Energy, Energy Degradation and Entropy: Conflicting Views of These Concepts in the Teaching of Thermal Phenomena

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Abstract. This symposium will look at the difficult concepts of energy and entropy and examine different approaches for addressing them in the teaching of thermal phenomena. The law of conservation of energy is one of the most important laws in classical physics, but the common conception of the Second Law as the law of increasing entropy would suggest to some that entropy is the more important quantity. The first presentation will examine the nature of entropy, the second will address experts' views regarding energy, and the following two will present examples of different approaches to teaching energy at different levels.

Introduction

Energy and entropy are both difficult concepts to grasp and therefore to teach. At the school level, the emphasis is on energy and its transformation from one form to another, together with the associated ideas of dissipation or degradation, and energy conservation. In the age of global warming, when energy and its efficient use from different sources, and basic thermodynamic ideas like the conversion of heat to work in heat pumps, form part of everyday conversation, it is essential that students not only leave school with a good grasp of basic ideas, but also that they are also prepared for further study at a deeper level.

Within higher education, the emphasis is on thermodynamics, which is commonly perceived to be a difficult subject to learn. Considering the contradictions inherent in the subject, it is perhaps not surprising. For example, a practical work process can be approximated to adiabatic if it occurs fast enough to limit the flow of heat into or out of the system, but the ideal adiabatic process is assumed to occur quasi-statically. No matter how thermally resistive the walls of a system might be, heat will flow over a long period of time, making the idea of a quasi-static, adiabatic work process seem like a contradiction. Likewise, an ideal engine is also assumed to operate quasi-statically, but a quasi-static engine cannot develop power and therefore can serve no useful function.

These difficulties stem from the modern interpretation of a reversible process, which is very closely linked to accepted ideas about energy dissipation and thermodynamic entropy. The modern idea of reversibility was first enunciated by Clausius, who developed the version of the Second Law of thermodynamics pertaining to increasing entropy in irreversible, but non-cyclic processes, and later promoted by Planck, whose Treatise on Thermodynamics [1] closely followed Clausius.

What is perhaps not so commonly appreciated is that there was a different view of reversibility related to cyclic processes at the time that Clausius was writing. In describing an ideal engine, Carnot wrote as if the cycle itself should be reversible, though he never explicitly stated as much, and Thomson, later Kelvin, also wrote about the reversibility of the cycle. In fact, Kelvin was not concerned with isolated work processes, only with cyclic processes, and framed his famous statement of the Second Law [2] in terms of such cyclic processes. Clausius also framed an earlier version of the Second Law applicable to cyclic processes [2] and both statements are concerned with energy in the form of heat and work. As such, they place both energy and cyclic processes at the heart of thermodynamics.

This symposium will address the teaching of energy, its transformation and dissipation and its connection to entropy and the laws of thermodynamics.

The symposium

Organised under the auspices of the GIREP Thematic Group on thermodynamics and energy, this symposium addresses a fundamental question as to the place of energy, energy degradation and entropy within the teaching of thermal phenomena. The symposium will be introduced by the distinguished physics educator, Professor Paula Heron, of the University of Washington, who will also moderate the discussion following the presentations. Professor Heron has researched the teaching of energy and thermodynamics in the past and until this year led the GIREP Thematic Group on Energy. There will be four contributions to the symposium.

1) **The nature of entropy: Clausius's conception and its consequences for thermodynamics**. Dr David Sands will outline the case against making entropy central to teaching thermodynamics by discussing the nature of entropy and in particular Clausius's thinking. He will show that not only is this outdated, but it is also flawed. He will argue that a revision of the concept of entropy and its place in the thermodynamics curriculum is required.
2) **Starting from the Top: Conceptualization of Energy by high-level experts in Science and Science Education**. The group of Professor Yaron Lehavi will describe their work on how experts in science and science education conceptualize different aspects of energy. They will argue that common conceptions can assist in refining curricula and enhancing teachers' pedagogical content knowledge.
3) **Approaching thermal phenomena from a thermodynamic perspective.** Professor Marisa Michelini will present her group's development of research-based didactic paths for teaching thermal phenomena and present the results of a long study in primary school and a shorter intervention at 16 years of age.
4) **Visualizing the Transition of Energy from Macroscopic to Internal: Can Simulations of Bouncing Solids do the Trick?** Professor Edit Yerushelmi will present a collaboration on the use of a novel 2-dimensional particles-and-springs simulation of a bouncing solid on middle-school physics teachers in professional development workshops. This simulation depicts the irreversible transformation of macroscopic mechanical energy into internal energy as the solid comes to rest.

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The nature of entropy: Clausius's conception and its consequences for thermodynamics.

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Abstract. The modern conception of entropy is examined in this presentation through an historical analysis of Clausius's thinking behind the concept. It will be shown that Clausius's view of heat as a property of a body has directly influenced notions about entropy today, particularly the idea that entropy increases in an irreversible process. However, this also conflicts with the First Law of thermodynamics and the connection between entropy increase and energy conservation will be examined. It will be argued that energy conservation is paramount and that energy, rather than entropy, is the central principle.

Entropy and its connection to energy

It is commonly recognized that entropy is not only one of the most confusing topics in thermodynamics, but arguably it is also one of the most confusing, and certainly one of the most enigmatic, concepts in physics. The essential difficulty is that there are different definitions of the concept that are often used interchangeably, but not all of which lend themselves to simple conceptual interpretations. Haglund, for example, has identified five common conceptions of entropy amongst undergraduate students [1], among which the idea of disorder is prominent.

It is not clear how the association of entropy with disorder arose. There are simply far too many papers to cite, but attention can usefully be drawn to the excellent and comprehensive guide to the topic written by Frigg and Werndl [2]. These authors discuss the different definitions and attempt to draw out the relationships between them. They make it very clear that the thermodynamic entropy has "*no intuitive interpretation as a measure of disorder, disorganisation or randomness (as often claimed). In fact such considerations have no place in TD [thermodynamics]*". In relation to statistical definitions, they stress that for the connections between the Gibbs and the Boltzmann entropy to hold, it is "*crucial that the particles are identical and noninteracting*" and that, "*It is unclear whether the conclusions hold if these assumptions are relaxed*". These authors conclude that, "… *there is no preferred interpretation of the probabilities that figure in the different notions of entropy*" and went on to add that "… *when considering the relation between entropy and probability [there] are no simple and general answers, and a careful case by case analysis is the only way forward*".

In light of the multiplicity of different forms and interpretations of entropy, as well as the lack of a simple general equivalence between the statistical and thermodynamic forms, it is perhaps not surprising that there exists a great deal of confusion around the topic. It is possible even that there is no single, universally acceptable definition that is conceptually easy to grasp and therefore appropriate to teach.

The author's own experience of the inconsistencies within thermodynamics, and entropy in particular, has led him to research the foundations of the concept by Clausius in the 19th century [3]. These researches have led to the conclusion that most of the difficulties with the concept of entropy can be traced to the idea that entropy is a property of a body. This view arose with Clausius and has been carried down to the modern day through the works of Planck [4].

To the author's knowledge, the question as to whether this is an appropriate conception of entropy is rarely, if ever, asked, but there is nothing within the theory of thermodynamics that requires entropy to be a property of a body. Entropy enters thermodynamics through the flow of heat and logically should be connected with heat flow. However, Clausius held the view, common at that time, that heat was a property of a body and although modern thermodynamics defines heat differently, as an exchange of energy according to the First Law, there was no corresponding revision of the concept of entropy.

A direct consequence of treating entropy as a property of a body, however, is that entropy must increase in an irreversible process. Yet, without a clear conception of the meaning of thermodynamic entropy and a clear, general conception of the link between statistical and thermodynamic entropies, we do not have a clear idea of just what it is that is increasing, the mechanism causing the increase, or indeed the effect of the increase. Moreover, the idea of entropy increasing in irreversible processes breaks the connection between entropy and heat flow. In an irreversible adiabatic process, entropy will increase even though there is no heat.

This is represented by the famous inequality of irreversible thermodynamics:

$$TdS \geq dQ \tag{1}$$

In the author's view, this equation is problematic. As heat is defined by the First Law, $dQ = dU - dW$, it implies that some property of the body with the units of energy, namely *TdS*, is increasing in a way that is not controlled by the First Law of thermodynamics. The relationship between entropy and energy is therefore central to any discussion of the teaching of thermodynamics. In this presentation, the author will examine Clausius's thinking behind the concept of entropy and show not only why he considered it to be a property of a body, but also the consequences of that idea for modern thermodynamics. He will explore the relationship between the concept of entropy increase and the First Law of thermodynamics and discuss recent work which sheds light on the nature of reversibility [5] as well as the connection between statistical and thermodynamic entropies [6] with a view to arguing that energy, rather than entropy, should be central to the teaching of thermodynamics.

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Starting from the Top: Conceptualization of Energy by high-level experts in Science and Science Education

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Abstract. The concept of energy is fundamental across sciences and science education curricula, yet lacks a consensus regarding the meaning of many of its features. This study delves into top-level experts in different domains in science and science education conceptualizations of energy and related concepts and examines a possible consensus or disparities among them. Through qualitative methodology and thematic analysis of the experts' interviews, shared classifications emerged. Four primary concepts—energy conservation, forms, transitions, and manifestations—were identified. Our findings can assist in refining curricula and enhancing teachers' pedagogical content knowledge, bridging gaps between student and expert understanding.

Introduction

The concept of energy is one of the most fundamental and unifying ideas across the natural sciences as well as across the curricula of science education programs. Despite its importance, however, there is no curricular consensus with regard to the definition of energy and the meaning of concepts related to it such as energy conservation, transfer or transformation [1-3]. Moreover, there is evidence that researchers from different scientific disciplines utilize differently energy considerations, apparently limiting its interdisciplinary nature [7]. Although alternative instructional approaches to teach energy and address these challenges were suggested in the past [1, 4-6], a deep drill-down into high-level experts in science and science education conceptualization of energy is required for a coherent and valid curriculum and teachers' PCK enhancement.

Research question

How do high-level science and science education experts conceptualize energy, including related concepts such as energy conservation, transfer, transformation, and forms, and what similarities, dissimilarities, and inner structures can be observed in their conceptualizations?

Method

This study utilizes qualitative methodology to examine scientists’ perceptions of various aspects related to the concept of energy [8]. We applied thematic analysis to the transcriptions of 8 semi-structured in-depth interviews of high-level experts from a wide range of disciplines in science and science education research. Open coding of the data was performed to identify and categorize salient patterns and themes, followed by an in-depth analysis of the central themes that emerged from the interviews. The coding underwent peer validation by the authors and an independent validator.

Findings

In analysing the interviews, we directed our focus towards identifying shared classifications pertaining to the notion of energy. Our analysis has revealed shared categories among the experts connected to the concept of energy. These categories were related to energy definition, its empirical, theoretical, historical and philosophical ground, its measurability, its (classic) relativistic nature and its relations to other physical theories (e.g. entropy or special relativity). Some subcategories were related to the use of energy in analysing processes and systems, while others to the teaching of science in general.

Conclusions

Our findings unveil the components that comprise the concept of energy as perceived by science and science education experts. Addressing these perspectives can refine science curricula frameworks and standards, and support programs focused on enhancing teachers' coherent pedagogical content knowledge about energy from a scientific aspect, a philosophical and historical aspect and a didactics aspect. This has the potential to narrow the gap between students' and experts' understanding.

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Approaching thermal phenomena from a thermodynamic perspective

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Abstract. The interpretation of thermal phenomena represents an obstacle at all ages and becomes an even greater problem at the university level for the study of thermodynamics. A wide PER literature has shown that many learning problems arise from unclear ideas and non-epistemic ontologies of temperature, heat and the first law of thermodynamics. With a research methodology based on a series of research-based implementations of conceptual proposals, we have developed an ICT-based path on thermal concepts. Here we present the didactic path and the result of a lengthy study in primary school and a shorter intervention at 16 years of age.

Introduction and aims

Thermal phenomena are common in everyday life and are among the first, and most important, experiences for children. Therefore, they constitute one of the most important topics in scientific education from kindergarten to university. It is not surprising, therefore, that they are part of studies on the Piagetian development of children [1] and on the first research on the subject from the same period [2]. The students' ontology of heat as a substance that emerged in these Canadian studies has been found in the ideas of children in France [3], England [4], Italy [5] and others [6]. The calorimetric approach and the belief that an early fluid model of heat, following the first historical interpretative ideas, was more natural has guided many didactic proposals and practice for years. More than 200 studies have shown that such interpretative models remain and persist in parallel with, or in conflict with, other interpretative proposals up to higher school levels [7, 8], creating problems in the understanding of thermodynamics that are still open today [9]. The possibility of offering real-time temperature measurements in teaching activities by means of on-line sensors with computers, which we have been implementing since 1990 [10], has led us to develop a didactic proposal on thermal phenomena with a thermodynamic approach, which we have also implemented with children of the kindergarten [11]. In this paper we present the path proposal developed as a result of many experiments in recent years and the evidence for the development of formal thinking and the conceptual gain for a correct physics competence in interpreting thermal phenomena.

Theoretical framework and research

Following the Model of Educational Recontruction [12] and an Inquiry Based Learning approach [13, 14] we have developed a research methodology [15] for conceptual path proposals based on a series of research-based implementations. One is for a vertical path on interpreting thermal phenomena from a thermodynamic perspective. It aims at the appreciation of the concepts of state and its transformation in thermal interactions, leaving learners free to follow their own trajectories to understand the verbs to feel, to be, to become, and to keep warm. The concepts of thermal equilibrium and temperature are merged. Different thermal interactions are examined and, through the examination of the graphs of the temporal evolution of temperature, thermal interactions between homogeneous and non-homogeneous systems, heating, change of physical state and thermal conductivity are described, conquering the physical meaning of the first law of thermodynamics. The research questions are:

1. How do students appropriate the concepts of temperature and heat in the path proposed with their chosen approach?
2. How do they construct formal thinking and how do they use it to interpret phenomena?
3. How do they use the concepts they learn to discuss common unexplored thermal phenomena?

Findings

The analysis of the results of a research based implementation, which was monitored for each conceptual step and conducted with a parallel control class in primary school [16] and a recent experiment with 16-year-old students have confirmed that children appropriate the concept of temperature as a state of thermal equilibrium (RQ1) and manage with mastery and coherence with discipline the terms of, *to feel*, *to be*, *to become*, and *to keep warm* (RQ3). By designing experiments, primary students learn to write Fourier's law of thermal equilibrium and the fundamental law of thermodynamics (RQ2). They interpret phenomena by thinking of heat as a process associated with a system becoming hot and temperature as a state of equilibrium (RQ3).

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Visualizing the Transition of Energy from Macroscopic to Internal: Can Simulations of Bouncing Solids do the Trick?

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Abstract. Secondary school physics commonly require students to identify energy forms and their transformations in mechanical phenomena (e.g. bouncing ball) to reinforce energy conservation. However, in most cases, energy is dissipated, and students and teachers have difficulty reasoning quantitatively on these transitions. We developed a novel 2-dimensional particles-and-springs simulation of a bouncing solid, depicting the transformation of macroscopic mechanical energy into internal energy as the solid comes to rest, as well as accompanying instructional module guiding students in exploring the dependence of irreversibility on the number of particles. We report middle-school physics teachers experience with the module in professional development workshops

Rationale, Theoretical Framework and Research Goals

Middle school physics curricula often emphasize the presentation of the various forms of energy and the transformation between them, in order to reinforce the concept of energy conservation [1]. However, in macroscopic everyday mechanical phenomena that serve in school experiments and demonstrations (e.g., a bouncing ball or a swinging pendulum), energy is lost over time. Students and teachers alike commonly rationalize this energy loss as heat dissipated into the environment. The dissipation is rarely coordinated quantitatively with conservation and the mechanism of transition to internal energy is often overlooked [2]. There are various approaches to address these challenges. For example, the calorimetric approach [3] quantifies changes in energy through the measurable change in temperature generated in a standard body in various processes. However, this approach does not clarify the mechanism of transition of macroscopic to internal energy.

Physical models and computer simulations that demonstrate the particle nature of matter can serve to bridge the micro-macro gap. For example, a cart with metal rings attached to a wooden framework with rubber bands has proven to be an effective physical model in illustrating the transformation of macroscopic energy into internal motion after collision with a wall to college students taking physics [2]. A particles-and-spring computational model of a solid has proved productive to bridge between microscopic mechanical energy and thermal energy in college level introductory courses [4]. Such models allow visualize internal energy as the sum of the particles' mechanical energies (potential and kinetic) and the process of dissipation as the spread of energy. However, the physical cart model is not quantitative while the computational model does not demonstrate how macroscopic mechanical energy transitions to internal microscopic energy. These models motivated us to construct a module that combines the cart model with a novel computational model of a solid bouncing on a hard surface. We aim to focus on energy concepts as well as on simplification assumptions underlying the models.

We report the research-based design of the instructional module. Two versions of the module incorporating different scaffolds were employed in five professional development workshops for middle school teachers. We studied the perceptions of workshop participants: what are the main messages they identified? How can they adapt it for teaching energy in their classrooms?

Methods and Findings

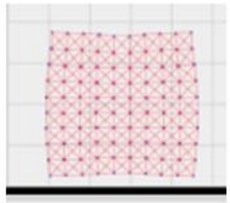

Fig. 1 The bouncing solid model

The computational model involved a two-dimensional bouncing solid, with particles interconnected by ideal springs (see Figure 1). The dynamics follows Newton's laws leading to exact conservation of the total energy. The fluctuations between macroscopic mechanical energy, observable through variables such as the solid's height above ground and its velocity, and internal energy, evident in the random particle movements within the solid were depicted graphically. In the workshop, the teachers first examined a video of the physical cart model and later interacted with the computational model, while working in groups on worksheets that scaffoleded the intended conceptual framework (e.g. the demonstration of conservation of energy by combining macroscopic mechanical energies and internal microscopic energies; the time arrow - irreversibility evident in the macroscopic phenomena that emerges as one increase number of particles. The two versions of the module differed in the structuring and problematizing mechanisms for scaffolding learners in these challenging tasks [5] in aspects such as the numerical and graphical displays, the exposure of the computational engine, and the comparison of the computational model to the physical one. The 8 hour module was implemented as part of a 30 hour yearlong professional learning community for middle school physics teachers. A total of 50 teachers experienced the module in 5 different communities. Semi-structured interviews were carried out with two teachers and two community leaders after the implementation of each version (Total of 8 interviewees).

In both versions, teachers were highly engaged. Analysis of the interviews following the first version highlighted the challenging cognitive demands involved in the module and led us to simplify the interface of the computational model significantly. In particular, hiding the computational engine that was initially accessible. On the other hand, problematization prompts were added to the module worksheets to highlight the novelty of central conceptual messages. We show that the 2nd version improved in facilitating connections between macroscopic mechanical and internal energy concepts.

Conclusions

We have developed an instructional module that effectively addresses the challenging concept of the transition from macroscopic to microscopic energy using a physical and computational model of solids bouncing from a surface. Implementation of the module in professional learning communities for middle school physics teachers gained positive responses. Future research will investigate if and how teachers can integrate this educational tool effectively and confidently into their classrooms.

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