Science & Education **11:** 279–291, 2002.

Difficulties in Learning Thermodynamic Concepts: Are They Linked to the Historical Development of this Field?

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Abstract. Students' misunderstanding of basic thermodynamic concepts is analysed on historical grounds. The persistence of some ideas from the caloric model are found to be reinforced by magnitude names and unit definitions that were brought up at the early stages of thermodynamic development. The failure of many popular textbooks to make a clear distinction between internal energy and heat is also explored and related to students' learning difficulties. Some hints that may help to improve students' understanding are presented.

1. Introduction

During the last five years we have monitored our students' literacy in thermodynamics after using different didactic approaches to improve their conceptual understanding (Bordogna et al. 2000).

To develop our teaching strategies we have taken account of the results of other researchers in physics education (Barrow 1988; Hierrezuelo et al. 1988; Leff et al. 1993; Alonso et al. 1995a) who have traced students' understanding of thermodynamic fundamental magnitudes. Some results indicate that scientific terms such as 'heat' and 'energy' are confused, in popular textbooks, with everyday language semantics and with common-sense knowledge. This situation retards and misleads the students' understanding of thermodynamic concepts. It has also been found that the persistence of misconceptions could be related to students' previous ideas (Viennot 1998, and references therein), which in turn may be paralleled with the evolution of scientific knowledge.

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To evaluate the results of our teaching strategies we designed some ad-hoc instruments. We did not find as much conceptual learning as we expected (Bordogna et al. 2000). This finding lead us to follow Tarsitani and Vicentini Missoni (1990): "…the knowledge of the history of science is useful at the very start of the didactic analysis …". Hence, we focused our investigation on the evolution and present state of teaching and knowledge concerning internal energy. This concept seems to be the most controversial in the literature, and one of the most difficult for students to grasp. Therefore, we thought that learning about its origin and evolution, as well as the ways it is presented and treated by different textbooks, mainly during the last years, would help us uncover hidden conceptual schemes not only in our students but also in scientists and teachers.

We report some of our findings related to the difficulties students have in understanding the internal energy concept. We also describe the failures and achievements from the ancient theories to today's statement of the First Law of Thermodynamics. In this description we include a brief discussion of the usual textbooks' recent editions of the related topics. From this review of the internal energy concept in the literature we suggest some ways to improve students' understanding of thermodynamics.

2. Students' Difficulties in Understanding Internal Energy

Several researchers have reported difficulties in the learning of basic thermodynamic concepts. Erickson (1985) and Tiberghien (1985), for example, have reviewed children's intuitive ideas about temperature and heat. Having detected similar problems in our students, we tried to follow up their learning through different assessment tools. In one of these studies (Bordogna et al. 2000) more than 500 students from Science and Engineering courses were given a written test with statements about energy, work and heat that they had to evaluate as right or wrong. More than 80% of the surveyed students were sure that the statements "heat is a form of energy" and "heat can be transmitted", were right, suggesting a confusion between heat and energy.

In the present article we show initial results from the recorded interviews of thirty-one volunteers from Science and Engineering courses in their third year of study, two years after taking basic thermodynamics in an Introductory Physics course. They were asked to analyse the following situation:

> *Two inclined planes, made of an insulating material, are initially at 0 °C. A metal (or, alternatively, wooden) block is sliding along one of them while an ice cube, of the same mass as the block, is sliding along the other plane. If the ice cube melts while sliding and the systems are thermally insulated, which energetic processes are involved in both situations within a thermodynamic framework?.*

This situation was designed to detect: (1) the capability of students to identify and model the systems; (2) the way basic thermodynamic concepts such as work, energy and heat had been used and (3) the language employed.

Only one student used the First Law of Thermodynamics to examine or explain the phenomena. *Heat* appeared as the central "tool" to perform the thermodynamic analysis. Heat was included directly or as a mediator between work due to friction and change in internal energy. Many students said that heat was a form of energy while others extrapolated the ideal gas model to the ice cube or wooden block without caring about their physical state. The most common confusion detected was between heat and internal energy (some responses are included in Appendix 1) in agreement with our previous findings.

We wondered about the causes for the persistence of such confusion in spite of our personal efforts to teach it properly over many years. As a first step to get an answer, we analysed the historical origin of the internal energy concept and the way the First Law of Thermodynamics was initially stated.

3. From Heat to the Internal Energy Concept: The First Explanations on Heat

Aristotle's cosmology (384–322 BC) included the concept of "fire" as one of the four basic "elements" of nature, first described by Empedocles (490–430 BC), the other three being "earth", "water" and "air". According to Holton and Brush (1984) the Greeks also introduced a conceptual scheme for heat: it was a special substance, not perceptible, easily diffused between bodies and possibly carrying weight. This model explained some observations, including thermal equilibrium. By the end of the 18th century, a structured caloric theory appeared. The Greek heat had become a subtle imponderable fluid. At about the same time, another school of thought was emerging. It introduced a mechanical model describing heat as related to the motion of particles inside hot bodies (Brush 1976; Holton & Brush 1984). Heat was the central concept to be analysed in thermal phenomena.

During the 17th and 18th centuries the scientific community considered light and heat as identical: a theory answering "what is light?" would also answer "what is heat?". In the early 19th century this principle reinforced the caloric theory because light was considered a substance. But the consolidation of the wave theory of light by 1830 made scientists think about a possible wave theory of heat, which would provide a smooth transition from the caloric theory to the later developments of William Thomson (Lord Kelvin) and Clausius (Brush 1976; Brush 1983). The change from the caloric theory to the wave theory of heat was not difficult since many of the properties of caloric could be attributed to ether. This idea agreed with the 19th century scientists' desire for unity: only one imponderable fluid was needed instead of two (Brush 1976).

In the caloric theory, the temperature of a body was associated with the density or tension of the free caloric fluid held by it. In some conditions, the temperature of a body did not change though it seemed that heat was flowing into it. Black (1728–1799) tried to explain this finding by cleverly proposing that the caloric fluid could be inside the matter. It could be either in the interior of the molecules, where the thermometer could not detect it (this form of heat was called latent heat), or in the intermolecular space, where it could go from the body to the thermometer (this form was called *sensitive heat*) (Holton & Brush 1984). Though this classification was afterwards discarded, some terms like latent heat are still in use.

The caloric theory was also questioned after Count Rumford's (Benjamin Thompson) famous cannon-boring experiments in 1798[1] which were the first quantitative study to relate work and heat. They were followed by Sir Humphry Davy's (1799) ice-rubbing experiments[2] (two pieces of ice melted at constant temperature). In both experiments heat was not conserved, as the caloric theory stated. Both Rumford's and Davy's experiments showed that movement and heat were related. Though these experiments were not considered crucial, they had not been thoroughly explained. From then on the mechanical model of heat (associated with some kind of movement) began to be accepted. Though the decline of the caloric theory was accelerated by the acceptance of the wave theory of light and by the increasing success of the kinetic theory, it did not disappear completely: some of its nomenclature remains in use today, generating misunderstandings and ambiguities (Brush 1983).

4. Appearance and Evolution of the Energy Concept

The slow decline of the caloric theory paralleled the emergence of a modern scientific concept, *energy*, which was introduced by Thomas Young in 1807 (Gauld 1998). By the middle of the 19th century, the quantitative measurements made by Joule, Mayer, and others established a clear relationship between heat, work, and energy (Holton & Brush 1984). Finally, in 1847, Helmholtz generalised the principle of conservation of energy into a universal law of nature that later came to be known as the First Law of Thermodynamics.[3] It is not clear whether the internal energy concept was suggested for the first time in 1847 by Helmholtz or in 1850 by Clausius (Baylin 1985; Tarsitani 1991; Çengel & Boles 1994) though it was surely used by Lord Kelvin in his articles of 1852 (Baylin 1985).

It must be remembered that Clausius kept heat and work at the centre of his thinking (Monleón Pradás 1990; Ulises Moulines 1990) but with a superposition of the concepts of heat and what we now call internal energy.[4] He was aware of Joule's experiments on the relationship between heat and work in different processes (mechanical, chemical, electrical, etc., ways of obtaining equivalent thermal effects on a system). Then, he tried to develop an application of the energy conservation principle to the interconversion of heat and mechanical work (Brush 1983). For a derivation of the relationship between heat and work similar to that of Clausius, which helps to the identification of the internal energy concept, we refer to Tarsitani's work (1991).

Clausius began by considering that the heat given to a body should be converted into sensitive heat (responsible for the system's temperature increase) and into latent heat (heat "consumed" in body dilatation) that is work production. This work could be: (1) internal work, necessary to overcome the intermolecular attraction and/or (2) external work, done by the system on the surroundings (see Appendix 2). External work depends on the kind of transformation experienced by the system (it does not depend on the heat given to it) while internal work depends on the system's internal structure. By adding the sensitive heat to the internal work, Clausius obtained a quantity independent of the transformation experienced by the system, depending only on its initial and final states. He thus introduced a state function which would later be called internal energy (U) (Tarsitani 1991; Çengel & Boles 1994)

$$U = L_{\text{int}} + Q_s, \tag{1}$$

where L_{int} is the internal work and Q_s the sensitive heat. A change in the system's state would induce a variation in this U function.

Then, when an amount of energy is given as heat (Q) to the body, an external work can be produced (L_{ext}) together with a change in the state of the system (ΔU). The relationship between the three magnitudes can be expressed as:

$$Q = L_{\text{ext}} + \Delta U. \tag{2}$$

In Equation (2) L_{ext} represents external work, i.e., the work done against an external pressure. This equation resembles the known expression for the First Law of Thermodynamics.

5. The First Law of Thermodynamics

Today we know that the internal energy is a state function that includes the electronic, vibrational, rotational, and translational energies of the molecules, the relativistic energy of the rest mass of electrons and nuclei, and the potential energy of the interactions between atoms and molecules. We should therefore express the energy E of a system as:

$$E = K + V + U, \tag{3}$$

where K is the body's macroscopic kinetic energy, V its macroscopic potential energy and U its internal energy. If the body is at rest and its interaction with external fields can be neglected, the energy will consist of only one term: the internal energy. Its change should then be produced either by exchange of energy with the surroundings by mechanical work (w) or by means of other processes at play when the system's temperature differs from that of the surrounding. The latter processes are called heat (q).

Table I. List of books reviewed

Resnick, R.; Halliday, D. & Krane, K.: 1993, *Física*, Vol. 1.
Tipler, P.: 1993, *Física*, Vol. 1.
Serway, R.: 1998, *Física*, Vol 1.
Giancoli, D.: 1994, *Física. Principios con Aplicaciones.*
Gettys, W.; Keller, F. & Skove, M.: 1991, *Física clásica y moderna.*
Alonso, M. & Finn, E.: 1995, *Física.*
Hewitt, P.: 1995, *Física Conceptual.*

Therefore, expression (2) can be rewritten as:

$$\Delta U = q - w, \tag{4}$$

where w stands for L_{ext} and q for Q. As q and w measure the transferred energy they must be expressed in the same units used for energy.

In Equation (4) emphasis is placed on the change in internal energy through two equivalent processes, work and heat, which are linked to external actions and are not state functions.

It should be remarked that only after Gibbs' papers of 1876 and 1878 internal energy and entropy came to be the fundamental concepts in thermodynamics (Ulises Moulines 1990). In Clausius' equation (2) instead, the central concept was heat according to the concepts' historical development (Ulises Moulines 1990; Tarsitani 1991). Many of our students' answers closely resemble this stage of the development of thermodynamic concepts (see Appendix 1). The same parallel is found in some textbooks' treatment of related topics.

6. Tracking Textbooks' Presentation and Treatment of Thermodynamic Concepts

Vázquez Díaz (1987) found that only the P.S.S.C. book (1966) made a clear and proper treatment of heat. Michinel Machado et al. (1994) published a study of the most popular textbooks used in Venezuela. The analysed books were the Spanish translations of widely used American textbooks written mainly in the 1980s. Michinel Machado and coworkers found that the way in which most of the books introduce or treat the concepts of work, energy, and heat were incorrect or confusing. Since most of the textbooks reviewed at that time have published new revised editions, we decided to check whether recent research in physics education has improved the presentation of thermodynamics. The analysed books, all in their Spanish editions, are listed in Table I.

We found that the differences between quantities such as heat and internal energy are correctly marked and the foundational concepts are carefully analysed. However, we have found some deficiencies in the use of both concepts.

Most books now use a definition of heat closer to the presently accepted one: a process of energy transfer associated with a temperature difference between the system under study and its surroundings. In spite of a correct initial definition, many authors (Resnick, 1993; Tipler, 1993; Giancoli, 1994; Serway, 1993; Hewitt, 1995) finally succumb to “heat is a form of energy”. This expression usually appears when heat units are introduced. This lapse can be understood, according to Alonso (1995a), if we remember that the calorie was defined when the nature of heat was still unknown.

The use of terms like thermal energy adds to the confusion: Giancoli (1994) considers thermal energy as equal to internal energy, while Tipler (1993) uses it as a synonym for heat.

We have found another example of the misuse of thermodynamic concepts in the textbooks’ explanation of Joule’s experiments on the mechanical equivalent of heat. Joule’s experiments referred to the different equivalent processes capable of producing the same increase in the system’s temperature. He analysed mechanical, electrical, chemical, etc., processes, which changed, in a definite amount, the system’s temperature (Ianniello 1991). Taking account on this we have revised the textbook presentation of this topic.

Joule’s experiments are correctly described and analysed only by Resnick et al. (1993) and Giancoli (1994). These authors point to the comparison of the mechanical work done on water by a device connected to falling weights, with the energy given as heat needed to achieve the same change in the system’s temperature. For example, Resnick et al. (1993, p. 608) comments: “... Basically, the mechanical work W done by the falling weights (measured in joules) produces a measurable temperature rise of the water ... Joule was able to deduce the number of calories of heat Q that, if transferred from some external source to an equal quantity of water at the same initial temperature, would have produced the same temperature increase ...”[5] (text from the original, Resnick et al. 1992).

In Tipler’s book (1993, p. 534) the description is not as clear as the previous ones. Tipler says: “... Joule used in his most famous experiment in which he determined the amount of work equivalent to a given amount of heat, that is the amount of work needed to raise the temperature of one gram of water by one Celsius degree. Once *the experimental equivalence of heat and energy* has been established, Joule’s experiment can be described as determining the size of the calorie in the usual energy units ...” (our italics, text from the original, Tipler 1991). There is an evident mixture between heat and energy. The paragraph suggests that Joule developed only one experiment. This, together with the experiment analysis that does not include the internal energy concept, induces the incorrect assumption that work is directly transformed into heat. This presentation is perhaps linked to the central role heat had in the beginnings of thermodynamics, before the First Law was introduced.[6] Interestingly, we have found the same assumption of work being transformed directly into heat in students’ responses (see Appendix 1).

Three books (Resnick et al. 1993; Alonso et al. 1995b and Gettys et al. 1991) explain internal energy properly. All of them introduce this concept from the beginning when dealing with mechanical-energy conservation. They define it as the energy associated with the internal structure of the system under study. Hence, in the chapters assigned to thermodynamics they need only to introduce the process named heat.

7. Some Reflections and Didactic Hints

As seen above, the confusion between heat and internal energy is present not only in students' minds but also in textbooks of introductory physics. Internal energy is a young concept compared to force and other mechanical ideas. Many thermodynamic terms, such as latent heat or heat capacity, were formulated as part of the caloric theory. On top of this the everyday use of the words "heat" (associated with temperature) and "energy" (as some kind of fluid kept inside bodies) adds to the confusion. The resulting mess becomes one of the main obstacles in the understanding of thermodynamic concepts.

Our brief historical review shows that the concept of heat has not only dominated the evolution of thermodynamics but has also suffered changes in meaning itself. From a substance (caloric, 18th century) to a form of energy transfer (nowadays), it has also been considered a wave (undulatory theory of heat in 1820-1830) and a form of energy (as Clausius, Joule and others interpreted in the middle of the 19th century). This last conception, coming from the need of relating heat to work and previous to the elaboration of the internal energy concept, is still found in textbooks reflecting some didactical inertia.

The historical data also shows that the confusion about names and meanings has been a constant in the evolution of thermodynamics as a discipline.[7] We, therefore, think that words or expressions with a limited range of validity (like thermal or hydraulic energy) should be avoided or clearly defined within the context of Equation (3). The terms used for some magnitudes of common use, like heat capacity, also cause misinterpretation. They make students think that bodies and systems contain heat. To help our students understand the subject, a didactic approach that emphasises, for example, the relationship between heat capacity and change in state functions (such as internal energy or entropy) instead of heat should be developed (Callen 1985).

To introduce internal energy, teaching approaches based on a macroscopic model have been used (Levine 1995). However, the idea of internal energy as a function of state without a microscopic referent model has been criticised as difficult to grasp by university students. Authors such as Alonso (1995a), Cárdenas et al. (1996), Michinel Machado et al. (1994), Chabay et al. (1999) and Reif (1999) have proposed instead to use a model of matter as interacting particles (bearing kinetic and potential energies) with internal structure. The learning results of both approaches need further analysis to decide whether a microscopic model of matter adds to students' understanding. There seems to be no historical or conceptual reasons to decide in favour of one approach.

In fact, none of the basic thermodynamic concepts are model dependent, so any representation (macroscopic or microscopic) should not interfere in the distinction of heat from internal energy. In this sense, a thorough work over the use and limits of physical models should go along with profound conceptual discussions leading to a better understanding of both concepts.

Several authors (Chabay and Sherwood 1999; Reif 1999) have recently highlighted the opportunity given by introductory courses to develop a unified and modern view of physics, avoiding compartmentalisation of topics such as mechanics and thermodynamics. Other authors have shown the importance of a clear definition of the energy concept in mechanics (Arons 1999). Energy and energy change are those notions which, among others, are associated with motion. But energy is one of the most abstract ideas in physics, besides being the only one, among the dynamic concepts, which is a state function (Ropolyi 1990). It is in mechanics where the first confusion appears in students' minds: everyday language together with textbooks' and teachers' limited definitions ("energy is the ability to do work", for example, see De Berg 1997) contribute to it. Then, it is in mechanics where the first battle must be won, i.e., where energy must be clearly defined and thoroughly understood.

We think that another cause of misunderstanding between energy and heat comes from a superficial treatment of the different "forms of energy". Recalling Equation (3), we can see that it gives the only three forms of energy: kinetic (K), potential (V) and internal energy (U). But Equation (3) by itself will not help much if, throughout the course, teachers do not worry about three ingredients suggested by Arons (1999). He has insisted on (1) a careful definition of the concept of "system"; (2) a definition of "state of a system" with a recognition of "changes in its state" and (3) an association of change of state with changes in the energy (E) of the system defined by Equation (3). If that equation, together with Arons' suggestions, is introduced in mechanics, it will give the correct frame to discuss heat and internal energy in thermodynamics avoiding the association of heat with a "form of energy".

To further improve learning, it would be worth discussing the meaning of the equal sign in the mathematical expression of the First Law (Equation (4)). Following Arons (1994) we could emphasise: the left side of the equation ("ΔU") refers to a change of the system from one state to another characterised by a different energy, while the right side (that is, "$q - w$") points to the processes (interactions with the surroundings) that induce this change. So, the equal sign is more than a mathematical symbol: it stands as a frontier between the system we are studying and the other systems acting over it. As this is also the case for other physical equations in mechanics (e.g. Newton's Laws, work-energy theorem, etc.), a thorough discussion of them (previous to the treatment of thermodynamics) should prepare our students to get a better understanding of the involved concepts.

8. Conclusions

The present article is a contribution to the search for relationships between students difficulty in learning thermodynamic concepts included in the First Law and the historical development of this field. It shows the parallel, in the intermixed use of the internal energy and heat concepts, between the first historical steps in the use of the First Law of Thermodynamics and current students' interpretation of thermodynamic situations. It also describes how many of the most widely used textbooks add to the identified problem (confusion between heat and internal energy) reflecting the troublesome didactic transposition of evolving conceptual frames. Most of the analysed textbooks focus their presentation on the transformation of heat to work and viceversa (Joule's experiments on the mechanical equivalent of heat) and on the principles enunciated by Kelvin and Clausius, without a reference to Gibbs's conceptual structure. It seems worth pursuing this analysis to find new ways of improving the teaching of thermodynamics in introductory physics courses.

Notes

[1] A nice description of Count Rumford's experiments can be found in Wolf (1961) and also, together with his biography, in Staudinger & Veronese (1976).

[2] A biography of H. Davy, together with a brief description of his experiments, can be found in Cabanis & Von Dechen (1971).

[3] Helmhotz' essay bore the significant title "On the Conservation of Force" mixing the words force and energy as was common in those days (Elkana 1977).

[4] Clausius associated heat with the *vis viva* of the microscopic particles that constitute the internal structure of the substance (Brush 1976; Sebastiani 1991) but, definitely, energy did not play a central role in his analysis (Ulises Moulines 1990).

[5] It would be desirable that phrases like "... the calories of heat Q ... transferred ..." were changed to "... the energy transferred as heat Q ...". Comparing some originals to their translations, we have found that the latter are not always reliable.

[6] The last English edition of Tipler's book (1999), which we were able to see after our analysis had been finished, has completely changed the treatment of Joule's experiments on the mechanical equivalent of heat. It introduces several figures, which help the reader to understand the relationship between the experiments and the First Law, and explicitly emphasise the possibility of changing the internal energy of the system by doing different types of work. Something similar can be found in other authors' new editions, which may be a symptom of the influence of physics education research.

[7] We might simply remember the confusion between "force" and "energy", which stood for nearly two hundred years (Elkana 1977; Gauld 1998) or the ambiguous emergence of the entropy concept, partially solved by Gibbs but still in process of being understood (Ulises Moulines 1990; Lieb & Yngvason 1999; Lieb & Yngvason 2000)).

Appendix 1

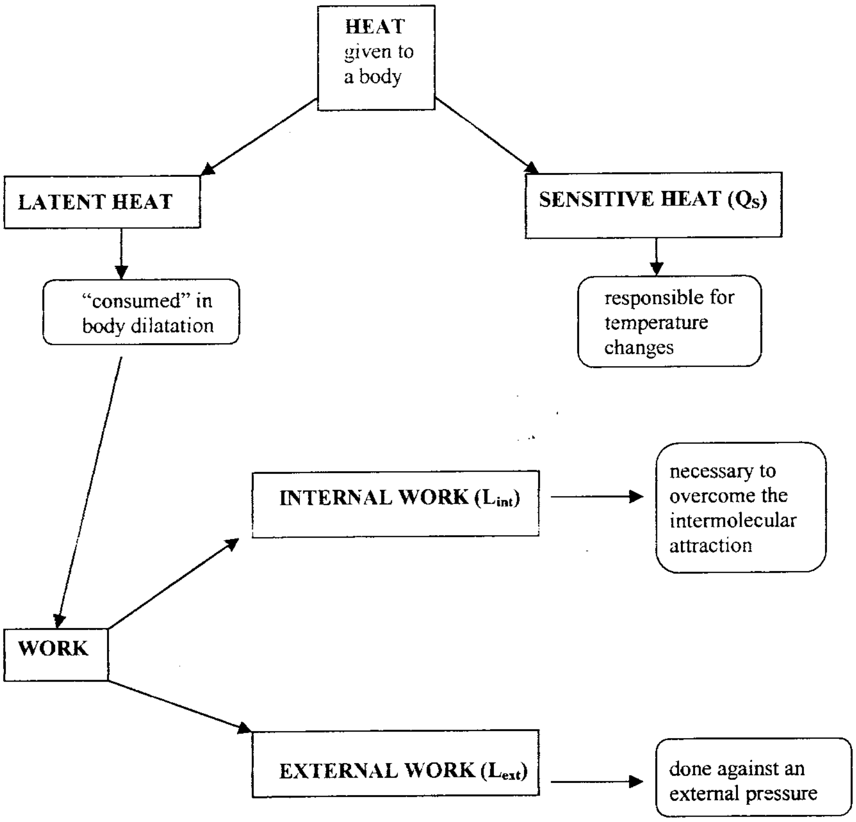
(I) "... *the energy gained* by the body is the work done and it *is heat*, and that heat is melting the ice ... I see the same for both: *the work done was turned into energy*, *into heat the body acquired*, in both cases *in internal energy*, it seems to be ..."(Third year Chemistry major).

(II) "... energy is going to be freed because as it is wrinkled, because of friction, it is going to let *energy come out in the form of heat* ... it gave it up in itself, because *heat is a form of energy, so energy is changing from kinetic to heat* ..." (Third year Chemistry major)

(III) "... an *amount of heat, needed to melt the ice*, will be consumed ... the potential energy is being lost from friction because it is an inclined plane ... so that ... *the heat change is the internal energy* ..." (Third year Engineering student.)

(IV) "... then, the *internal energy did not change, because internal energy depends only on temperature.* In the wooden block only the internal energy is increasing because temperature is increasing ..." (Third year Chemistry major)

Appendix 2. Clausius' Scheme to Analyse the Heat Given to a System, According to Tarsitani (1991)



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