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Exploring Bachelard's Epistemological Obstacles in Physical Chemistry Textbooks: The Case of Thermodynamics Concepts

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ABSTRACT

Background: Although textbooks are used at all education levels, they are not free from errors, mistakes, and misconceptions. In the literature, many works have investigated textbooks in various ways, with particular emphasis on the influence of language. **Objectives**: The objectives of this study were to identify types of epistemological obstacles, according to Gaston Bachelard's philosophy, associated with the Classical Thermodynamics concepts in higher education physical chemistry textbooks commonly utilised in chemistry and related programs in Brazil. **Design**: We employed a qualitative methodology based on content analysis to identify thermodynamics concepts and types of epistemological obstacles in higher education textbooks. **Setting and participants**: For the identification of epistemological obstacles, we selected three representative textbooks used in university programs: P. W. Atkins, D. Ball, and I. Levine. **Data collection and analysis**: We only analysed the chapters that addressed Classical Thermodynamics, specifically focusing on the concepts of temperature, heat, work, energy, internal energy, and entropy. We used *a priori* categories that encompassed the obstacles identified by Bachelard. **Results**: Our findings revealed the presence of general knowledge, verbal, substantialist, and realist obstacles in the selected textbooks, with the concepts most associated with these obstacles being heat, energy, and entropy. **Conclusions**: By applying Bachelard's ideas, we were able to identify epistemological obstacles in higher education textbooks. This may be one of the causes of the perpetuation of misconceptions and historical, scientific errors related to the concepts of thermodynamics.

Keywords: Chemistry teaching; Analogies in science education; Thermodynamics concepts; Textbooks; Bachelard's philosophy.

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Explorando obstáculos epistemológicos de Bachelard nos livros didáticos de físico-química: o caso dos conceitos termodinâmicos

RESUMO

Contexto: Embora os livros didáticos sejam utilizados em todos os níveis de educação, eles não estão livres de erros, enganos e equívocos. Na literatura, muitos estudos investigam os livros didáticos de várias maneiras, com ênfase especial na influência da linguagem. **Objetivos**: os objetivos deste estudo foram identificar tipos de obstáculos epistemológicos, segundo a filosofia de Gaston Bachelard, associados aos conceitos clássicos da Termodinâmica em livros didáticos de físico-química do ensino superior comumente utilizados em cursos de química e afins no Brasil. **Design**: Uma metodologia qualitativa, baseada na análise de conteúdo, foi aplicada para identificar obstáculos em livros didáticos de ensino superior. **Ambiente e participantes**: Foram selecionados três livros didáticos representativos em programas universitários para a identificação de obstáculos epistemológicos: P. W. Atkins, D. Ball e I. Levine. **Coleta e análise de dados**: Apenas os capítulos que abordam a Termodinâmica clássica foram analisados, com foco nos conceitos de temperatura, calor, trabalho, energia, energia interna e entropia. Foram utilizadas categorias *a priori*, que correspondem aos obstáculos apontados por Bachelard. **Resultados**: Identificou-se a presença dos obstáculos do conhecimento geral, verbal, substancialista e realista nos livros didáticos selecionados, sendo que os conceitos mais associados a esses obstáculos foram calor, energia e entropia. **Conclusões**: Aplicando as ideias de Bachelard, conseguimos identificar obstáculos epistemológicos mesmo nos livros didáticos do ensino superior. Esta pode ser uma das causas da perpetuação de equívocos e erros científicos históricos relacionados aos conceitos da termodinâmica.

Palavras-chave: Ensino de Química; Analogias no ensino de ciências; Livro Didáticos; Conceitos de Termodinâmica; Filosofia de Bachelard.

INTRODUCTION

Textbooks are pedagogical tools for learning used by students and teachers across various disciplines and academic programs, from elementary school to university. It is crucial to investigate them to ensure their quality and promote adequate access to scientific knowledge.

Several studies in the literature have evaluated chemistry textbooks, considering different aspects. These evaluations include the representation of gender (Becker & Nilsson, 2021; Gee et al., 2022), the incorporation of green chemistry (Johnson et al., 2020), the influence of electronic textbooks and videos (Aslam & Saeed, 2022; Day & Pienta, 2019; Pulukuri & Abrams, 2021), the level and interpretation of visual representations (Chen et al., 2019; Roncevic et al., 2019; Shehab & BouJaoude, 2017; Upahi & Ramnarain, 2019), the importance of textbooks and their utilization by teachers (Anderson et al., 2020; Vojíř & Rusek, 2022), the presence of investigative experiments or illustrations of experiments (Chen & Eilks, 2019), the levels of semantic and syntactic difficulty (Quílez, 2021; Rusek & Vojíř, 2019), potential oversights in discussions (Chang et al., 2020; Jensen, 2015; Keifer, 2019; Park et al., 2020), the treatment of different models and theories (Galbraith et al., 2021), the presence of myths (Kvittingen et al., 2021), the alignment with the curriculum (Khaddoor et al., 2017), the proposed exercises (Gulacar et al., 2022), and the level of theoretical explanations (Martorano, 2014).

In a recent review by Meyer & Pietzner (2022), the influence of textbook language and reading was assessed. The review revealed that these aspects have primarily been investigated in relation to the understanding of concepts and non-textual explanations, with recent growth in the exploration of these non-textual aspects. However, the authors of this review emphasised the need for further research to examine textual explanations in textbooks, as many studies have focused on vocabulary-related issues such as classification, difficulty levels, and specialised terms. The review also highlighted the need for studies of how morphological changes can impact comprehension and learning in students, along with the development of strategies to address these changes.

One way to investigate the influence of language on textual reading and learning is to examine textbooks in search of epistemological obstacles, a concept introduced by Bachelard (2002). These obstacles hinder the acquisition of knowledge since they are linked to students' preconceived ideas and common cultural beliefs, often obstructing the rationalisation of concepts and promoting naive ideas, misconceptions, and inappropriate metaphors.

In the literature, research on epistemological obstacles frequently emerges in the field of mathematics (Gravier & Ouvrier-Buffet, 2022; Hariyani et al., 2022; Hillesheim & Moretti, 2019; Kandaga et al., 2022). In the context of science education, Bachelard's philosophy has been applied in various ways. For instance, Souza et al. (2018) employed the history of the nature of light to demonstrate, in a high school classroom, how scientific theories are constructed and the collaborative nature of scientific work. Trintin and Gomes (2018) utilised Bachelard's epistemological framework to evaluate how high school physics textbooks approach the concept of force. Their findings revealed a significant reliance on metaphors to explain force, potentially leading to difficulties in comprehending more rationalised explanations. Pazinato et al. (2021) also employed the epistemological framework to investigate the development of the concept of chemical bonding in high school students. They observed that the students progressed from naive, common-sense notions to more rationalised conceptions, aligning with Bachelard's ideas.

Loguercio et al. (2001) analysed chemistry textbooks alongside high school teachers, using the concept of epistemological obstacles. The authors identified challenges faced by teachers in recognising these obstacles, either due to a lack of familiarity with Bachelard's ideas or because their own understanding of chemical knowledge had been shaped by these obstacles, thereby impeding critical examination.

Physical chemistry is often considered challenging for students, and a negative perception of the subject persists (Donnelly & Hernández, 2018; Donnelly & Winkelmann, 2021). Numerous researchers, such as Finkenstaedt-Quinn et al. (2020), have identified a variety of difficulties, misconceptions, and struggles, particularly in the teaching and learning of thermodynamics. Some investigations (Atarés et al., 2021; Firetto et al., 2021; Meli et al., 2022) have recognised students' difficulties in physical chemistry, highlighting common misconceptions. However, these studies often do not delve into the reasons behind these errors or explore why students are easily swayed by inadequate explanations.

Thus, this research sought to answer the following research questions: What concepts of classical thermodynamics presented in higher education textbooks on physical chemistry are associated with Bachelardian epistemological obstacles? What types of epistemological obstacles, according to Gaston Bachelard's philosophy, are present in the chapters on thermodynamic concepts in the physical chemistry books most widely used in higher education?

The objective of this study was to identify the types of epistemological obstacles associated with classical thermodynamics concepts in three physical chemistry textbooks widely used in higher education programs related to chemistry in Brazil, drawing from Bachelard's philosophical framework.

THEORETICAL BACKGROUND

Gaston Bachelard was a philosopher of science dedicated to investigating the impacts and outspreading in science after the work of Einstein. In his book, Bachelard (2002) proposed that the development of scientific thought follows certain stages: the pre-scientific, the scientific, and the new scientific mind. However, the transition from one stage to another does not occur automatically, and not everyone will reach the most advanced stage. Furthermore, the progression towards new stages of scientific thought is not an easy process; it encounters impediments, delays, and slowdowns, which Bachelard (2002) refers to as epistemological obstacles.

Epistemological obstacles are not indicative of complex phenomena or inherent weaknesses in human perception. They are internal, conflicting interferences that are often rooted in common-sense structures, personal perspectives, metaphorical interpretations, and unconscious interference. Bachelard emphasises that these obstacles are errors recurrent throughout the history of science rather than isolated psychological cases and that students often encounter and repeat them on their path towards mastering scientific knowledge. Table 1 provides a summary of the epistemological obstacles presented by Bachelard (2002).

Table 1

Characteristics and examples of epistemological obstacles

Obstacle	Characteristic	Example*
Primary experience	Experiences are placed before and above criticism, and the vividness of observation is never left out. Curiosity is satisfied, with knowledge being replaced by admiration and ideas by images.	Explosion in a chemistry classroom.
General knowledge	Vague ideas that favour inappropriate generalisations. The concept is distorted and amplified.	Fermentation in breastfeeding babies.
Verbal	Utilisation of words learned in a non-scientific context and with divergent connotations.	Sponginess of the air.
Unitary and pragmatic	Explanation based on the unity of nature.	The link between planets and metals.
Substantialist	Assignment of diverse qualities to a substance (superficial, deep, or occult). The substance must have something	Electric fluid.

	inside.	
Realist	Visual metaphors as scientific explanations preventing abstraction.	Hg or As bars prevent plague.
Animist	Assignment of life and anthropomorphic properties to inanimate objects.	Illness of minerals.
Libido	Sexualisation of inanimate objects.	Gender in minerals.
Quantitative	Numbers are utilised without significance or only for curiosity observations.	Abusive use of decimal numbers.

*These examples will be discussed in detail in the text below.

These examples were compiled by Bachelard (2002) from the history of science. Bachelard sought to understand how obstacles manifest themselves by studying confused minds in the pre-scientific stage. For instance, an explosion in a chemistry classroom becomes a primary experiential obstacle because students vividly remember the explosion and the associated emotions but struggle to recall the chemical reactions that led to it. The fascination with witnessing an explosion hinders rationalisation. Bachelard also discusses how fermentation was mistakenly perceived as a form of movement, leading to inappropriate generalisations. For example, the belief that shaking babies after breastfeeding accelerates acid fermentation in the stomach constitutes a general knowledge obstacle due to an exaggerated recommendation.

Another example involves the misuse of the word “sponge” in the past when it was incorrectly employed to explain how air dissolves in water. Rather than air dissolving in water, the air was likened to a sponge absorbing water through its pores. This type of verbal obstacle arises from the usage of an explanation without sufficient proof or evidence. Additionally, a connection between planets and metals was perceived as indicative of unity in nature, resulting in recommendations to treat diseases with specific metals corresponding to the planets associated with the affected organs. This exemplifies a unitary and pragmatic obstacle.

Bachelard further highlights misconceptions about the nature of electricity, such as interpreting it as emitting a viscous emanation that attracts objects towards it. This represents a substantialist obstacle. In the context of disease prevention during epidemics, a curious metaphor was employed:

individuals were advised to carry arsenic bars or mercury sachets because "poisons attract poisons" (specifically, into the interior of the bar). This "treatment" exemplifies a realist obstacle, as it relies on a metaphor of attraction. Rust was once attributed as a disease of iron, suggesting that it occurred due to the metal being removed from its natural environment. This reflects an animist obstacle, as only living beings can become ill.

Gender assignments were also applied to minerals, and even chemical reactions were explained in terms of copulation, leading to students assigning an active role to acids and a passive role to bases. This sexualisation of concepts represents a libido obstacle. Lastly, even numbers can pose a quantitative obstacle, such as the excessive use of decimals or the inappropriate application of measurement instruments.

For further information on epistemological obstacles, it is recommended to consult the works of Bachelard (2002), Lopes (1992), Filho and Carneiro (2006), Lôbo (2008), and Finzi (2008).

The presence of epistemological obstacles can impede the ability to ask meaningful questions, restricting the exploration of problems and experiments. Students may develop a belief that they already possess all the answers, resulting in a preference for concrete and non-rationalized ideas instead of abstract thinking. Consequently, they may resort to memorising information without truly grasping its underlying meaning or rely on personal explanations based on common sense. Bachelard recognised this challenge and directly addressed it in the context of education:

> Science teachers imagine that the mind begins like a lesson [...]. They have not given any thought to the fact that when young people start learning physics, they already possess a body of empirical knowledge. It is not therefore a question of *acquiring* experimental culture but rather of *changing* from one experimental culture to another and of removing the abundance of obstacles that everyday life has already set up. (Bachelard, 2002, p. 28)

To change the experimental culture, science must break away from common sense. According to Bachelard, students also need to challenge their existing knowledge in order to develop mastery of scientific thinking, which he refers to as epistemological rupture. In the context of chemistry education, it is essential to provide appropriate textual and non-textual elements to overcome recurring obstacles and prevent reliance on common sense in a scientific context.

Bachelard underscores the significance of addressing students' prior knowledge, which encompasses a range of ideas, metaphors, fantasies, and dreams. While students typically start at a pre-scientific stage, they can make faster progress towards more rational stages by overcoming these obstacles. It is crucial for teachers to be prepared to facilitate this process and avoid perpetuating historical, scientific misconceptions and errors. Scientific education, or the cultivation of a scientific mindset, as outlined by Bachelard's philosophy, occurs through the correction of errors. This correction allows for the transition from a pre-scientific stage to scientific and new scientific stages. Pazinato et al. (2021) observed this transition in their study, which showcased the application of Bachelardian principles in learning chemical concepts.

METHODOLOGY

This work is one of the stages of doctoral research concerning the difficulties and possibilities related to the process of teaching and learning thermodynamic concepts studied in the Physical Chemistry I-B discipline of the Chemistry, Chemical Engineering, and related Engineering programs at the Universidade Federal do Rio Grande do Sul (Brazil). Thus, this article aims to identify the types of epistemological obstacles, according to Bachelard's philosophy, associated with the concepts of classical thermodynamics in the books by Atkins et al. (2018), Levine (2009), and Ball (2014), which are among the physical chemistry books most used in Brazilian higher education chemistry programs. These three books are national and international references for physical chemistry in higher education.

The qualitative content analysis (CA) approach was used to carry out the documental analysis. The search process involved thorough document analysis, multiple readings, and rereading of chapters where concepts were explained, ensuring comprehensive coverage of all relevant categories. Bardin (2016) divides CA into three main stages: I) pre-analysis, II) material exploration, and III) treatment of results, inference, and interpretation. Therefore, for the pre-analysis, the chapters selected, based on the reading of the summary and a reading of the relevant chapters of the books, were those that presented the concepts of classical thermodynamics, such as temperature, heat, work, energy, internal energy, and entropy. Based on this pre-analysis, the chapters selected were chap. 1-6 (Atkins et al., 2018), chap. 1-7 (Levine, 2009), and chap. 1-5 (Ball, 2014). In the material exploration stage, the texts, illustrations, and exercises were read to identify and map possible epistemological obstacles, according to Bachelard's approach. In the stage of processing the results, examples of epistemological obstacles classified as general knowledge obstacles, verbal obstacles, substantialist obstacles, and realist obstacles were considered as categories of analysis. These were categorised by the analysis of metaphors, raw images, valued ideas, and all algorithmic, textual, and/or pictographic elements that would allow attribution of the characteristics of an epistemological obstacle, according to Gaston Bachelard.

Steps II and III were replicated by two researchers in order to validate the research results. The researchers independently evaluated the three books to identify possible obstacles, followed by a meeting in which the results were presented in order to define the terms considered by the three researchers as converging with the epistemological obstacles postulated by Gaston Bachelard.

RESULTS AND ANALYSES

The examples of obstacles found were categorised based on the types of predetermined analysis categories representing the types of epistemological obstacles: general knowledge obstacle, verbal obstacle, substantialist obstacle, and realist obstacle. Tables were used to display the obstacles identified in the textbooks, with the identifying words/expressions highlighted in bold. It is important to note that the presence of these obstacles does not imply that the authors necessarily consider viewpoints to be incorrect or theories to be outdated. According to Bachelard, all obstacles are influenced by the unconscious. Additionally, it does not suggest that the textbooks are entirely useless or reprehensible but rather that they may contain certain terms and expressions that can increase the difficulty of students in learning and comprehending physical chemistry. Thus, there is no intentional adherence to any specific obstacle. Initially, epistemological obstacles may be surprising, as even Bachelard himself admitted to being shocked by his own conclusions during his studies. Due to the limitations of this article, reading the primary reference (Bachelard, 2002) may be necessary for further inquiries.

General knowledge obstacle

The general knowledge obstacle is characterised by inappropriate generalisations and by considering something as natural or easy, as well as by establishing bizarre relationships. This obstacle appears in the books of Ball and Levine, with the occurrences shown in Table 2.

Table 2

Occurrences of general knowledge obstacle

Book	Occurrence
Ball	P. 3: “However, there is an even more fundamental idea that is usually assumed but rarely stated because it is **so obvious**. Occasionally, this idea is referred to as the Zeroth law of thermodynamics [...].”
	P. 4: “[The zeroth law] is **obvious from personal experience** and fundamental to thermodynamics.”
	P. 5: “Phenomenological thermodynamics is based on experiment, on measurements that **you might make in a lab, garage, or kitchen**.”
Levine	P. 2: “In Sinclair Lewis’s 1925 novel Arrowsmith, the character Max Gottlieb, a medical school professor, proclaims that ‘Physical chemistry is power, it is exactness, **it is life**’.”

In Ball’s book, this obstacle appears with the use of the word “obvious” when the author addresses the zeroth law of thermodynamics, invoking common-sense experience. For Bachelard, there is no continuity between science and common sense. A valorisation of the experience occurs in the text, and a valorisation always deters readers from questioning their own knowledge. In science, there must always be an explanation. Specifically, for concepts, Bachelard pointed out:

> It is then that we understand that science realises its objects without ever just finding them ready-made. […] A concept becomes scientific in so far as it becomes a technique, in so far as it is accompanied by a technique that realises. We are, therefore, very conscious that the problem of modern scientific

> thought is once again a problem that is philosophically intermediate. (Bachelard, 2002, p. 70)

Science realises its objects; it does not pick up from nature or common life. However, this does not mean that science is disconnected from the problems and challenges of the time, but when science approaches a problem, it does so with a method and a technique. The difference is apparently subtle but important. Thus, Bachelard argued that the formation of the scientific mind occurs against nature, against natural allurements and colourful, diverse facts. Furthermore, the formulation of the Zeroth law of thermodynamics was the latest formulation, not the first, in the history of thermodynamics. The same argument applies to making measurements in a garage or kitchen. Until the 19th century, this could happen, but not today. The Zeroth law is not an obvious statement but rather a generalisation of experience, which, based on the finding of thermal equilibrium, allows the macroscopic definition of temperature.

In Levine's book, when the author introduces the notion of physical chemistry, he quotes a novelist associated with some of the leading names in the development of thermodynamics. The quote is a generalisation under the seductive charms of the facility. For Bachelard, this represents "generalities which have no connection with the phenomenon's essential mathematical functions." (Bachelard, 2002, p. 65).

Verbal obstacle

Bachelard investigated this obstacle considering the abusive utilisation of the word "sponge", which was an abusive image in the pre-scientific mind stage. In fact, "sponge" does not occur as a verbal obstacle, but other words with common-sense connotations act as such. The occurrences of these verbal obstacles were detected in Atkins' book and are shown in Table 3.

Table 3

Occurrences of verbal obstacle

Book	Occurrence
Atkins	P. 36: "The thermal motion of the molecules in the hot surroundings **stimulates** the molecules in the cooler system to move more vigorously [...]" P. 80: "[...] heat **stimulates** random motion of atoms whereas work **stimulates** their uniform motion, and so does not change

	the extent of their disorder."
	P. 37: "For example, a chemical bond might break if a lot of energy becomes concentrated in it, for instance, as **vigorous** vibration."
	P. 40: "A reversible change in thermodynamics is a change that can be **reversed** by an infinitesimal modification of a variable."

Stimulus and vigour could be obstacles in these sentences because of their common-sense connotation. Vigour means a characteristic of human physical strength, which has no relation to the structure of matter; furthermore, it is indefinite: what is precisely a vigorous vibration? Regarding stimulus, it can be used as an incentive, an example being students stimulating others to study enough to avoid reproach. A stimulus can fail as a human act, but the transfer of energy will occur according to the laws of thermodynamics. In an interesting study, Yun (2020) pointed out that scientific concepts are better learned by students when the meaning of the concept is made with words and expressions in the scientific context, while the learning of a concept is harder when scientific terms are mixed with common sense. Hence, we can propose that if the terms vigour and stimulus keep their common-sense meaning, they could act as an epistemological obstacle for students.

The term "reverse" in the quote from page 40 may induce the reader to associate "reverse" with a reversible chemical reaction. In our experience with students, many of them answer that a reversible process is one that "can go backwards". A reversible change goes far beyond the possibility of being reversed since it is a transformation that occurs in infinitesimal steps, all of them maintaining equilibrium, which is the definition students must understand.

An example of a verbal obstacle that was not included in Table 3, precisely because it does not explicitly appear, is "energy". In Levine's book, energy is not defined at any moment. In the Atkins and Ball books, there is a definition of energy in the text, with Atkins providing the definition with the same emphasis as the other concepts. Ball provides a definition when the concept "work" is defined, even though "energy" appears many times earlier in the text. Therefore, in Ball's book, the definition of energy may pass unnoticed. If a scientific textbook does not define energy, the readers will maintain their own definitions derived from common sense.

It is important to recognise that the concept of energy is hard to define. Even the classical definition presented in Atkins' book, which is the capacity to do work, does not precisely define energy. In the words of Feynman:

> [...] there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism or anything concrete; it is just a strange fact that we can calculate some number, and when we finish watching nature go through her tricks and calculate the number again, it is the same. (Feynman, Leighton, & Sands, 1965)

Despite these conceptual difficulties, understanding what is *not* energy is also important, especially in these times of fake news and the growth of anti-scientific activity. Students need to dissociate energy from mystical concepts and common-sense usage. Such ideas frequently appear in the minds of children and, in the absence of adequate scientific education, will remain unaltered, being classified as epistemological obstacles, even without adopting Bachelard's philosophy (Detken & Brückmann, 2021).

Substantialist obstacle

This obstacle occupies a central place in the work of Bachelard due to its frequent presence and the likelihood of other obstacles appearing along with it. There were many occurrences of this obstacle in all the books (Table 4).

Table 4

Occurrences of substantialist obstacle

Book	Occurrence
Atkins	P. 49: "Such systems do work on the surroundings, and therefore some of the energy supplied to them as heat **escapes back** to the surroundings as work."
	P. 83: "Energy is **released as heat** to the cold sink; [...]"
	P. 85: "Because dw and dw_{rev} are negative when energy **leaves**

	the system as work, [...]"
Ball	P. 22: "Atoms and molecules **contain** energy. As such, some of their properties can be related to the Boltzmann factor. For example, gas phase atoms and molecules **have** translational energy, [...]." P. 24: "Energy can also be **stored** in motions that are described as vibrations: [...]" P. 24: "Molecular gases **possess** other forms of energy." P. 58: "As heat is **added** to the H_2O, its temperature will rise [...] As we heat it up, it will continue **to gain** energy until it melts at 273 K. At this point, **the addition** of more heat does not increase its temperature." P. 68: "[...] illustrating that our cells are using a **very compact form** of energy." P. 90: "The system can be **broken up** into smaller microsystems whose individual states [...]"
Levine	P. 46: "[...] the **amount** of heat that flowed from body 2 to body 1." P. 48: "He then speculated that work and heat were both **forms of energy** and that the total amount of energy was conserved." P. 60: "[...] (the work done on the gas) is negative, and q (the **heat added** to the gas) is positive."

The obstacle highlights the prevalence of the term "heat". Heat, along with "energy" and "work", can undergo storage, addition, escape, release, flow, and exchange, which are words that perfectly align with substance-based descriptions. These terms suggest the presence of a nucleus-like entity that holds energy and only releases it under specific circumstances. Despite the author's statement that heat and work are modes of energy transfer, not forms of energy itself, there are instances where they are indeed treated as forms of energy (for example, on page 68 of Ball's book, there is mention of a "very compact form of energy". Bachelard identified this characteristic and proposed the existence of a myth of interiority to explain it:

> The idea behind substantialism is often illustrated simply in terms of *containing*. Something has to *enclose*, and the quality that lies deep has to be enclosed. [...] Thus, the quality *heat* is kept safely within the substance by being wrapped [...]. This intuitive valorisation of what lies within can lead to curious statements being made. [...] When intuitions like these are analysed, we soon realise that for the pre-scientific mind, the *substance has an inside*, or better, that substance *is* an inside. (Bachelard, 2002, pp. 105-106)

In the history of science, heat was perceived as a substance within the framework of the caloric fluid theory. According to this theory, as described by Schubert (2019), a substance called caloric was believed to exist in heat, fire, igneous fluid, and the matter of fire and heat. Lavoisier included caloric in his list of elements, and even Dalton incorporated it into his atomic theory. Caloric was considered an imponderable fluid that was conserved, attracted to the atoms of substances (to inner), but also repelled itself. Temperature was viewed as a measure of the presence of caloric. Despite the eventual rejection of this theory, some remnants of its characteristics persist, which align with Bachelard's myth of interiority, as the concept of caloric filling the inner parts of bodies while simultaneously repelling itself, suggests internalisation. Hence, it can be argued that the caloric theory was valued because it accounted for this internal presence within bodies.

The consequences of this myth have been observed in the literature, although not explicitly recognised as epistemological obstacles. According to Doige and Day (2012), treating heat as a noun can lead to confusion among students. They recommend avoiding terms such as “heat flow”, “heat transfer”, “heat loss”, “heat gain”, “heat absorbed”, and “heat evolved”, with it being better to use the term “heat” as a verb, adverb, or adjective. Although Doige and Day (2012) do not reference Bachelard in their work, their warning aligns with the substantialist obstacle. Furthermore, students often struggle to comprehend different forms of energy, mistakenly equating everything to a generalised concept of energy. This lack of understanding, as identified by Nilsson and Niedderer (2014), hampers their ability to explain basic chemical reactions or determine whether work has been performed. In relation to energy, Macrie-Shuck and Talanquer (2020) present an interesting study revealing that students often perceive energy as a fluid-like fuel that can be stored, transported, and placed inside objects and substances. This connection between contemporary literature and Bachelard's philosophy highlights how Gaston

Bachelard provided an explanation for the persistence of errors, confusion, and misconceptions, referred to as epistemological obstacles.

Realist obstacle

In the case of the realist obstacle, abstract thinking is replaced by concrete ideas or images to such an extent that accessing the abstraction becomes difficult, leaving only crude images. The final and most prevalent obstacle identified is the realist obstacle, often manifested through metaphors. Therefore, no specific words are highlighted in bold typeface in Table 5, which provides instances of the realist obstacle found in the selected textbooks.

Table 5

Occurrences of realist obstacle

Book	Occurrence
Atkins	P. 19: "Intermolecular forces are also important when the temperature is so low that the molecules travel with such low mean speeds that they can be captured by one another."
	P. 35: "The energy lost as work by the system, [...]"
	P. 38: "A system is like a bank: it accepts deposits in either currency (work or heat) but stores its reserves as internal energy."
	P. 83: "No energy enters the system as heat, so the change in entropy is zero."
	P. 90: "Hydrogen bonds tend to organise the molecules in the liquid so that they are less random than, [...]"
	P. 150: "An increase in entropy is expected when one gas disperses into the other, and the disorder increases."
Ball	P. 32: "That means that the system is losing energy in the form of work. The infinitesimal amount of work dw lost by the system to the surroundings [...]."
	Example 2.1, p. 34: "That is, 621 joules have been lost by the system during the expansion."
	P. 39: "Although both work and heat are types of energy transfer, one major distinction is that work is an ordered form of energy

	transfer while heat is a disordered form of energy transfer.” P. 90: “The preceding discussion of the entropy of mixing brings us to a useful general idea regarding entropy, that of order. Having two pure gases on either side of a barrier is a nice, neat, relatively ordered arrangement. Mixing the two of them, a process that occurs spontaneously, is a more random, less-ordered arrangement. So this system proceeds spontaneously from a more-ordered system to a less-ordered system.” P. 96: “The concept of order brings us to what we call the third law of thermodynamics:” Exercise 3.41, p. 99: “The first law of thermodynamics is sometimes stated “You can’t win” and the second law is stated similarly as “You can’t even break even.” Explain how these two statements can be considered apt (though incomplete) viewpoints for the first and second laws of thermodynamics.” Exercise 3.46, p. 99: “Which system has the higher entropy? (a) a clean kitchen or a dirty kitchen? (b) a blackboard with writing on it or a completely erased blackboard? [...]”
Levine	P. 79: “As some wit has put it: The first law says you can’t win; the second law says you can’t break even.” P. 107, Problem 3.35: “What is the relevance to thermodynamics of the following refrain from the Gilbert and Sullivan operetta H.M.S. Pinafore? “What, never? No, never! What, never? Well, hardly ever!” P. 134: “The second law of thermodynamics is the law of increase in entropy. Increasing entropy means increasing disorder. Living organisms maintain a high degree of internal order. Hence one might ask whether life processes violate the second law.”

The concept of entropy, defined as order/disorder, prominently appears in this obstacle. Other metaphors include the gain or loss of energy, comparing a system to a bank, using metaphors like “you can’t win” and “always lost” to represent the laws of thermodynamics, and an exercise involving opera and the entry/exit of energy, with gaseous atoms capturing each other. Despite textbook authors acknowledging that disorder is a misconception, they still employ this idea to explain entropy, leading to an evident contradiction. The explanation of disorder often dominates the concept of entropy, but towards the end of the millennium, Lambert (1999) began questioning this approach.

The mistake in using the disorder metaphor lies in equating the increase in entropy with changes in the macroscopic pattern of objects, which solely reflects human beings' perceptions of organisation and disorganisation. As discussed by Lambert (2002), entropy is qualitatively related to the dispersal of energy, and disorder is better suited to Shannon's measure of information (Ben-Naim, 2011). Analogies, such as representing energy levels with lines, boxes, or cards, must be approached with caution since students may mistakenly view these representations as concrete realities. Illustrations in textbooks can further reinforce such misconceptions, as noted by Ben-Naim (2011), thereby perpetuating epistemological obstacles. Levine's book provides examples of such illustrations, shown here in Figures 1 and 2.

Figure 1

The illustration suggests a relation between entropy and disorder (Levine, 2009, p. 91).

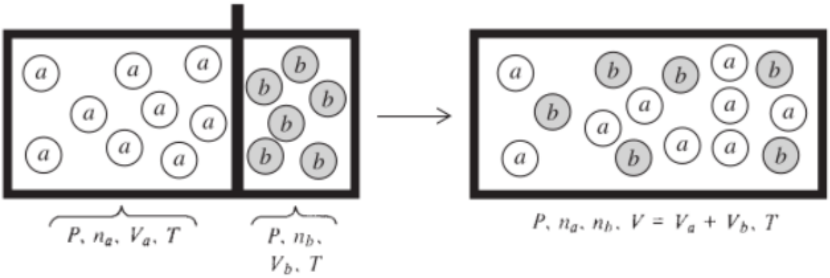
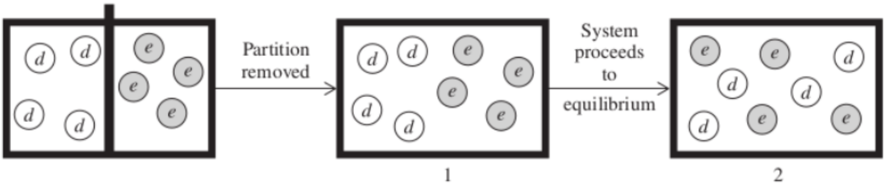


Figure 2

The illustration suggests a relation between entropy and disorder (Levine, 2009, p. 98).



By merely looking at these figures, without understanding the microstates concept, the students will only see human disorder. They will link this to the mess in the room or the shuffling of cards, and in responding to exercises, such as those on page 99 in Ball's book, there will be a fixation on what can be concretely seen since the obstacle is realistic. These images do not have a direct link with the microstates concept. The correct interpretation of Figures 1 and 2 is that entropy increase occurs when the partition is removed, not when the gases mix.

Why does disorder seem so appealing, even after several discussions of the problems with this metaphor? Again, Bachelard can contribute. In the realist obstacle, corrections are blocked because there is a rapidly inadequate generalisation, which leads to relying on sensorial data and a general description in order to avoid mathematical aspects. Bachelard points out:

> It so happens that the best way to avoid objective discussions is to take refuge behind substances, to attribute to substances the most diverse of nuances, and to make them the mirrors of our subjective impressions. The virtual images that realists thus form as they admire the myriad nuances of their own personal impressions are among the very hardest to destroy. (Bachelard, 2002, p. 151)

Here, Bachelard shows that some images are too strong for a realist mind: there is a feeling of having, of possessing. This feeling is sustained by miserliness, not intentionally, but as a movement of the unconscious. To have something generally means containing it, and once inside, it should never be lost. Bachelard writes:

> The psychoanalysis that ought to be founded in order to cure people of substantialism is the psychoanalysis of the *feeling of having*. The complex to be broken up is that of saving the pennies [...] It is this complex that draws attention to the little things that *must* not be lost since they cannot be found if they are lost. Thus, a little object is very carefully looked after. A fragile vase is the one that lasts the longest. Do not lose anything is, therefore, initially a normative prescription. This prescription then becomes a description; it goes from the normative to the positive. (Bachelard, 2002, p. 137)

Thus, one can attribute to the metaphor of disorder the characteristics of a hasty generalisation: it disregards microstates (in Ball's book, microstates are given as a way of "breaking the system"), use a coarse and easy image (images of objects scattered around, the scratched slate, the dirty kitchen), and is based on the sense of sight to explain a phenomenon. Probability in microstates is in the abstract order, while disorder is in the concrete order. The first cannot be apprehended by sight, but the second can, because it is easy to imagine disorder as some "mess" or disarrangement, whereas the notion of a microstate depends on mathematical constructions. In this way, the real increase in entropy is neglected in favour of what the eyes can see and about which it is not necessary to think: "It's a piece of cake"; there is nothing more to add; here is the hasty generalisation and the eagerness to arrive at it. The feeling of having is also present here, albeit in an indirect/inverted way: disorder is the order that has been lost. It is the loss of the queen of spades when the cards are shuffled; the cutlery lost in the dishes to be washed, the concept erased on the blackboard, the heat or work lost by the system, and so on.

Other considerations can be made regarding the feeling of having, in this case. Although there is loss, it will never be total. The queen of spades, although lost in the shuffle, is contained in the deck of cards, the cutlery will be found when the dishes are washed, and the concept on the blackboard will be taken up again in the next class. Thus, according to Bachelard's ideas, the realist finds his own consolation. These considerations may seem to be an extrapolation of the images and metaphors worked on previously, but it is enough to remember for how long people tried to build a perpetual motion machine or to recover the "lost caloric" in steam engines to realise that these undertakings contained miser motivations.

For the concept of entropy, because of all the arguments above, we suggest, following Lambert (1999), that the idea of entropy as a disorder must be abandoned. Disorder is an obstacle-word, a term that does not assist in understanding entropy and just prevents the concept from being learned.

The other situations, excluding entropy cases, proceed according to the same miser realism. When Atkins proposed an analogy between the system and a bank (p. 38), this can be related to Bachelard's ideas: there is something kept in, which has value, is contained by a core, and may be exchanged (analogous to a barter).

Are analogies and metaphors to be banned?

All these considerations may give the impression that Bachelard condemned all metaphors and analogies for science teaching. However, this is not true. Analogies and metaphors must be used, knowing their limits and avoiding extrapolations that hide daydreams, mistakes, and misunderstandings. If a metaphor or analogy is inadequate, it is possible to rectify it. The following examples can be given: Heat and work are forms of energy transfer, in the same way that bank deposits and instant payments are forms of money transfer, but a deposit or an electronic payment is not money. For entropy, a possible metaphor is the consideration of the books on a shelf. If there are fifty books and fifty spaces, there are a certain number of possible combinations for arranging the books. If the number of spaces increases, the number of possible combinations will increase. In this situation, it can be said that there was an increase in entropy, as there are now more spaces to place the books. The owner of the books, however, can place them in an even more orderly manner.

All persons involved in the teaching of chemistry must recognise the limitation of any metaphor and analogy for appropriate use of them, not depend exclusively on the textbook, and know strategies to overcome epistemological obstacles.

CONCLUSIONS

Physical chemistry textbooks used in a higher education thermodynamics course were analysed using content analysis to identify epistemological obstacles. The selected books (Atkins, Ball, and Levine) exhibited the following obstacles: realist and substantialist (all books), verbal (only Atkins), and general knowledge (excluding Atkins). These obstacles were primarily associated with the concepts of heat, work, energy, and entropy. The presence of these obstacles does not imply that the authors advocate incorrect scientific views or outdated theories. Instead, it indicates the presence of remnants of antiquated theories and inadequate use of analogies and metaphors that seemingly could aid understanding but, in reality, may reinforce common-sense ideas and impede the mastery of scientific knowledge.

The most prevalent obstacles in the textbooks were the realist and substantialist ones. Bachelard’s concept of the myth of interiority explains the persistence of these obstacles, where substances are valued due to their interior nature or the presence of something precious within. As a result, contradictions, improper generalisations, and misconceptions persist in the minds of students. History has shown numerous obstacles that have endured for centuries.

The terms energy, heat, and work were often treated as substances that can be added to a system, exchanged, leave it, or re-entered, which is terminology appropriate for substances rather than for forms of energy transfer. In the case of entropy, the textbooks frequently associated it with the disorder. Drawing upon Bachelard’s ideas and the literature, it is proposed that the concept of disorder acts as an obstacle, hindering a correct understanding of entropy. Therefore, it is suggested that this idea be abandoned in favour of defining entropy as energy dispersion.

Analogies and metaphors need not be banned from chemistry teaching. However, they must be used appropriately, acknowledging their limitations and avoiding reinforcement of common-sense ideas and errors. Gaston Bachelard’s philosophy provides a powerful framework for understanding why students struggle to progress beyond common-sense or realistic explanations of scientific phenomena. Identifying epistemological obstacles is crucial in recognising the difficulties inherent in the teaching and learning of classical thermodynamics concepts, especially when prominent textbooks perpetuate erroneous analogies due to a lack of awareness regarding the role of epistemological obstacles in the learning process. This understanding opens possibilities for alternative teaching approaches that can minimise or adapt to these obstacles, promoting the higher level of rationalist knowledge expected at the higher education level.

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AUTHORS’ CONTRIBUTIONS STATEMENT

JDS was responsible for formal analysis, investigation, and methodology. CGP and PAN provided project administration, resources, and supervision. All authors actively participated in the discussion of the results, reviewed the manuscript, and approved the final version of the work.

DATA AVAILABILITY STATEMENT

The data supporting the results of this study will be made available by the corresponding author, CGP, upon reasonable request.

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