critical positioning with regard to unbridled consumption and technological development. Above all, education is expected to disseminate knowledge that permits informed decisions about the sciences in their multiple dimensions and the urgency of contemporary global problems. It is also expected to provide inputs for critical and innovative initiatives during the course of an uncertain future that is constantly under construction. The hope is that in times of crisis (and beyond), students will be able to have agency over their learning processes, even looking out over the long term, benefiting themselves and their surroundings. Traditional curricula – consisting of subjects that focus on transmitting "objective" content without mentioning meta-scientific elements – tend to produce a two-dimensional version of science that does not include nuances or divergences. Critical (and scientific) thinking demands the ability to consider diverse, competing, and sometimes contradictory interpretations; a version of science that excludes the importance of error, assumptions, and diversity of opinion reduces the complexity of scientific endeavor to the use of an instrument.

We can say that we achieved the reflections proposed to the readers of this article using a complex methodology: we sought to *weave* a possible history for thermodynamics with reflections originating in the history of science and the philosophy of science, mainly by building knowledge that goes beyond strictly thermodynamics and can pervade a worldview. As a theoretical and reflective text, it is not intended to exhaustively present proposals or examples but rather evoke reflections and inspire (potential) changes in science education.

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