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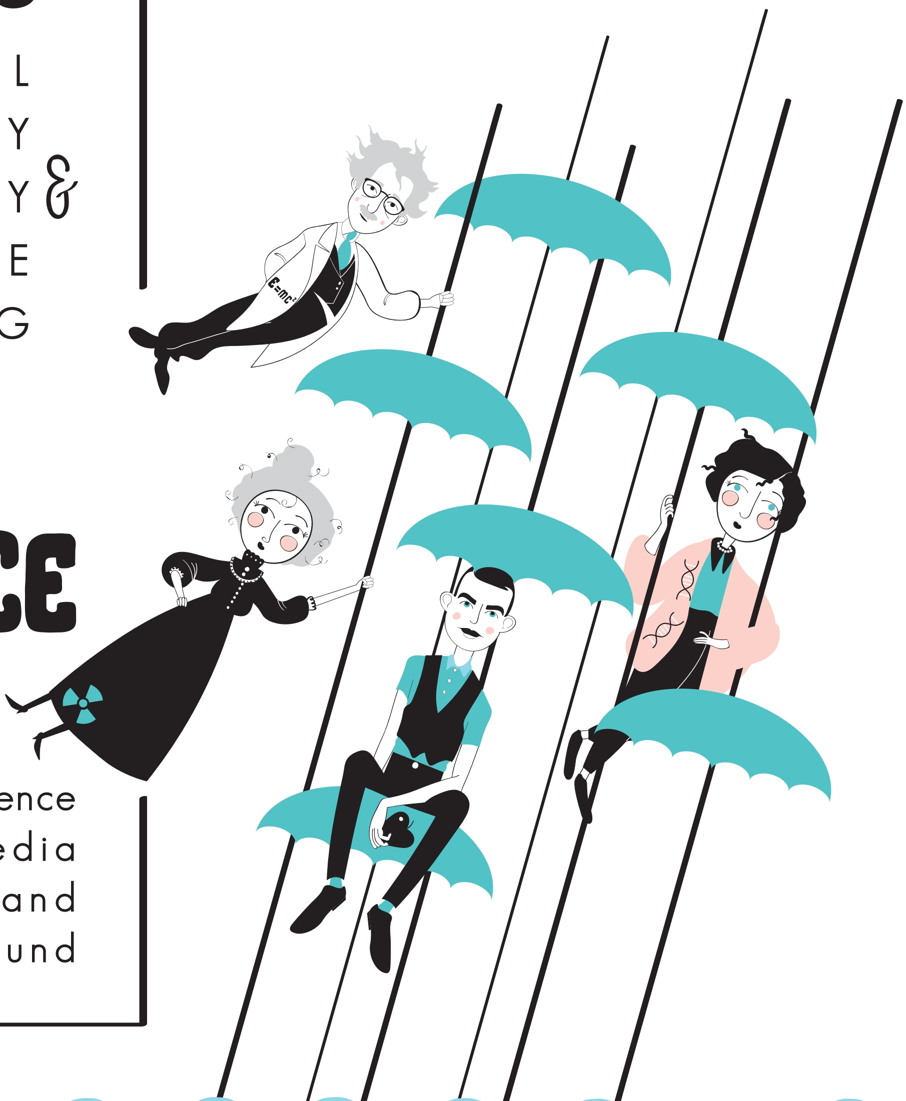

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Teaching and Learning of the First Thermodynamics Law: The Sufficiency of the Macroscopic Framework from an Epistemological and Didactical Perspective

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Abstract

This study refers to the distinction between the macroscopic and microscopic frameworks of thermodynamics and its impact on the teaching and learning of essential principles of the field, such as the conservation of energy through the first law of thermodynamics. We engage in an epistemological analysis and a cognitive approach in order to investigate the limits of the two frameworks and the outcomes of their conflation. From the viewpoint of epistemology, we present a historiographical analysis and also a textbook analysis reflecting the formation of the separate branches of classical and statistical thermodynamics. Through the approach of the cognitive aspect, we report the results from the recent body of research that implies that the blending of the two frameworks impedes the students' accurate interpretations of thermodynamic processes. On this account, we suggest that the macroscopic framework is sufficient for the teaching and learning of introductory level thermodynamics and we briefly present the design principles and results of a teaching and learning sequence for the first law of thermodynamics in upper secondary school students.

Introduction

Thermodynamics is a fundamental scientific topic, as it suggests a generic theory of energy that explains the differentiation between various forms of energy and specifies the conditions and the limits of physical phenomena and technical processes (Baehr, 1973). Therefore, it is customarily included in the secondary school curriculum and in several university courses in a variety of disciplines such as physics, engineering, chemistry and biology. One of the most essential aspects of introductory thermodynamics is the First Law of Thermodynamics (FLT), which represents the conservation of energy for thermodynamic systems and describes the qualitative and quantitative conversions between heat, work and change of the system's internal energy (Baehr, 1973).

Due to the importance of the topic for many experimental sciences, technical applications and scientific literacy for the modern citizen, students' understanding of the concepts of thermodynamics has been under investigation for several years (Kautz, Heron, Loverude, & McDermott, 2005; Kautz, Heron, Shaffer, & McDermott, 2005; Leinonen, Asikainen, & Hirvonen, 2012, 2013; Leinonen, Raesaenen, Asikainen, & Hirvonen, 2009; Meli, Koliopoulos, Lavidas, & Papalexiou, 2016; Meltzer, 2004). The relevant research indicates that students demonstrate numerous alternative frameworks in order to describe phenomena and processes related to the FLT. One prevailing category includes explanations related to the microscopic world. Although an expert can efficiently explain thermal phenomena with the use of microscopic models, the latters are severely distorted when included in the novice learners' explanations. In fact, micro-level descriptions appear to impede the students from obtaining an energy-related understanding of the thermodynamic processes, especially if they have been introduced prematurely (Leinonen et al., 2012; Meli et al., 2016). We elaborate on these aspects through the presentation of the results of two research works, one for upper secondary school level (Meli et al., 2016) and one for the beginning years of tertiary education (Kautz, Heron, Loverude, et al., 2005; Kautz, Heron, Shaffer, et al., 2005).

Since there is strong evidence in the literature that the students' cognitive needs call for a clear distinction between macroscopic and microscopic thermodynamics for the teaching and learning of the FLT, the question arises if the epistemology of the field would also support this choice. The epistemological perspective includes a historical analysis on the scientific facts that led to the FLT as well as the analysis of the textbooks as the knowledge of reference for this law. Therefore, in this study we report epistemological evidence and research outcomes from a cognitive perspective in order to support a macroscopic approach for the teaching and learning of the FLT at introductory levels. As an application of the above, we designed and implemented a relevant research-based Teaching and Learning Sequence (TLS) (Ruthven, Laborde, Leach, & Tiberghien, 2009) for upper secondary school students (16-17 years old). Among the other goals of the TLS, we investigated the transition between the macroscopic and microscopic frameworks they utilized and the sufficiency of the macroscopic approach for their explanations of the thermodynamic processes.

Epistemological analysis: historiographical report and textbooks' approaches of classical and statistical thermodynamics

The diversion from the research on the nature of heat

The distinction between "hot" and "cold" has been a recurring question since the very early stages of civilization. However, at the beginning of the era of scientific thinking and the industrial revolution, natural philosophers were concerned with the nature of heat, as the time had come for the latter to be exploited and therefore accurately measured. Two theories, that at that time appeared to be incompatible with each other, were troubling the emerging scientific community. The first theory perceived heat as a "subtle fluid" and developed into the "caloric theory". The roots of this conception can be found in the fire-like element called "phlogiston", which Antoine Lavoisier (1743-1794) replaced with a massless, non-visible fluid, present in all thermal phenomena. The second theory on the nature of heat focused on the motion of the smallest entities and it has been characterized as a "kinetic theory" (Cardwell, 1971). However, the micro-level structure was beyond reach for the thinkers of the 17th century. On the one hand, Daltonian chemistry, which introduced the atom with specific features, was not yet accepted, and, on the other hand, the energy theory that can efficiently interpret the motion of the atoms was established near the end of the 19th century. On this account, the kinetic theory was set aside, as dealing with motion within the unknown micro-world was considered to be a dubious scientific approach.

The obscurity of the nature of heat was not able to prevent physicists, engineers and other scientists from pursuing scientific knowledge and technological achievements. A characteristic, yet outstanding, example is that of Lavoisier, the father of the caloric theory, and Pierre-Simon Laplace (1749-1827), rather in favor of the kinetic theory, who successfully collaborated for a theory of heat that was beyond any assumptions on its nature (Cardwell, 1971). A substantial number of distinguished scientists made the same claim; for example, Jan Baptiste Joseph Fourier (1768-1830), Nicolas Léonard Sadi Carnot (1796–1832) and Rudolf Julius Emanuel Clausius (1822-1888) were among the experts on heat that did not perceive microscopic level explanations as essential for their research. As for instance, Clausius had a very specific view on the nature of heat: he believed that the particles of a body are constantly moving and heat was the magnitude of their "vis viva", namely their kinetic energy as it was perceived at that time period. However, he made a clear distinction between the nature of heat and the functional properties of heat, therefore he established his thermodynamic theory, that led to the formulation of the FLT, by setting aside the mysteries of the microscopic world (Harman, 1982).

By the end of the 18th century and during the 19th century, the focus had shifted from the nature of heat to the conservation of heat, followed by the conception of the heat-work equilibrium and finally the formation of the FLT. The road towards the conservation of energy was not paved with microscopic explanations, but rather with the conclusions deriving from the macroscopic features of a very large device; that was the steam engine, accompanied by the constant struggle for the improvement of its efficiency. As Cardwell (1971, p. 292) vividly mentions: "The sight of the primitive steam-engine tirelessly pumping ton after ton of water out of a mine, or of a crude early locomotive hauling a train of trucks along a rough, uneven railway-track, did more for science than all the speculation of the philosophers about the nature of heat since the world began".

The formulation of the macroscopic and the microscopic perspective

The elaborate research for the improvement of the steam engine led to the formulation of distinct knowledge of reference within the discipline of engineering, which utilized a different framework than the one of physics. University engineering textbooks, beginning from the late 19th century and up to this day (i.e. Baehr, 1973; Hirshfeld & Barnard, 1913), focus on the macroscopic properties of matter and especially in relation to the energy changes the working substances undergo. Therefore, they usually specify in their prologues that they deal with classical (macroscopic) thermodynamics.

On the other hand, thermal physics textbooks introduce statistical (microscopic) thermodynamics before the classical theory. Statistical thermodynamics was emerged during the 19th century, following the total acceptance of the Daltonian theory for the atoms and the establishment of energy theories. It has been developed through extended mathematical models that require specific expertise, even among scientists. However, significant scientific figures of that time period had reservations about the statistical direction of thermodynamics. For example, Max Planck (1858-1947) appeared to be

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skeptical, even opposed, towards the microscopic level approaches, as he mentions in the preface of his book *Treatise on Thermodynamics* that "obstacles… are due not only to the highly complicated mathematical treatment, but principally to essential difficulties… in the mechanical interpretation of the fundamental principles of Thermodynamics" (Planck, 1903, p. viii). In order to settle this rivalry between the two branches of thermodynamics, Josiah Willard Gibbs (1839-1903) proposed a compromise that included the formation of separate theories for macroscopic and microscopic thermodynamic properties of matter, when he wrote that "although, as a matter of history, statistical mechanics owes its origin to investigations in thermodynamics, it seems eminent worthy of an independent development, both on account of elegance and simplicity of its principles, and because it yields new results and places old truths in a new light in departments quite outside of thermodynamics" (Gibbs, 1902, p. viii).

However, a century later, the conflation of the frameworks in physics textbooks is still evident. As for instance, the university physics textbook *Sears and Zemansky's university physics: with modern physics* by Young & Freedman (2012) includes both macroscopic and microscopic approaches of thermodynamics in distinct chapters, as it is expected from a book with generic content. What can probably trouble the novice learner is the co-existence of the two contexts in the definition of a physical quantity or in the interpretation of a phenomenon. For example, within the chapter labeled "The First Law of Thermodynamics", which traditionally refers to the macroscopic dimension, one can find the definition of work done in a volume change: "We can understand the work done by a gas in a volume change by considering the molecules that make up the gas. When one such molecule collides with a stationary surface, it exerts a momentary force on the wall but does no work because the wall does not move" (Young & Freedman, 2012, p. 626). The obvious reference to the microscopic aspect can be disorientating, since the examined topic is expected to discuss the conservation of energy in macroscopic thermodynamics.

Cognitive analysis: Microscopic models as a source of conceptual impediment for explaining thermodynamic processes

Through the examination of the epistemology of thermodynamics it becomes apparent that the microscopic perspective did not play a crucial role in the development of the theories that led to the conservation of energy and the formulation of the FLT. Additionally, the microscopic and the macroscopic research approaches resulted in separate knowledge of reference for physics and engineering concerning thermodynamics. From a cognitive point of view, the conflation of these two frameworks causes numerous difficulties for a substantial percentage of upper secondary school students (e.g. Meli et al., 2016) and university beginners (e.g. Kautz, Heron, Loverude, et al., 2005; Leinonen et al., 2012; Loverude, Kautz, & Heron, 2002) when they deal with phenomena that require explanations in terms of energy.

The pertinent literature reveals that the above-mentioned samples in many cases attempt to involve microscopic models while trying to explain observed phenomena or tasks that involve variables that can be dealt with macroscopically. Although the microscopic framework can offer adequate explanations, its use suggests a complex endeavor that more often than not surmounts the students' knowledge level of thermal phenomena and thermodynamics. As a consequence, the students use this framework improperly, namely they ignore or misuse several variables (Rozier & Viennot, 1991), and therefore they fail to provide sufficient interpretations of the phenomena (Leinonen et al., 2009). Additionally, in this context they tend to include references to the chemical properties of the thermodynamic systems (Leinonen et al., 2009; Meli et al., 2016).

In the research of Meli et al. (2016) a sample of 54 students at the age of 16-17 are challenged to provide an explanation for the combustion of a small piece of cloth due to an adiabatic compression. They had followed a traditional instruction, as determined by the official physics curriculum, that included the kinetic theory of gases, followed by the introduction of thermodynamic processes explained through the laws of gases and, at last, the FLT. Microscopic-chemical models, on the one hand, was the most prevailing framework for the interpretation of the phenomenon at hand, since it was involved in the 29% of the recorded answers, provided by a discrete cluster of 21 students. The majority of these responses focus on the explanation of the combustion as a result of a temperature raise. This change in temperature is explained through the increase of the internal energy of the molecules and their collisions. Additionally, they sometimes refer to the existence of oxygen molecules and the related chemical reactions. On the other hand, only 17% of the responses included the FLT as an explanation framework and just 2% used it correctly. It is possible that upper secondary school students prefer microscopic explanations, since they feel more familiar with these than the newly introduced energy framework of the FLT. Furthermore, they may perceive the micro-level as the ultimate source of scientific interpretations for the macroscopic phenomena.

Microscopic explanations are also prevailing in the university students' samples (Kautz, Heron, Loverude, et al., 2005; Kautz, Heron, Shaffer, et al., 2005; Leinonen et al., 2012, 2013, 2009; Meltzer, 2004). We take for instance the work presented by Kautz, Heron, Loverude, et al. (2005) with a sample of 45 students that were enrolled or had completed the second quarter of an algebra-based physics course or the sophomore-level thermal physics course. The task was about the isobaric heating of a gas and called for explanations for the increase in both pressure and temperature. Among the physics and chemistry students, in average 20% responded that the change in pressure occurred due to the increased velocity of the molecules of the gas and their additional collisions with the walls of the gas container. The change in temperature was explained through the additional collisions between the molecules or the increase in the density of the gas. In the second part of this work (Kautz, Heron, Shaffer, et al., 2005), the researchers focus on the exploration of the students' micro-level interpretation and they come to the conclusion that these models are in some cases so severely faulty that impede the development of functional representations of essential concepts in the field of thermodynamics, including the conservation of energy and its expression through the FLT.

Cognitive-related choices with reference to the epistemological analysis: design and outcomes of a teaching and learning sequence

Considering the evidence that the epistemological and cognitive perspectives provide against the conflation of macroscopic and microscopic frameworks of thermodynamics, this study proposes the instruction of a well-defined classical thermodynamics sequence for the

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macroscopic qualitative and quantitative interpretations of phenomena, in advance of elements of statistical thermodynamics, according to the goals of the course. In our case study, we designed and implemented a research-based TLS for the second year of the Greek upper secondary school, in which the students are introduced for the first time to thermodynamics. The sample consisted of 19 students from a high school in Athens. The TLS consisted of 12 units and it was completed in 5 weeks.

The aim of the TLS is the introduction of the energy conservation in thermodynamic processes through the FLT. It includes several components complementary to the FTL, such as properties of the system, efficiency and cycles. Throughout the TLS, we examine Newcomen's steam engine and we focus on the gas in its motor as an example of a thermodynamic system. One of the prime aspects of this instruction is the exclusion of all microscopic viewpoints; definitions, interpretations of phenomena and mathematical expressions are dealt with at a purely macroscopic level, with special focus on the energy magnitudes and their interactions for the formation of the FLT. In our point of view, this is a sufficient approach for the teaching and learning of the FLT. The kinetic theory of gases, which suggests the microscopic approach in the physics curriculum of the upper secondary school, can be introduced to the students as a distinct further analysis, following the completion of macroscopic thermodynamics. This order in the instruction of thermodynamics is compatible with both epistemological and cognitive analysis and can untangle the conflation of the two frameworks, which is the source of many difficulties for the students.

Although there was no instruction related to the microscopic level up to the point the TLS was about to be implemented, the pre-test revealed that almost 20% of the students spontaneously utilized microscopic models to –incorrectly– interpret the distribution of energy in several thermodynamic processes (adiabatic, isothermal, isochoric and isobaric), in at least one of the nine written tasks they were given. In the post-test (same tasks as in the pre-test), a week after the completion of the TLS, none of the students made any references to the micro-level. In a very brief presentation of the students' answers in the post-test, depending on the task, 47.4%-89.5% of the responses were correct and all of them had statistically significant difference ($p<0.05$) in comparison to the pre-test. It was evident by the students explanations that their restriction within a specific framework, which is compatible with the epistemology of the field and the students' conceptual capabilities, allowed them to construct solid representations for the related phenomena and the FLT. These results verify our initial decision to completely avoid the conflation of the two frameworks throughout the design and the implementation of the TLS.

Discussion

In this study we attempt to support the sufficiency of the macroscopic framework for the teaching and learning of introductory thermodynamics and particularly the FLT. On this account, we especially discuss the unnecessary, from our point of view, conflation of the macroscopic and the microscopic framework of the field. In order to reinforce our perspective, we present a short epistemological analysis for the development of early thermodynamics, which includes historiographical elements and examination of selected textbooks as the knowledge of reference. In addition, we discuss the cognitive issues that have come to light through the recent works in upper secondary school students and

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university beginners. Finally, we very briefly present part of the design and the pertinent results of a TLS on the FLT, with a small sample of 16-17 year old students.

A timeline of early thermodynamics, beginning from the 17^{th} century, reveals that the original focus of the preliminary research was rotating about the nature of heat, but soon enough these concerns became irrelevant to the rapidly growing discoveries on the functional properties of heat that were enhanced by the continuous improvements of the primitive steam engine. Many prominent scientists set the microscopic interpretation of heat aside, as they had put their effort in the clarification of the conservation principles underlying a thermodynamic system. By the mid 19^{th} century the body of classical (macroscopic) thermodynamics had been formed at large and a distinct branch, that of statistical (microscopic) thermodynamics had started to develop at quick pace. The relevant textbooks depicted the newly acquired knowledge accordingly: the disciple of engineering focused on the macroscopic properties of thermal phenomena that were relevant to the function of the engines, while in physics both frameworks were integrated in the knowledge of reference of the field. However, this separation is not always clear and there are cases of conflation in physics textbooks that can disorientate the novice learner.

In addition to the above, there is a growing body of research investigating the alternative frameworks that the young students (upper secondary school and first years of university) utilize instead of the appropriate application of the FTL. The results indicate a very specific issue with the students' unsuccessful attempts to incorporate microscopic aspects in their explanations of various thermodynamic processes and the application of the FLT. This cognitive aspect, along with the evidence deriving from the epistemology of the field, suggests, in our opinion, that the instruction of introductory thermodynamics should have a clear focus regarding the framework it introduces to the students. Keeping in mind that the microscopic models demand a high level of expertise in order to be correctly handled, we chose to design and implement a TLS for the FLT that employs a strictly macroscopic approach. The results were very encouraging, in the sense that many students made the transition between the erroneous microscopic (or other) explanations towards sufficient interpretations of the thermodynamic processes through the principle of the conservation of energy. Therefore, since the students are confronted with several conceptual difficulties while dealing with microscopic models and the latters do not suggest a necessary or a sufficient condition for the teaching and learning of the FLT, there is no justification for the conflation of classical and statistical thermodynamics in the instruction of thermodynamics at introductory levels; on the contrary, the restriction in the macroscopic framework appears to be very promising for eminent results.

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