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Vincent Natalis
University of Liège, Belgium

Bernard Leyh
University of Liège, Belgium

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How Difficult is it to teach Thermodynamics in Tertiary Education? Teachers' Opinions and Predominance of the Disorder Metaphor

Vincent Natalis, Bernard Leyh

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Abstract

This study explores the challenges faced by tertiary education instructors in teaching thermodynamics, with a specific focus on entropy. This study completes and adds to the current literature by providing self-reported perceptions of difficulty by teachers, which is lacking, compared to students' opinions, in this area of research. Through a survey of 41 French-speaking thermodynamics teachers in Belgium (N = 26 full answers, N = 15 partial answers), we report various obstacles in thermodynamics identified by instructors, including content aspects such as their abstract nature, or diverging opinions on mathematical difficulties. For teaching management aspects, instructors report that they have enough resources to teach, but that maybe they have too many non-teaching tasks. For entropy specifically, instructors report that it is challenging due to its abstractness, to its lack of perceptibility, and to the disconnection between macroscopic and microscopic perspectives, among others. 77% of respondents use the disorder metaphor. Invoked reasons include helping students visualize entropy, making it simpler, or making it more concrete. Comparison between teachers' opinions and students' opinions reported by Sözbilir (2004) shows agreements on some difficulties, but also tensions, such as the pedagogical relevance of the lecture format, the need for links with everyday life, or the promotion of conceptual understanding.

Introduction

Teaching thermodynamics poses multiple didactical challenges. The most recent review by Bain et al. (2014) concludes that: "*Four themes emerged in the scholarly literature pertaining to the teaching and learning of thermodynamics in undergraduate or tertiary settings: factors influencing student success in physical chemistry, the mathematics of physical chemistry, students' reasoning using the particulate nature of matter, and students' alternative conceptions of the First, Second, and Third Laws of Thermodynamics, spontaneity, and equilibrium*." (p. 333). This study is part of the first theme, as it will explore teachers' conceptions of students' difficulties, as well as the difficulties associated with the thermodynamics content they cover. Research in thermodynamics education has often focused on student difficulties (Bain et al., 2014; Sreenivasulu & Subramaniam, 2013), the order in which to introduce concepts (Tsaparlis, 2016), or conceptual change (e.g. Partanen, 2016), but less so on teaching difficulties, as perceived by instructors. The existence of two competing methods (classical, macroscopic vs. statistical, microscopic) to teach thermodynamics also emphasizes the classical difficulty of combining the macroscopic and microscopic points of view in chemistry (Johnstone, 1991; Taber, 2013). A key solution to this problem appears to be the use of simulations to alleviate mathematical complexity and promote the transition between the two points of view (e.g. Zwier, 2018). Students often lack motivation towards thermodynamics (Donnelly & Hernández, 2018) and this might be, at least in part, attributable to the pedagogical choices of the teachers. These choices are often inspired by textbooks that are more content-centered than learning-centered (Donnelly & Winkelmann, 2021). Improving motivation might come from favoring learning-centered approaches (Fox & Roehrig, 2015), or reducing cognitive load by promoting teaching methods that promote deep learning of thermodynamics, instead of unreflective learning (Partanen et al., 2024). For example, a recent study by Schwedler & Kaldewey (2020) showed the positive impact of using molecular simulation on student motivation in a first-year undergraduate course of physical chemistry.

To the best of our knowledge, only three articles have targeted teachers' perceptions of physical chemistry difficulties (Fox & Roehrig, 2015; Sözbilir, 2004) and entropy difficulties (Camacho et al., 2015) in the literature, revealing a gap of knowledge: teachers' beliefs at the thermodynamics level of granularity. For example, in physical chemistry education research, Mack & Towns (2016) have demonstrated that chemistry teachers at one university reported having various didactical goals when teaching thermodynamics, such as explaining the particulate nature of matter, or mathematical modelling, but also social, and epistemic goals; but the authors did not aim at probing teachers' perceived difficulties in their own subject. Fox & Roehrig (2015) have reported multiple beliefs of physical chemistry instructors. For example, 78% of respondents believe that both the instructor and the student are responsible for the understanding of physical chemistry, while "[…] *21% of instructors believed that the student is mostly responsible and the instructor is somewhat responsible, and only 1% of instructors believed that the instructor is mostly responsible and the student is somewhat responsible."* (p. 1462). The study also reports instructors' beliefs about student struggles, such as, for example, their lack of mathematics or physics prerequisites, the connection of mathematics with physical chemistry concepts, and their lack of effort. Sözbilir (2004) contrasted students' (N = 91) and teachers' (N = 2) opinions about the difficulties inherent to physical chemistry. Students' favored reasons include their own lack of motivation, the abstractness of content, the high quantity of content, the lack of promotion of deep understanding and the teacher-centered teaching. According to the two teachers, physical chemistry is difficult because, for example, students have backgrounds that are too different, or because they have a low socio-economic status; or because the teacher lacks material resources.

Thermodynamics relies on two central concepts: energy and entropy. Teaching entropy correctly is thus a critical endeavor for thermodynamics education. The most recent comprehensive works about entropy education include (Sreenivasulu & Subramaniam, 2013) and (Bain et al., 2014), which listed numerous alternative conceptions concerning the first and second law of thermodynamics. Atarés et al. (2021) also identified in the literature, in addition to the aforementioned prevalence of entropy alternative conceptions, student-focused obstacles: strategic learning, abstractness, the disorder metaphor, and the high mathematical needs. Camacho et al. (2015) investigated teachers' opinions about the learning struggles of students concerning entropy, as well as teachers' own conceptualization of entropy. They showed that the teachers believed students struggled, for example, because of their lack of mathematics prerequisites, lack of interest, alternative conceptions, or word confusion.

While reports of students' difficulties do not lack (e.g. Bain et al., 2014; Tsaparlis, 2016), teachers' perception of these difficulties do. Therefore, the objective of this study is twofold. First, we wanted to document and analyze teachers' opinions of difficulties at the thermodynamics level of granularity, since results exist in the literature only at a broader level (physical chemistry) or for a specific subject inside thermodynamics (entropy). Second, stimulated by the work of Camacho et al. (2015), and because this article is part of a larger research effort around the improvement of the teaching of entropy, we also wanted to dive into teachers' conceptions of entropy, starting with the links they establish with disorder, since it is the most often used descriptor of entropy.

Through this work, we will provide researchers with valuable information that they can confront with the recommendations of science education research and the difficulties reported by students. We will also provide instructors with a synthetic picture of their colleagues' opinions, which can be in itself difficult to obtain, as teachers rarely have the chance to observe and question their colleagues in tertiary education.

Research Questions

RQ1) What challenges do thermodynamics instructors identify in teaching thermodynamics at the tertiary level?

RQ2a) What do thermodynamics instructors at tertiary level find difficult to teach about entropy and the second law of thermodynamics, and why?

RQ2b) What are thermodynamics instructors' uses of the disorder metaphor at the tertiary level, and what do they think about it as a didactical tool to teach entropy?

Method

Respondents

In Belgium, tertiary education is shared between two institutions, universities and "Hautes Écoles". "Hautes Écoles" organize either bachelor's only or bachelor's + master's degrees and are more focused on technical education directly preparing to industry positions, while universities organize bachelor's and master's degrees and center on theory-focused education preparing to research positions. 27 institutions were screened to see if they proposed a chemistry bachelor or chemistry engineering bachelor: 4 universities (Université Libre de Bruxelles (ULB), Université Catholique de Louvain (UCL), Université de Mons (UMons), Université de Namur (UNamur)) under the supervision of the French-speaking government of Belgium (our own university, Université de Liège (ULiège) was excluded, because we had already collaborated with the thermodynamics teachers of our institution in previous research, which might have influenced their pedagogical opinions); as well as 23 Hautes Écoles: Haute École de la Province de Liège (HEPL), Haute École Louvain en Hainaut (HELHa), Haute École Condorcet (HE Condorcet), Haute École Vinci (HE Vinci), Haute École Libre Mosane (HELMo), Haute École de Namur-Liège-Luxembourg (Hénallux), Haute École Galilée (HEG), École Pratique des Hautes Études Commerciales (EPHEC), Haute École en Hainaut (HEH), Haute École Charlemagne (HECH), Institut Catholique des Hautes Études

Commerciales Saint-Louis (ICHEC-Saint-Louis), Haute École Francisco Ferrer (HEFF), Haute École Bruxelles-Brabant (HE2B), Haute École Albert Jacquard (HEAJ), Haute École Libre de Bruxelles Ilya Prigogine (HELB), Haute École Robert Schuman (HERS), Haute École Lucia de Brouckère (HELdB), Haute École de la Province de Namur (HEPN), Haute École de la Ville de Liège (HEL), École Industrielle et Commerciale de la Province de Namur (EICVN), Institut Supérieur Industriel de Promotion Sociale de Charleroi (ISI-PS), Institut Roger Lambion, Institut Provincial Supérieur Henri La Fontaine (IPS HLF) and Institut de Technologie.

Questionnaire and Software

The online survey was sent by mail to all teachers associated with a thermodynamics course in one of the aforementioned institutions. It consisted of 4 parts.

- Personal information: age range, institution name, job status, if the respondents were thermodynamics researchers and their area of expertise, if they were education researchers and their area of expertise, number of years of experience in teaching thermodynamics, teaching diploma.
- Thermodynamics difficulties: why they found thermodynamics hard to teach, why they found entropy hard to teach, and to what extent they agreed with statements from Sözbilir's article (2004) "What makes physical chemistry difficult? […]".
- Declared practice: if they used figures that connected macroscopic and symbolic/microscopic points of view, to what extent they found that usage important, if they had access to enough of such figures, if they proposed entropy-related laboratories to their students and if so, the topics of these laboratories, and, from a list, what topics they covered in their course and how difficult they found these concepts to teach.
- Disorder metaphor: whether the respondents used it; if they did, to what pedagogical aim they used it, what limits they gave to the validity of the metaphor and if they used counterexamples; if they did not, why, and if they used another metaphor instead.

The full questionnaire is available in the Supplementary Information, Appendix I. Graphs were produced in software R or Microsoft Excel. All quotes were translated by DeepL online and corrected by the authors, mainly for specialized vocabulary.

Results

Respondents' Characteristics

The 4 universities, as well as 8 "Hautes Écoles" (HEPL, HELHa, HE Condorcet, HE Vinci, HELMo, HERS, HEL, ISI-HLF), did offer a chemistry or engineering chemistry bachelor. 4 "Hautes Écoles" did not answer to our requests, which means the respondents might come from any of the 4 universities and the 4 "Hautes Écoles" (no identification data was collected). 41 people completed the survey, and 26 filled it out completely. Most respondents worked at the university (fig. 1), had between 10 and 15 years of experience teaching thermodynamics (fig. 2) and about half of them had a "Haute École" teaching diploma, or a teaching certificate for secondary school (fig. 3, please note that we specified "N/A" for respondents that did not answer the question, as opposed to those who specifically declared they had "no formal training"). 21% of respondents perform(ed) research in thermodynamics. Areas of expertise included crystallization, phase diagrams, energy storage, molecular dynamics, molecular modelling, thermodynamical cycle optimization, or Carnot batteries. No respondents reported research activities in pedagogy or science education. 8% of teachers organized thermodynamics laboratory in the context of their thermodynamics courses.

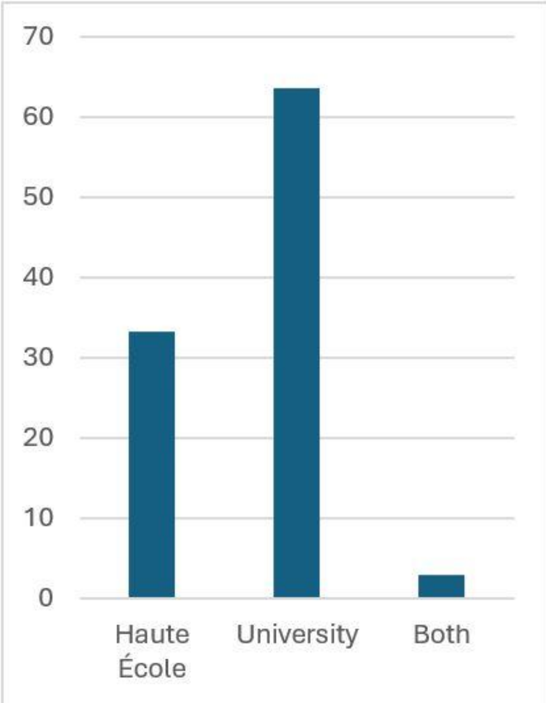

Figure 1. Percentages of Respondents in Each Institution (N = 33)

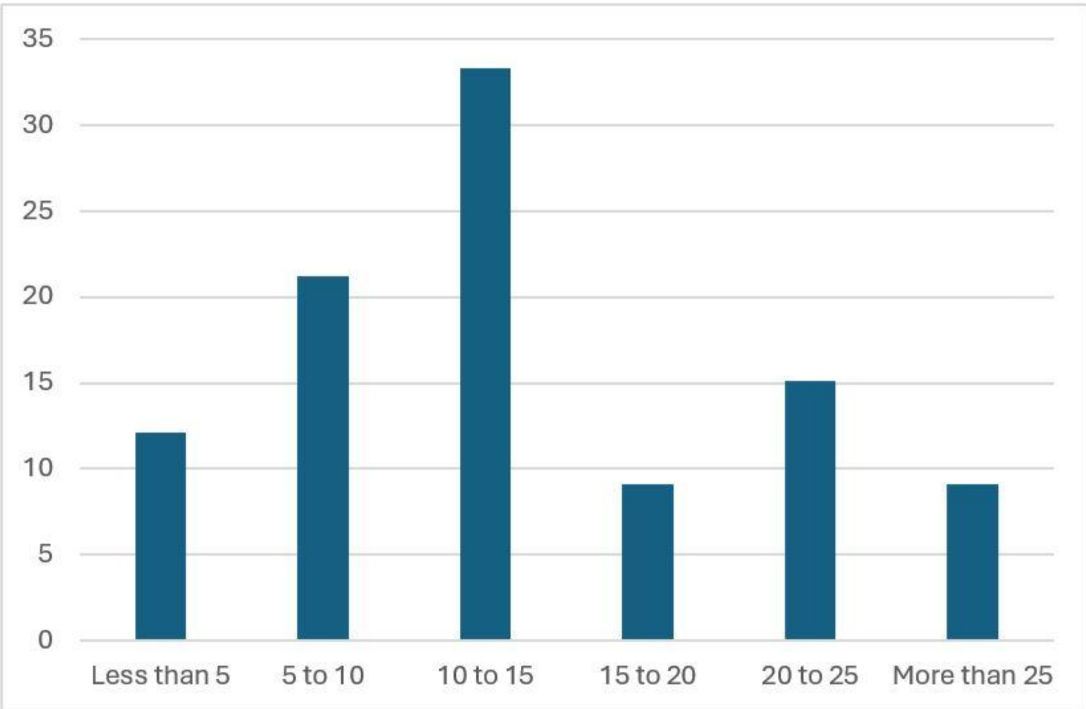

Figure 2. Percentages of Respondents with Years of Experience Teaching Thermodynamics (N = 33)

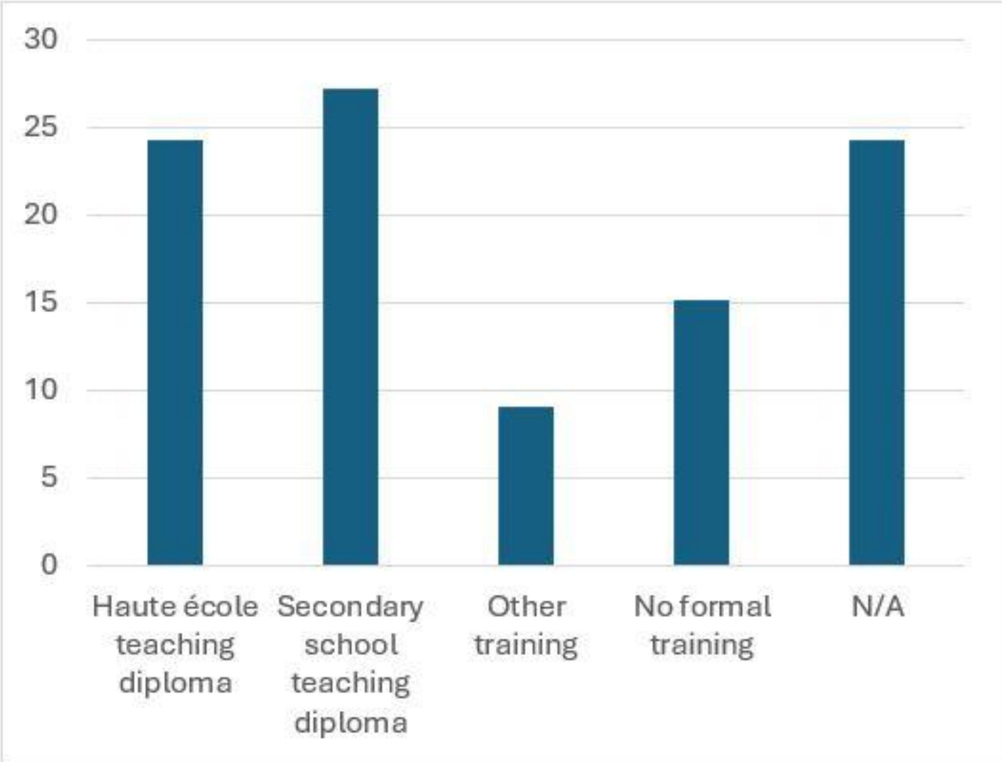

Figure 3. Percentages of Respondents that have specified a Teaching Diploma (N = 33)

RQ1: What challenges do thermodynamics instructors identify in teaching thermodynamics at the tertiary level?

Students, Teaching Context and Teaching Management

The questions codes we use hereafter are available in the full questionnaire (Appendix I of the Supplementary Information). We address in the following paragraphs a combination of two questions, a multiple-choice question (Q17) and an open question requiring a written question from respondents (Q15). First, in fig. 4, we show the opinions of teachers about the difficulties that Sözbilir (2004) identified in interviews with two Turkish university professors. These hurdles are divided into four categories: students (S), teaching context (TC), teaching management (TM) and content (C) (SE stands for socio-economic).

Teachers mainly agree with the student-centered statements, except for "students are socio-economically disadvantaged", with which 75% of them completely disagree (cd, 30%), disagree (d, 25%), or rather disagree (rd, 20%). Two important statements are favored by teachers: 68% of them completely agree (ca, 12%), agree (a, 28%) or rather agree (ra, 28%) that "students lack the prerequisite concepts to fully understand this subject, as physical chemistry is cumulative" and 67% (ca:23%, a:19%, ra:23%) that "students have very different levels of prior knowledge, and the groups are heterogeneous". These descriptive statistics underpinning students' lack of prerequisites, and the heterogeneity of their prerequisites, are completed by teachers' written answers to the question "according to you, what makes teaching thermodynamics difficult?". This question (Q15) was accessed by respondents before the Sözbilir (2004) statements, to avoid influencing them.

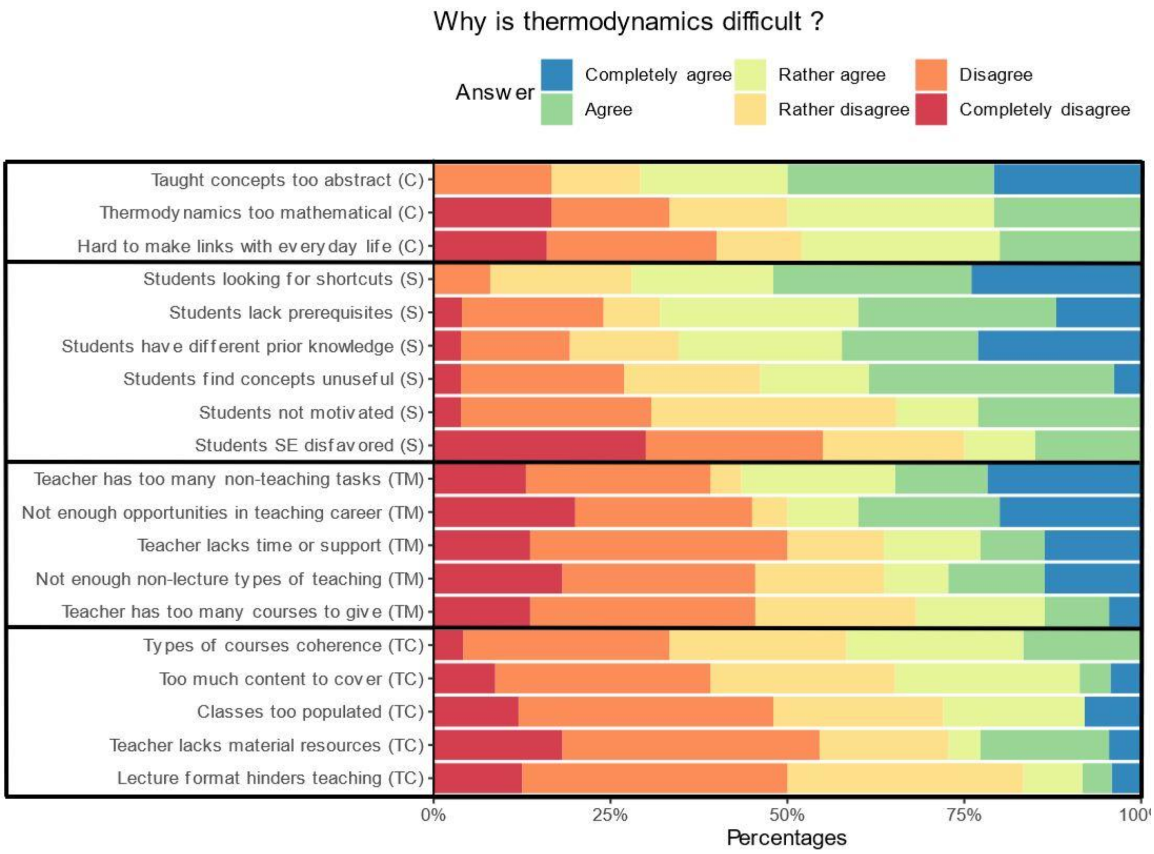

Figure 4. Percentages of Answers on Why Teaching Thermodynamics is Difficult (N = 26)

For example, one teacher states that the main difficulty in teaching thermodynamics lies in the "*Few student prerequisites (in first undergraduate year).*" that students possess; a second nuances that "*Students are probably not sufficiently made aware of [thermodynamics] at secondary school.*", and a third blames "*The large amount of maths, which students don't master.*" when they enter tertiary education. Secondary school content is addressed in the discussion section of this article. Finally, a teacher suggests that the difficulty in thermodynamics lies with students' behavior rather than prerequisites: "*It also requires a certain amount of commitment on the part of the student, as the concepts build on each other, which requires students to work on a regular basis as soon as the first course week, which is often not the case*.".

Concerning the teaching context, the respondents completely disagree, disagree, or rather disagree with all the suggested statements, showing some discrepancy with Sözbilir's respondents: "the lecture format does not allow the subject matter to be explained properly" (cd:13%, d:38%, rd:33%, tot:84%), "the teacher lacks material resources to teach" (cd:18%, d:36%, rd:18%, tot:72%), "the classes are too populated" (cd:12%, d:36%, rd:24%, tot:72%), "the teacher has too many courses to give" (cd:14%, d:32%, rd:23%, tot:69%), "there is too much content to cover" (cd:9%, d:30%, rd:26%, tot:65%), and "it is difficult, pedagogically speaking, to optimize the coherence between the theoretical course, the exercises and the laboratories" (cd:4%, d:29%, rd:25%, tot:58%). A reasonable explanation for the overall disagreement of teachers with these items might be the different teaching conditions in tertiary education in Turkey (from which Sözbilir's respondents came from) and Belgium (this study). According to the Organization for Economic Co-operation and Development (OECD), in a recent report on educational systems (2023), two indicators (C1, p.267-284 and C2, p. 285-289) can support this hypothesis.

Indicator C1 is the total expenditure on educational institutions per full-time equivalent student (in 2020). For tertiary education, Belgium spent 14791 $ on each student, while Turkey spent 7418 $ per student (Table C1.1, p.281). Indicator C2 tracks the total expenditure on educational institutions as a percentage of gross domestic product (GDP). In 2020, Belgium spent 1.8% of its GDP on tertiary education, Turkey 1.2%.

Accordingly, statements about teaching management were mostly disfavored: “the teacher has too many courses to give” (cd:32%, d:23%, rd:18%, tot: 73%), “the teacher doesn't have enough time or support” (cd:14%, d:36%, rd:14%, tot:64%), “the teacher doesn't have enough opportunities to organize other types of courses (tutorials, laboratories, remediations, etc.) around the theoretical course” (cd:18%, d:27%, rd:18%, tot:63%). Still, teachers completely agreed (ca), agreed (a), or rather agreed (ra) with a single proposition: “the teacher has too many non-teaching tasks to perform” (ca:22%, a:13%, ra:22%, tot:57%). In the same category lied the most disputed statement: “there aren't enough opportunities for career development in teaching”, with a group of 45% of teachers choosing “disagree” (25%) or “completely disagree” (20%) and another group of 40% of teachers choosing “agree” (20%) or “completely agree” (20%). A finer analysis shows that the latter group is made up of 5 “Haute École” teachers and 3 university teachers, while the former is composed of 1 “Haute École” teacher and 8 university teachers. Thus, this statistic might say more about the varying opportunities in the two types of Belgian institutions rather than about thermodynamics teaching, specifically.

Content

Most teachers only completely agree, agree, or rather agree with but one “content” statement: “the taught concepts are too abstract” (ca:21%, a:29%, ra:21%, tot:71%), and report contradictory opinions for the statement “thermodynamics is too mathematical” (a:21%, ra:29%, tot:50% vs. cd:17%, d:17%, rd:17%, tot:49%). Most of them completely disagree, disagree or rather disagree with the proposition that “it's hard to make links with everyday life” (cd:16%, d:24%, rd:16%, tot:56%).

Multiple written comments complete these descriptive statistics, starting with abstractness: “*[Thermodynamics] requires new capacities for abstraction in the first year at university.*”, “*These are very abstract notions, which sometimes require you to accept that they are not linked to anything tangible.*”. 28% of written comments mention abstraction as a difficulty. One instructor states that “*[Thermodynamics is] a mixture of mathematics and abstract concepts, which makes it difficult for students to understand.*”, which segways into the second difficulty: mathematics. In addition to the lack of mastered prerequisites mentioned in the student-related section of the results, and the mix of abstraction and mathematics just described, other more specific aspects connecting chemistry and mathematics are drawn out by teachers: differential equations (“*All the properties are linked via various differential equations, which can complicate things.*”), students' dislike of mathematics, “*many formulas*”, and boredom (“*I think it's boring because it's so formal and mathematical.*”).

Analysis of all written comments revealed many content-centered difficulties, which are listed below.

- Historical binarity: “*An important historical aspect stemming from the steam engine.*”, “*[Thermodynamics] combines a historical and still relevant macroscopic vision with a molecular vision that is still not very* *perceptible*.”.

- Postulates: “*[Thermodynamics is] based on principles that you have to 'accept'.* ”.
- Misconceptions: “*Having taught [thermodynamics] in the first year of a bachelor's degree, I find that many students arrive with misconceptions about energy and entropy that are hard to shake off.*”.
- Interdisciplinarity between physics and chemistry:
  - “*For first-year chemistry students, thermodynamics 'doesn't look like' chemistry.”.*
  - “*Even if [thermodynamics] is taught in a chemistry course, it comes under the heading of physics, which some students find repulsive or frightening*.”.
  - “*It implies considering different disciplines: above all chemistry and physics [...] or rather elements deemed less central/essential to these disciplines.”.*
- Specific concepts and their associated validity domains:
  - “*Some formulas are used at constant volume, others at constant pressure, which can be confusing*.”.
  - “*The concept of enthalpy itself is not always well understood. Its distinction from the notion of heat (which is broader) is difficult for many students to understand. Enthalpy (or its variation) is sometimes confused with temperature (or its variation).*”.

Figure 5 documents the answers of teachers to a question asking them to evaluate the difficulty of teaching specific thermodynamical concepts, provided they cover them in their course (Q23). It reports the percentages of answers on a Likert scale to the question “Indicate, for each of the concepts in the list below, 1. whether you are covering it as part of one of your thermodynamics courses. 2. If you cover it, your perception of the difficulty to teach this concept.”. The x-axis represents the percentages of agreement to the difficulty of each concept, and the percentages in the parenthesis represent the fraction of teachers who cover this topic. Opinions of teachers (N = 26) who did not cover a concept were not included. In this section, two types of percentages should not be confused: the percentages of teachers who cover a concept (in parenthesis in the y-axis labels of fig. 5), and the percentages of teachers’ opinions (x-axis of fig. 5). Two concepts stand out as very difficult (vdi), difficult (di) or rather difficult (rdi) for over 75% of teachers: the Clausius definition of entropy (vdi:13%, di:25%, rdi:44%, tot:82%) and the second law of thermodynamics (vdi:8%, di:20%, rdi:52%, tot:80%), which are respectively covered in their course by 59% and 89% of respondents. Many other entropy-related concepts (entropy itself, entropy-temperature diagrams, the Boltzmann definition of entropy, standard entropy) are also estimated as at least “rather difficult” by at least 50% of teachers who cover this subject. However, two concepts linked to entropy are not perceived as difficult: the third law of thermodynamics and the entropy of mixing. The concepts which induce the least difficulties are “isolated, closed and open systems”, “endothermic, exothermic and athermic reactions”, “types of energy”, “Hess diagrams”, and “the first law of thermodynamics”. Concepts connected to the second law are clearly thought of as the most difficult in thermodynamics.

As a counterpoint to the RQ1 results, in the written answers to the question “why do you think thermodynamics is difficult to teach?” (Q15), some respondents stated that they did not find thermodynamics difficult to teach: four of them without giving any reason, and two claiming that *statistical* thermodynamics is easy to teach: “*I teach statistical thermodynamics ... and it's very easy to teach*”; “*It's a difficult subject to teach if you don't start with the phenomena that occur on a microscopic scale, between the particles that make up matter. If you start from* *this understanding of the corpuscular world (not necessarily quantum to begin with), it's much simpler*.". Finally, a teacher advocates for the spacing of thermodynamics over two semesters: "*As a first-year course, the concepts are new to students. So they need time to grasp and 'digest' them. That said, I don't find this chapter particularly difficult to teach. I prefer to teach it in two separate stages over the two terms: thermodynamics of the first law in the first term and thermodynamics of the second law in the second term. The time elapsed between the two and the January exam then allow the students to have studied the concepts of the first law and to have acquired them before tackling the second law.*".

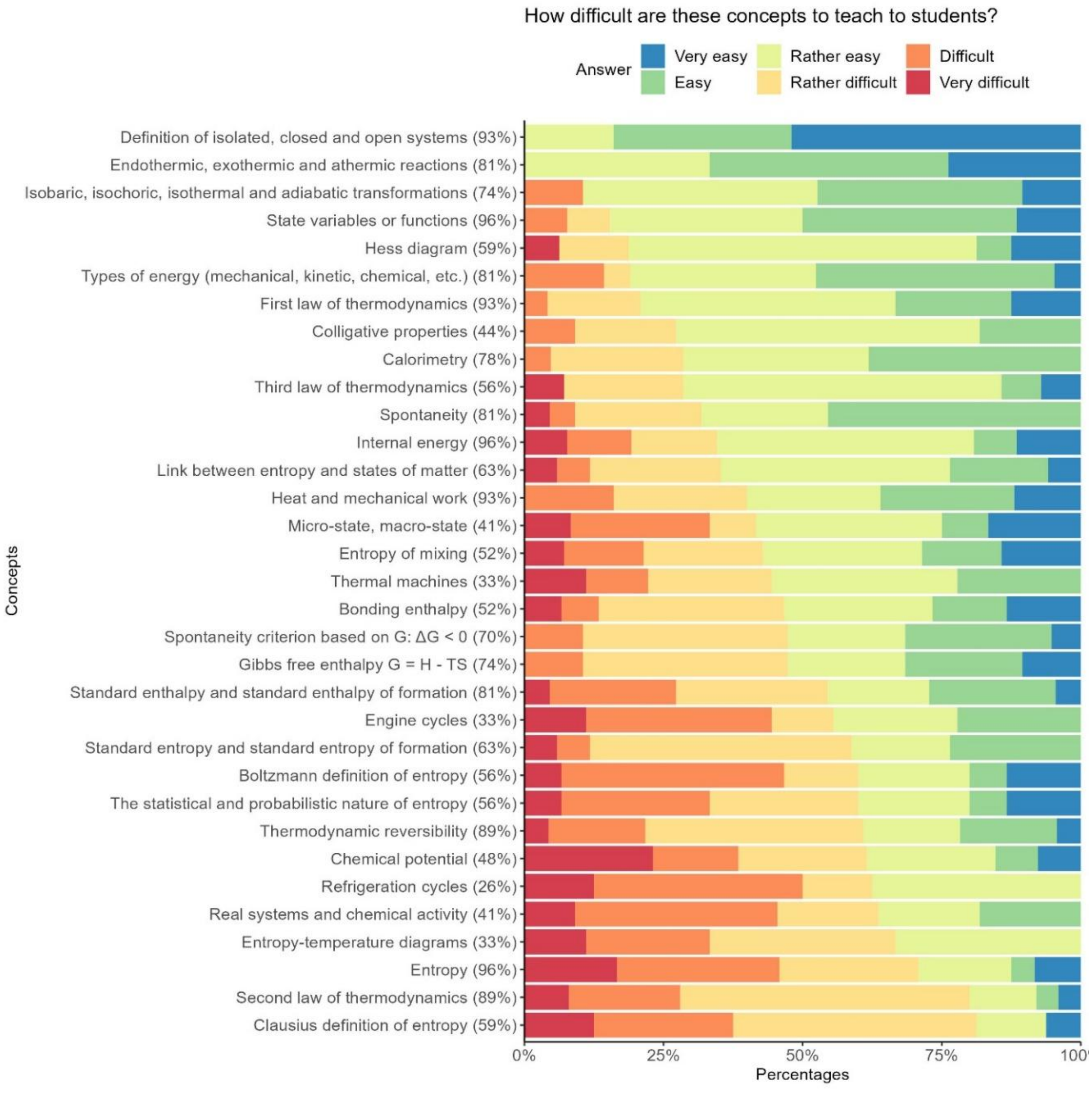

Figure 5. Percentages of Answers on How Difficult Concepts are to teach (N = 26)

RQ2a: What do thermodynamics instructors at tertiary level find difficult to teach about entropy and the second law of thermodynamics, and why?

The difficulties inherent to entropy specifically were investigated in the following questions.

- When you talk about entropy, do you use the metaphor of disorder (entropy is a measure of disorder, like a messy room or a shuffled pack of cards)? (Q11)

- If they answered "yes" to Q11:
    - For which educational purposes do you use it? (Q12)
    - When you use this metaphor, how do you define its validity domain? Do you give any counterexamples? (Q13)
- If they answered "no" to Q11:
    - Why not? Do you use another metaphor instead? (Q14)

o Why is the concept of entropy difficult to teach? (Q16)

Answers to Q16, which answer the RQ2a, underscore the same obstacles as with thermodynamics: abstraction. Multiple teacher opinions nuance this fundamental hurdle: entropy is hard to relate to everyday life, it is not concrete, it is hard to visualize, especially at small scales, at which it is not perceptible with our senses. A counterpoint is provided by one of the teachers: "*Personally, I find the concept of energy much more complicated, because a lot of students think they know what it is, when in fact they do not.*", raising an age-old debate of whether it is easier to teach concepts that have an everyday meaning (like energy) and a scientific meaning, or if it easier to teach concepts that only have a scientific meaning (like entropy).

In the following, we list difficulties inherent to entropy that were not addressed in the "thermodynamics difficulties" section, which could indicate specific obstacles in the teaching of entropy.

- Different disciplinary "philosophies": "*[Entropy] is seen in quite different ways in different curricula (chemistry approach vs. thermodynamics approach).*".
- Complexity: *"[Entropy] remains a complex concept that is logically linked to the second principle, which is itself very complex in its consequences.*"; "*It is conceptual, made up of small theoretical notions that are easy to tackle independently, but complex to understand when put together.*".
- Lack of practical use: *"[Entropy is] not used in the field by chemical technicians and fortunately there's ΔG to get a better overview.*"; "*I also believe that for chemists, bio-engineers, biologists, etc., the important thing is to use the concepts and not to replicate them. So they need to have a practical notion of the concept*".
- Student maturity: "*[...] the concept is introduced in the first and second years, and the students don't yet have the necessary knowledge background at that stage*".
- Specific didactical difficulties:
    - "*Difference between ΔS_{system} and $\Delta S_{environment}$.*"; *"It is difficult to teach because you have to talk about the entropy of the universe. The concepts of system and universe are difficult for our students to understand."*.
    - "*It is difficult to attribute to disorder the ability to steer the evolution of a system in one direction or another over time [...] Entropy variation incorporates the notion of the arrow of time, the evolution of a system towards equilibrium. But this time is never defined or quantified.*".
    - "*Because the second principle is an INequality*" (emphasis by the teacher).
    - "*$dS=dq_{rev} / T$ is also an abstract concept. Why do we have to use a reversible path and the result is ultimately independent of the path because S is a state function[?] This is confusing.*"; "*Problem [is] that we use $q_{reversible}$ even if the system is not reversible*".

- "*In the absence of a basic understanding of statistical mechanics, it is practically impossible to calculate entropy using Boltzmann's relation for concrete cases in the first year.".*

Some teachers do not find entropy difficult to teach, as was also pointed out in the "thermodynamics difficulties" section. Two argued it was thanks to the statistical thermodynamics approach, though one signals that this method may "[…] *[shift] certain problems/difficulties towards perhaps more complex mathematical concepts.*". Two other teachers further the point raised in the "abstraction" paragraph: other concepts typical of thermodynamics, such as temperature, energy, or heat may *look like* they are more comprehensible and contain less hurdles, but it might be an illusion fueled by the familiarity created by them having an everyday meaning; it could be argued that they are no less complicated than entropy.

RQ2b: What are thermodynamics instructors' uses of the disorder metaphor at the tertiary level, and what do they think about it as a didactical tool to teach entropy?

Teacher Use and Reasons for Use

In this question, 77% of teachers stated that they did use the metaphor, and 23% claimed they did not. Let us first analyze the justifications of the former group. The teachers claim that they use the disorder metaphor "*To make the concept of entropy more concrete.*" and to help create mental images of entropy: "*So that students understand the concept and visualize it more clearly.*", "*The idea is to make entropy correspond to something they can see.*", "*So that students can imagine what entropy represents.*", "*To make it easier to understand and link the defined magnitude to something concrete.".*

Another reported approach to the reduction of the leap of abstraction that entropy requires (compared to other concepts, such as heat, temperature or energy), is to use the disorder metaphor as a first, simplifying step: "*As the students have not yet seen [energy] state occupancy, I prefer to introduce them to [entropy] in a simple way.*", "*The disorder metaphor is used to introduce the notion of entropy to the students in the first instance (introductory part of the chapter on the second law of thermodynamics). Secondly, this metaphor is related to the notion of the number of accessible microstates, when Boltzmann's formula for entropy is given.".*

This approach is analogous to the one used by Atkins et al. (2023) in their famous physical chemistry textbook, in which, after having used "disorder" as an explanation for entropy, the authors signal that disorder is an "*ill-defined*" first step: "*The concept of the number of microstates makes quantitative the ill-defined qualitative concepts of 'disorder' and 'the dispersal of matter and energy' that are used widely to introduce the concept of entropy: a more 'disorderly' distribution of energy and matter corresponds to a greater number of microstates associated with the same total energy.*" (p. 79).

Other teachers mention that the main point of the metaphor has always been "*To illustrate that a system with a large number of configurations is more likely to be encountered than one with fewer.*" (a disordered situation is more *probable* than an ordered one); "*Rather to explain that a system that can have a greater number of configurations is more likely (thermostat). I use the metaphor of the bus (more likely to have the configuration of*

1 passenger on 10 different benches than the configuration where 5 benches are occupied by 2 passengers (the others remaining free)).".

Finally, as with other statements from the questionnaire, some teachers mention using the disorder metaphor to illustrate a specific concept. For example:

- Differentiation of heat and work: "*I also draw a parallel with the ball bouncing off the ground, which loses some of its energy in the form of heat, due to the disordered movements of the atoms in the ground, as opposed to work like pushing a piston.".*
- States of matter: "*To show that the entropy of a gas is naturally greater than that of a liquid or solid*.".
- Third law: "*To introduce it and illustrate the 3rd law.*", "*This metaphor is used to provide an intuitive justification for the third law of thermodynamics (S = 0 for zero disorder).".*
- Reaching equilibrium discussions: "*To introduce the notion of a reaction leading to an equilibrium, I introduce the disorder criterion as a second criterion in addition to the energy criterion.*".

Use of Counterexamples

48% of the teachers who *do* use the disorder metaphor declare not using any counterexamples, and not giving limits to the metaphor. In the 52% of teachers who declared giving some counterexamples at Q13, some, but not all, gave some precisions in the associated open question.

For example, three teachers reported that they mention broad limits: "*The limit of using a situation in the macroscopic world to describe a situation in the microscopic world.*", "*[I use the disorder metaphor] while explaining the true definition, but insisting that it's not something they need to know.*"; "*I point out that this is not exactly the same thing and that there are underlying mathematical equations.*". Four other teachers give precise limits, such as:

- the temperature dependence of entropy: *"Entropy is defined at a given temperature. It is difficult to integrate this concept with that of a well-ordered or badly-ordered [student room].*";
- the exhaustion students can feel when they tidy up their room, that could be confused with the energy lost by a system: "*You might object that it took a lot of energy to make a mess of the tidy room.*";
- energy exchange, the counter-intuitive formation of a perfect crystal: "*Generally, I use the formation of crystalline solids for systems of particles interacting as hard spheres. Maximizing entropy implies the formation of a perfectly ordered crystal, which is rather counter-intuitive. It just goes to show the limits of the entropy equals disorder concept.*";
- the specific meaning of "disorder": "*Entropy does not describe disorder in the everyday sense of the term. Rather, it measures the distribution of thermal energy in a system. Entropy does not take into account the specific nature of individual particles in a system*.".

The second and third points from this list illustrate a limitation of the disorder metaphor which is usually wrongly applied only to the system: by doing so, the essential contribution of the heat exchange with the environment and its associated entropy change are concealed.

Teacher Arguments for Avoiding the Disorder Metaphor

23% of teachers *do not* use the disorder metaphor. Two teachers point out two very different reasons. The first one emphasizes the lack of similar properties between entropy and disorder: "*On a microscopic scale, the components of matter are distributed randomly between all possible states, resulting in the most probable distribution, which corresponds on a macroscopic scale to the maximization of a function (entropy) that measures this distribution between microstates. This has nothing to do with the notion of order and disorder. I always work on entropy using statistical physics, which is very simplified for first-year students. This also makes it easy to understand why entropy increases for a transformation occurring in an isolated system - it's simply the play of chance.".* The second teacher states that a course for engineers does not require a microscopic explanation: "*The reason for this is the confusion that arises when entropy is viewed in different ways (molecular and macroscopic scales). For example, in thermodynamic cycles, the definition of entropy is* $dS=dq_{rev}/T$*. The link with disorder is present but is not useful for understanding the phenomena in cycles, which are based much more on the properties of entropy = state variable.*".

Some teachers mention they use other proxy words for entropy, some inspired by statistical thermodynamics, such as "*Richness in terms of the number of positions and speeds accessible to molecules.*", or "*The number of configurations or states that a system can have.*"; two other teachers propose broader terms: "*A measure of irreversibility.*", and "*A fragmentation of energy.*".

Discussion

As a respondent elegantly puts it, one might wonder if *"[Thermodynamics] is harder to understand than to teach.*". Our aim, with this study, has precisely been to complete the picture of thermodynamics difficulties, which are often studied in the literature from the students' perspective, and not from the teachers', even though teachers' opinions directly shape their pedagogical choices when it comes to attributing time and resources to tackle obstacles within their courses. To the best of our knowledge, only three peer-reviewed studies reported some data on teachers' opinions about physical chemistry or entropy (Camacho et al., 2015; Fox & Roehrig, 2015; Sözbilir, 2004).

The main comparison for the present study is Sözbilir's article (2004), who interviewed two university teachers and provided qualitative descriptions of difficulties encountered in thermodynamics teaching. Sözbilir also performed a survey about learning difficulties identified by students. In Table 1, these students' opinions are put in perspective with the teaching difficulties identified by our responding teachers. Thus, Table 1 compares the opinions about physical chemistry difficulties of $N = 91$ students in Sözbilir's (2004) study and the opinions of teaching difficulties in thermodynamics of our $N = 26$ responding teachers, for statements where substantial agreement shows up. For teachers' opinions, the percentages encompass the "rather agree", "agree" and "completely agree" levels of the Likert scale.

Students (for physical chemistry) and teachers (for thermodynamics) agree that difficulties lie in the abstractness of concepts, the cognitive load linked to the broad content coverage, the need for optimization of different teaching activities (laboratories, exercises), the lack of motivation for the course and the exam, that students have diverse backgrounds and thus, can lack some prerequisites, and, to a lesser extent, that there is a lack of material resources.

Table 1. Sözbilir's (2004) Student Opinions vs. Teachers' Opinions (this work).

According to students, learning difficulties in physical chemistry might be caused by…	%	According to teachers, teaching difficulties might be attributable to…	%
Abstract concepts	52	Taught concepts too abstract	71
Overload of course content	41	Too much content to cover	35
Inconsistency between exam/lecture/lab	37	Difficulty to optimize the coherence between the theoretical course, the exercises and the laboratories	42
		Lack of complementary activities (laboratories, problem solving classes)	36
Physical chemistry is too mathematical	33	Thermodynamics is too mathematical	50
Lack of resources	22	Teachers lack material resources	27
Absence of motivation	37	Absence of motivation of the students	35

In Table 2, three tensions between students' and teachers' perceptions are made apparent by comparing possible improvement strategies of physical chemistry teaching, as assessed by N = 91 students in Sözbilir's (2004) study and the opinions on teaching difficulties in thermodynamics of our N = 26 responding teachers, for statements where students and teachers rather disagree. For teachers' opinions, the percentages encompass the "rather agree", "agree" and "completely agree" levels of the Likert scale.

- Students ask for a better promotion of conceptual understanding, but, on the contrary, teachers feel that students favor "tips and tricks", that is, shortcuts to complex problems, in lieu of conceptual learning.
- Students ask for more links with everyday life, but almost half of respondent teachers find these links hard to make.
- Students question the traditional lecture style and suggest collaborative group activities, whereas teachers overwhelmingly do not think the lecture format hinders efficient teaching.

Table 2. Sözbilir's (2004) Student Solutions vs. Teachers' Opinions of Difficulties (this work).

According to students, learning difficulties in physical chemistry might be solved by…	%	According to teachers, teaching difficulties might be attributable to…	%
Promoting conceptual understanding	19	Students looking for shortcuts	72
Linking contents to daily life	56	Hard to make links with everyday life	48
Promoting group work and discussions	48	Lecture format hinders teaching	17

Fox and Roehrig (2015) report that out of the N = 331 physical chemistry teachers that they surveyed, 61% think the reason students struggle with physical chemistry is that they "lack the necessary math background", while 38% believe that students do not "make connections between the concepts and mathematics.". Furthermore, the prime cause for student difficulties identified by instructors in Camacho et al. (2015) is identical: lack of mathematics prerequisites, as believed by 41% of the N = 12 interviewees. Our results support the findings of these two studies: 68% of our respondents rather agree, agree or completely that "students lack the prerequisite concepts to fully understand this subject, as physical chemistry is cumulative" and 57% that "students have very different levels of prior knowledge, and the groups are heterogeneous", while, in open written answers, three teachers point out the lack of science or mathematics prerequisites.

To provide some elements of context, in French-speaking Belgium, students can choose between two options of science: "basic" (one 50-minute lecture per week for each major discipline in natural science, that is, physics, chemistry and biology) and "advanced" (two 50-minute lectures per week for each discipline) in the 5th and 6th years of secondary school (16-18 years-old, 11th-12th grade). For mathematics, students can also choose between: "essentials" (two 50-minute lectures per week), "basic" (four 50-minute lectures per week) and "advanced" (six to eight 50-minute lectures per week). Students are all taught thermodynamics concepts (as listed in Table 3), but these remain limited when students choose the "basic" option.

In Table 3, we report thermodynamics topics, as well as mathematics concepts underpinning thermodynamics, that are covered in the last three years of secondary school (15-18 years old, 10th-12th grade). For science, in plain text, we list concepts covered at all levels and in bold, concepts only covered in "advanced" classes. For mathematics, in plain text, we list concepts covered at all levels, and in bold, concepts only covered in "basic", and "advanced" mathematics (but not "essentials"). With an asterisk (*), we signal that for advanced students, the reference program explicitly mentions not talking about entropy, rather, talking about "disorder" (Decree for terminal competences in mathematics and science, 2014).

Table 3. Science and Mathematics Concepts covered in Secondary School

Physics	Chemistry	Math
Energy transformations, heat, temperature, phase change, gravitational potential energy, kinetic energy, electric energy, mechanical energy conservation, first law, thermal machines, refrigerators, machine efficiency, renewable and non-renewable energy, **second law, heat and phase change, photon energy**	Heat, exothermic, endothermic, athermic reactions, heat capacity, **enthalpy, ΔH, Q=cmΔT, molar and specific heat, calorimetry, disorder* for spontaneity**	Series, probability, probability laws, **integrals, derivatives, exponentials and logarithms**

Concerning mathematics prerequisites, we established the following list, according to our own experience and to the mathematical support chapters provided by Atkins et al. (2023) in their physical chemistry textbook.

- Macroscopic thermodynamics: derivatives, partial derivatives, integrals, Taylor series
- Statistical thermodynamics: probabilities, logarithms, exponentials, combinatory analysis

As a complementary piece of information, let us report that for another research (Natalis & Leyh, 2024), we enrolled N = 287 students participating in an introductory thermodynamics course at the University of Liège. Among them, only 2% had chosen “essentials of mathematics” in secondary school. Therefore, 98% had chosen either “basics of mathematics” or “advanced mathematics”, covering all the necessary topics for thermodynamics, as listed above. However, for entropy coverage in secondary school, 16% of students in that cohort had chosen “basics of science” and had not covered entropy or the second law, and 84% had chosen “advanced science” courses, in which entropy is only alluded to through the disorder metaphor.

Our respondents’ written answers also detail which mathematical problems affect the teaching of thermodynamics: differential equations, the mixture of mathematics and abstractness, the mixture of chemistry and mathematics, students’ dislike of mathematics, the large number of formulas, and the possible boring nature of the mathematical formalism.

Though prerequisites have been put forth by our respondents as a difficulty, their first concern with thermodynamics teaching, and with entropy teaching, is abstractness. This specific issue had not been underpinned by Fox & Roehrig (2015) nor Camacho et al. (2015). In our results, 71% of instructors rather agree (21%), agree (29%) or completely agree (21%) that “the taught concepts are too abstract”, while 28% of written answers mention abstractness as a hurdle. In interviews with chemistry students about the difficulties of physical chemistry, Tsaparlis, (2016) showed that students found macroscopic thermodynamics easier than quantum chemistry because they had already covered that topic in secondary school. The opinions of teachers throughout our questionnaire were very positive on statistical thermodynamics. Some went as far as to say that it allowed a problem-free explanation of entropy, while some nuanced that claim by stating that it may displace the conceptual problem toward mathematical complexity. Students of Tsaparlis’ (2016) study also believed that statistical thermodynamics is more difficult than classical thermodynamics because of its higher mathematical complexity.

Limitations

First, teachers self-reported their opinions in a precise set of questions chosen by the researchers, most of them multiple choices questions, which limited our interpretation. Analysis and coding could have benefited from other methods such as interviews and follow-up questions. The number of respondents is also quite modest. However, this sample should be representative of the beliefs of the French-speaking thermodynamics teachers of Belgium, since the total number of thermodynamics teachers at tertiary level is quite small, too. Finally, the question devoted to teacher’s opinions on specific concepts was introduced in the last part of the questionnaire. A possible bias towards “entropy is difficult” could therefore have been induced, because several previous questions framed entropy as a difficult concept.

Conclusion

This study aimed at documenting the opinions of tertiary education teachers about the pedagogical difficulties in their introductory course. For thermodynamics in general, difficulties include (a) the lack of prerequisites of students, which is surprising given these prerequisites are, in theory, covered by secondary school teachers and (b) the abstractness of concepts, among others (e.g. historicity, interdisciplinarity). Teachers also report overall good material teaching conditions, except for the too high number of non-teaching tasks, and diverging opinions on mathematical complexity. When asked to rank the difficulty of teaching specific concepts they cover, teachers reckon the most difficult concepts are entropy-related concepts such as entropy itself, the Clausius definition of entropy, entropy-temperature diagrams or the Boltzmann definition of entropy. On entropy specifically, instructors report that it is very abstract, complex, lacks practical use and crystallizes difficulties in teaching microscopic and macroscopic aspects of thermodynamics. 77% of teachers use the disorder metaphor to teach entropy, some of them to make it simpler, others to address specific issues. Some respondents acknowledge not mentioning any limitation to the use of the metaphor. Comparison of teachers' and students' opinions on difficulties in thermodynamics shows some agreements on problems (e.g. abstraction, too much content to cover) and tensions on solutions (e.g. relevance of the lecture format, request from students for links with everyday life, which teachers find hard to make).

Ethics Statement

All responding teachers were contacted by mail and could answer freely to the questionnaire. Informed consent for the questionnaire was obtained by an agreement in compliance with the Belgian GDPR guidelines (General Data Protection Regulation, 2016), since the Fédération Wallonie-Bruxelles Government does not require an ethics committee approval for educational studies when no personal data is gathered.

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Author Information

Vincent Natalis
https://orcid.org/0000-0002-7778-5438
University of Liège
Allée du Six Août, 11, 4000, Liège
Belgium
Contact e-mail: *vincent.natalis@uliege.be*

Bernard Leyh
https://orcid.org/0000-0001-8447-5836
University of Liège
Allée du Six Août, 11, 4000, Liège
Belgium

Appendix I. Full Questionnaire

For terms and abbreviations used in the questionnaire that are specific to the French-speaking part of Belgium and are marked with an asterisk (*), some explanation for the international reader is available in Appendix II.

GDPR informed consent

The collection of your data is part of an analysis of teaching practices relating to the teaching of thermodynamics, entropy and the second principle of thermodynamics. The data collected in this form are: an estimate of your age, whether you work at a Haute École or university, your job title, whether you do research in thermodynamics and/or pedagogy and on what subject, the number of years you have taught thermodynamics, your pedagogical training, your use of the metaphor of disorder, the subject areas you address and your perception of their difficulty, whether you organise laboratories and their subject(s), your use of images addressing the submicroscopic point of view, your perception of several difficulties in teaching thermodynamics. The data will be recorded in a computer file on a university server by Vincent Natalis (UR DIDACTIfen, Didactique de la Chimie, B6c 2/7, vincent.natalis@uliege.be, 043663335) of the University of Liège in order to produce a scientific analysis of your data as part of a doctoral thesis at the University of Liège on improving the teaching of thermodynamics in higher education. Your data will be kept for as long as it needs to be aggregated into anonymous statistical data. These data will be processed on the basis of this consent. Your data will not be passed on to third parties. They will be anonymised. In accordance with the provisions of the General Data Protection Regulation (EU 2016/679) and the Law of 30 July 2018 on the protection of individuals with regard to the processing of personal data, you may exercise your rights with regard to this personal data (right of access, rectification, erasure, limitation, opposition, portability and withdrawal of consent) by contacting Vincent Natalis (UR DIDACTIfen, Didactique de la Chimie, B6c 2/7, vincent.natalis@uliege.be, 043663335) or, failing that, the ULiège Data Protection Officer (dpo@uliege.be - Monsieur le Délégué à la Protection des Données, Bât. B9 Cellule 'GDPR', Quartier Village 3, Boulevard de Colonster 2, 4000 Liège, Belgium). You also have the right to lodge a complaint with the Data Protection Authority (https://www.autoriteprotectiondonnees.be, contact@apd-gba.be). Your completion of this questionnaire constitutes your positive agreement to these terms.

Personal data

Q1. What is your age?

- 18-25
- 25-35
- 35-45
- 45-65
- Over 65

Q2. In what institution(s) do you work?

- Haute École
- University

Q3. (If Haute École is chosen) What is your function?

- Maitre de formation pratique*
- Maitre-assistant*
- Chargé de cours*
- Other: ….

Q4. (If university is chosen) What is your function?

- Assistant* or PhD student
- Chargé de cours*
- Académique permanent* (professeur*, professeur ordinaire*)
- Researcher (FNRS*, FRIA*,…)
- Other:….

Q5. Are you currently doing research in the field of thermodynamics?

- Yes
- No

Q6. (If “Yes” was chosen at Q5) Can you briefly explain the subject(s) of this research?

Q7. Are you currently doing any research in the field of pedagogy and/or didactics?

Q8. (If “Yes” was chosen at Q7) Can you explain the subject of this research in a few lines and/or give a few key words?

Q9. How many years have you been teaching thermodynamics?

- Less than 5 years
- 5-10 years
- 10-15 years
- 15-20 years
- 20-25 years
- 25-30 years
- 30-35 years
- 35-40 years
- More than 40 years

Q10. What teaching training do you have?

- CAPAES*
- AESS*
- CAP*
- Other:…

The disorder metaphor

Q11. When you talk about entropy, do you use the metaphor of disorder (entropy is a measure of disorder, like a messy room or a shuffled pack of cards)?

- Yes
- No

Q12. (If "Yes" was chosen at Q11) For which educational purposes do you use it?
Q13. (If "Yes" was chosen at Q11) When you use this metaphor, what limits do you place on its validity? Do you give any counterexamples?
Q14. (If "No" was chosen at Q11) Why not? Do you use another metaphor instead?

Difficulties in teaching thermodynamics

Q15. Why do you think thermodynamics is difficult to teach?
Q16. More specifically, why do you think the notion of entropy is difficult to teach?
Q17. Didactic research by M. Sözbilir (What Makes Physical Chemistry Difficult? Perceptions of Turkish Chemistry Undergraduates and Lecturers, Journal of Chemical Education, 2004) identified several difficulties in teaching thermodynamics at postgraduate level. To what extent do you agree with the following suggestions for teaching difficulties, adapted from this article?

Choose the appropriate answer for each item: Totally disagree, disagree, rather disagree, rather agree, agree, totally agree.

- The students have very different levels of prior knowledge, and the groups are heterogeneous.
- The students are socio-economically disadvantaged.
- Students do not seek to understand, they look for tricks to solve problems more easily.
- Students are not motivated for this course.
- Students do not find the concepts taught useful enough.
- Students lack the prerequisite concepts to understand the subject properly, as physical chemistry is cumulative.
- The teacher lacks the material resources to teach the course.
- Class sizes are too large.
- There is quantitatively too much material to see.
- The lecture format does not allow the subject to be explained properly.
- It is difficult, pedagogically, to optimise the coherence between the theoretical course, the exercises and the laboratories.
- It is difficult to make links with everyday life.
- Thermodynamics is too mathematical.
- The concepts are too abstract.
- You don't have enough time or support.
- You have too many lessons to give.
- You have too many non-teaching tasks to perform.
- There aren't enough opportunities for career development in teaching.
- You don't have enough opportunities to organise supervision (rehearsals, tutorials, laboratories, remedial work, etc.) around the theoretical course.

Practices

Q18. Here are a few figures relating to thermodynamic concepts that deal with the microscopic aspect of matter.
Example of macroscopic representation (glacier, air) - microscopic (water molecules and their movements)
Retracted for publication in open access. This figure was taken from Tro, N.J., Chemistry: a molecular approach (2017, 4th edition), Pearson.
Example of symbolic representation (graph) - microscopic (nitrogen, dihydrogen and ammonia molecules).
Retracted for publication in open access. This figure was taken from Tro, N.J., Chemistry: a molecular approach (2017, 4th edition), Pearson.
Do you use this type of representation, which matches the microscopic viewpoint with the macroscopic and/or symbolic viewpoints? Choose the appropriate answer for each item: I use it…

- Never
- Vary rarely
- Rarely
- Sometimes
- Often
- Vary often

Q19. Why do you think this use is important?
Q20. Do you think you have enough iconographic resources (images, figures) in treatises, manuals or websites to illustrate this microscopic viewpoint in thermodynamics?

- I have plenty enough
- I have enough
- I don't have enough
- I don't have enough at all

Q21. Do you organise thermodynamics laboratories that deal with the notion of entropy as part of your course?

- Yes
- No

Q22. What is the theme of the laboratories and the experiments carried out, in brief?
Q23. For each of the items on the list below, indicate the following
1. Whether it is covered in one of your thermodynamics courses. Choose: yes or no.
2. If you cover it, your perception of the difficulty that this subject has in being taught to students. Choose the appropriate answer for each item: very easy, easy, rather easy, rather difficult, difficult, very difficult.

- Definition of isolated, closed and open systems
- State variables or functions
- Thermodynamic reversibility
- Spontaneity
- Types of energy (mechanical, kinetic, chemical, etc.)
- Internal energy
- Heat and mechanical work
- First principle of thermodynamics

- Endothermic, exothermic and athermic reactions
- Isobaric, isochoric, isothermal and adiabatic transformations
- Calorimetry
- Standard enthalpy and standard enthalpy of formation
- Hess diagram
- Binding enthalpy
- Thermal machines
- Engine cycles
- Refrigeration cycles
- Entropy
- Clausius definition of entropy
- Statistical and probabilistic nature of entropy
- Boltzmann's definition of entropy
- Microstate, macrostate
- Second principle of thermodynamics
- Entropy of mixing
- Entropy-temperature diagrams
- Link between entropy and states of matter
- Third principle of thermodynamics
- Standard entropy and standard entropy of formation
- Gibbs free enthalpy $G = H - TS$
- Spontaneity criterion based on G: $dG < 0$
- Chemical potential
- Real systems and chemical activity
- Colligative properties

Q24. Would you like to comment on and/or add one or more additional subject points that are missing from this list and that you feel are essential to your teaching?

Appendix II. Explanations of Terms used in the French-speaking Belgian Education System

- Maitre de formation pratique*, Maitre-assistant* and Chargé de cours* are the three job statuses for teachers in “Haute École”, the Belgian teaching institutions in charge with 3-years bachelor programs focussed on technical education directly preparing to industry positions .
- Assistant* is the job status of PhD students who are employed by their university. These contracts often last 6 years, and assistants have more teaching responsibilities than PhD students that are beneficiaries of external fundings.
- Chargé de cours*, Professeur* and Professeur ordinaire* are the three academic statuses for teachers in universities.
- FNRS* stands for *Fonds National de la Recherche Scientifique*, National Fund for Scientific Research. It is a public institution that provides funding for the salaries of research positions and for scientific projects.
- FRIA* stands for *Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture*, Fund for Research Training in Industry and Agriculture. FRIA funds PhD projects that are related to natural science, life science, engineering science and agriculture.
- CAPAES* stands for *certificat d'aptitude pédagogique approprié à l'enseignement supérieur*, certificate of aptitude for teaching suited to higher education. It is the diploma obtained at the end of the training required for teaching in “Haute École”.
- AESS* stands for *agrégation de l’enseignement secondaire supérieur*, diploma in upper secondary education and AESI stands for a*grégation de l’enseignement secondaire inférieur*, diploma in lower secondary education. In Belgium, students go to secondary school from ages 12 to 18, which is subdivided into lower secondary education (ages 12-15) and upper secondary education (ages 15-18). Teachers willing to obtain the AESS* must have obtained a master’s degree and teachers willing to obtain the AESI* must have obtained a bachelor’s degree. CAP* stands for *certificat d’aptitudes pédagogiques*, certificate of teaching ability, which is the diploma appropriate for teachers that can prove they have experience in a discipline (e.g. a laboratory technician, for the course of chemistry) but have not passed the official AESS or AESI, so that they can get a definitive job status as a teacher.