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Students' Conceptions of the Second Law of Thermodynamics—An Interpretive Study

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Abstract

Thirty-four clinical interviews were conducted with Grade 10 students (15-16 years old) who had received four years of physics instruction. The interview's focus was to understand students' responses from *their* point of view and not solely from the physicist's angle. The results of the study confirm and deepen, on the one hand, findings from other studies concerning students' severe difficulties in learning the energy concept, the particle model, and the distinction between heat and temperature. On the other hand, students' qualitative conceptions in a new area—the second law of thermodynamics—are revealed. For instance, in the case of irreversibility (i.e., the idea that all processes take place by themselves only in one direction), most students came to conclusions similar to those of modern physicists. But their explanations of irreversibility are based on significantly different conceptual frameworks. The results of the study suggest that a mere enlargement of the traditional physics curriculum by the addition of ideas of the second law is not sufficient to familiarize students with these ideas. A totally new teaching approach to heat, temperature, and energy is necessary. In this approach, basic qualitative ideas of the second law should be a central and integral part from the beginning of instruction.

Introductory Remarks on the Significance of the Second Law of Thermodynamics in Science Instruction in Lower Grades

> Once or twice I have asked gatherings of people who—by the standards of traditional culture—are thought to be highly educated: How many of them could describe the second law of thermodynamics. The response was cold: It was negative. Yet I was asking something which is about the equivalent of: Have you read a work of Shakespeare? (C.P. Snow, cited in Marx, 1983)

It is interesting that not only the highly educated members of society appear to be ignorant of the second law but also school science, at least in lower grades. In science classrooms, this law is given scant attention. Students between the ages of 12 and 16 are rarely taught even the basic ideas of this law, although it is undoubtedly as important as the first law of thermodynamics (the principle of energy conservation), which has received a great deal of attention in science classrooms for some 20 years.

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The basic (qualitative) ideas of the second law are presented in Figure 1. They not only provide deep insight into the way nature works, but also provide a basis for understanding society's energy supply problems. Teaching energy degradation ideas facilitates a better understanding of the energy concept. Students often reject the idea of energy conservation because it seems to contradict everyday experiences where degradation is the dominant impression (cf. Duit, 1983a).

In the past 10–15 years, a number of new approaches to teaching the second law—even for students in lower grades—have been developed. These approaches do not usually take into consideration students' ideas and students' learning difficulties. Whereas numerous studies, both on students' conceptions and students' conceptual change, are available for many science topics, substantial research on students' understanding of this topic is still missing. There are some studies on students' conceptions of energy degradation (Brook & Driver, 1984; Solomon & Black, 1983). There are also studies on students' ideas of "order-disorder-information" (Schaefer, 1983) and Piagetian studies on the idea of chance (Bliss, 1978). Further, in studies on thermal equilibrium, heat conduction, and latent heat, aspects of the basic ideas of the second law are investigated (Harnaes, 1985; Shayer & Wylam, 1981; Tomasini & Balandi, 1987; Wiesner & Stengl, 1984; Wiser, 1987). But, in general, we know very little about students' conceptions here.

Aims, Design, and Procedure for the Study of Students' Conceptions about the Basic Ideas of the Second Law

Aims

The study presented in this article is a preliminary step in remedying the aforementioned research deficiencies. It investigates students' conceptions and not conceptual change. Furthermore, it does not deal with all of the basic ideas presented in Figure

Irreversibility and asymmetry in nature
All "real" processes take place by themselves in one direction only. Heat travels by itself only from a warmer to a colder body. While the process of changing work into heat can take place at a given temperature, one cannot reverse it to get the work back again.

Energy degradation
In every process which occurs in the real world, energy loses value (i.e., is degraded).

The universe exhibits a tendency toward...
even distribution of matter and energy, disorder, and loss of information.

The destructive and constructive aspects of the second law
Usually the "destructive" aspect of the second law is emphasized. But there is also a "constructive" aspect. The creation of new structures does not occur "in opposition" to the second law but because of it. Atkins (1983) stated this idea very clearly: "The very nature of nature is decay but decay drives creation."

Figure 1. Basic (qualitative) ideas of the second law.

1. Instead, it focuses on irreversibility, although it also examines energy degradation and the tendency toward disorder.

We wanted to find out whether students learn the basic ideas of the second law from traditional physics instruction (which does not give much attention to these ideas) and whether the conceptions students gained through several years of traditional physics instruction may form a fruitful starting point for teaching and learning the basic ideas presented in Figure 1. In other words, we wanted to investigate the possibility of introducing the basic ideas of the second law into physics instruction (as it is usually given in German schools). In particular, we wanted to examine whether some slight enlargements and reorganization of traditional physics instruction are sufficient or whether major changes are necessary in order to familiarize students with the basic ideas of the second law.

The Sample Interviewed in the Study

To meet these aims we interviewed 34 Grade 10 students (15–16 years old). The students had been taught physics for four years (two periods per week) in a German grammar school, which is the highest level in our school system. The students were drawn from nine classes in seven schools in order to avoid the influences of particular classes and schools; 15 of the students were female and 19 were male. They were chosen randomly. All students had covered the same syllabus in physics. The concepts of heat, temperature, energy, and the particle model (all of which play an important role in our study) were given considerable attention during the four years of physics instruction our students received. (A list of the subject-related themes of the syllabus is presented in Appendix A.) Basic ideas of the second law, as presented in Figure 1, were not the focus of the instruction. Although the educational strategies used varied from teacher to teacher, there were some general features of physics instruction that were obvious to us in the classes we studied. Instruction was usually rather teacher centered, but ideas were generally developed during class discussion. Demonstration experiments played a major role, but students' experiments were also common.

The Interview Method

The method employed was the clinical interview. The interviews were conducted by the two authors of this article. Students were presented with the situations described in Appendix B. The situations were sketched on cards. The tools shown on the cards (e.g., a piece of metal, a beaker filled with water, a pendulum) were also presented to the students, but experiments were not actually carried out. We followed an interview guide (see the abbreviated version in Appendix B), but we had the possibility to follow students' ideas if we thought that this would be fruitful. The interviews were recorded and transcribed.

We started the interview with rather open questions. Our main intention was to help students to develop their own ideas. However, we also guided students' attention by particular leading questions toward the aspects we were interested in (see, for instance, the questions we posed in problem 4.2 in Appendix B).

Further, two types of intervention were used. At specific points in the interview, we asked the students for explanations using the concepts and models taught in physics (if students had not used them so far). We then tried to investigate the consistency of students' explanations during different parts of the interview. Therefore, we confronted students with answers they had given before. Interventions like the ones we used force students to think in directions mainly determined by the interviewer. Students then had less chance to develop their own ideas. Because of this, we assessed students' spontaneous answers and forced answers (after guidance and after interventions) separately.

On the Nature of the Study

The study was deliberately based in a constructivistic framework, as, for instance, outlined by Driver (1989). It is qualitative in nature, not quantitative. It follows the tradition of interpretive research (Erickson, 1986). Its main aspects resemble Marton's (1981) phenomenography. We try to make sense of students' reactions to interview situations; we try to understand their responses from their point of view, rather than employing the physicist's viewpoint as the main or even the only frame of reference.

The interpretive position has important consequences for the way we proceeded. When we designed the study presented here, we started from problem sets used in physics textbooks as examples of the ideas of the second law. On the basis of our study of the relevant literature and on the basis of our experiences with research on students' conceptions in general, we developed preliminary ideas concerning the frameworks students might use to explain the processes physicists explain using ideas of the second law. We designed our first version of an interview from these considerations and tried it with 7 students. From these findings, we revised and further developed our ideas of students' conceptions. A second version of the interview was carried out with 14 students (see findings from this part of the study in Duit & Kesidou, 1988). The two pilot studies resulted in the present version of the interview and in a fairly substantial amount of knowledge concerning students' conceptions.

It is the major problem of interpretive studies to get to know students' conceptions in spite of the hermeneutic circle [i.e., despite the fact that our knowledge of students' conceptions is dependent on *our* constructions, which are based on *our* conceptions (Johansson, Marton, & Svensson, 1985; Jung, 1987)]. We believe that our strategy of various steps, which enabled us to revise our constructions of students' conceptions in a "spiral" process, has considerably enlarged the validity of our interpretations.

On the Interpretation Process

The findings presented in the following are the results of an interpretation process on two levels. On the first level, we classified students' responses for each interview question into categories. The categories were constructed on the basis of our initial ideas about students' conceptions, which were formed during the two pilot studies described earlier, and the data of the main study. Thorough descriptions of the categories facilitated an assessment of all interviews. The categories were developed by the first author, but the students' responses were categorized by both authors independently. The description of a category was only accepted if there was over 90% agreement between the two evaluators. On the second level, we tried to describe the conceptions that students used to explain the processes presented to them. Both the categories of responses and the students' responses in the interview were used in this process. Here we also attempted to cross-check our interpretations as far as possible.

It may be surprising that students' responses still play a direct role in the interpretation process, although the responses have already been classified according to the categories.

The reader must keep in mind that this scoring process reduces data to information that is in some way objective (i.e., to categories that may be described in such a way that different raters can agree in the rating process). When students use a term like energy, it is easy to put such an answer into a reference category (e.g., "use of the term energy"). But students put into this category may have had different ideas in mind when they used this word. It is therefore necessary to go back to students' responses in order to ascertain what they meant by a certain term by the way they used it. Svensson (1985) argues in favor of such contextual analysis of the data, because the same data may have totally different meanings in different contexts.

What has been sketched rather briefly here is a certain "weakness" of studies carried out within an interpretive frame. We are aware of the limitations of the interpretations we present in the following. We know that we present *our* constructions of students' conceptions. But we try to provide some information (e.g., by giving examples from students' responses) that allows readers to consider whether they would come to the same conclusions concerning such students' conceptions. Of course, such attempts are limited in a relatively short article like this one. [Details about the interpretation process and a large number of students' quotes can be found in the full report on this study (Kesidou, 1991)]. Further, there is the problem of translating students' answers from German into English. Our translations are interpretations. Hence the examples from students' responses are not really objective data, but in some way subjective.

Findings of the Study

The main findings of our study are summarized now. We try to portray the frameworks most often employed by our students to make sense of the phenomena presented in the interview.

Differentiation between Heat and Temperature

It is well known from many studies that students have severe difficulties in adequately differentiating between heat and temperature (Brook, Briggs, Bell, & Driver, 1984; Tiberghien, 1983). In our study we recognized similar difficulties.

In the first problem (see Appendix B) students were invited to explain a temperature equalization process in their own words. When they employed the terms *heat* and *temperature*, we asked them to outline their understanding of these terms and to describe what heat and temperature have to do with one another (see Problem 1.2). Students' responses were classified in the categories presented in Table 1.

The majority of the students in our study viewed temperature as a variable that can be measured and/or quantified. Heat was usually not seen as a measurable or quantifiable concept. When asked to explain what heat and temperature have to do with one another, 18 students (53%) mentioned that temperature measures or quantifies heat. Five students said explicitly that temperature can be measured and/or quantified whereas heat cannot.

Intensity and Extensity—Frameworks to Explain Thermal Processes

Students' explanations of thermal processes in other problems used in the interview allow a much more in-depth view of the distinctions they make between heat and temperature.

Table 1
Students' Understanding of the Words Heat and Temperature

Categories of responses	Number of students (n = 34)	(Percent of students)
	Heat	
Energy	12	(35%)
Heat energy	3	(9%)
Energy may be gained by heat	2	(6%)
Temperature	4	(12%)
High temperature	4	(12%)
Sensual impression	2	(6%)
State of being hot	2	(6%)
Movement of particles	5	(15%)
	Temperature	
Amount of energy	5	(15%)
Energy	4	(12%)
Heat	3	(9%)
Temperature can be plus or minus	2	(6%)
Measure or unit of heat	9	(26%)
Degree	5	(15%)
Measurable quantity	4	(12%)
Speed of particles	3	(9%)

To ease an understanding of students' frameworks as presented below, the physicist's view of heat and temperature will be briefly summarized. First of all, the distinction between extensive and intensive quantities as they are used here will be explained. If two identical systems are put together, the values of the extensive quantities double, whereas the values of the intensive quantities stay the same. Extensive quantities may be viewed as analogous to substances. It makes sense to speak about amounts of these quantities. It is also legitimate to view them as amounts being contained in a system or transported from one system to another. Intensive quantities may not be viewed as substances. Whereas it makes sense to ask "how much" for extensive quantities, it is suitable to ask "how strong" or "how high" for intensive quantities.

Heat is the form of energy that is transported from one system to another due to temperature differences. From the physicist's point of view, heat is a process variable. Therefore it is wrong to state that a body contains a certain amount of heat. But it makes sense to view heat as an extensive quantity. If a specific amount of heat (Q_1) is transported and if this is followed by another amount of heat (Q_2) the total amount of heat transported is $Q_1 + Q_2$. Temperature, on the other hand, is an intensive quantity. If two bodies at temperature T are brought into contact then the temperature of the two bodies is still T.

Heat as intensity and temperature as degree of heat. Seen within the intensity-extensity framework it is interesting to find a considerable number of students who view heat as an intensive quantity and temperature as degree of heat, at least in some of their responses.

In Problem 4, students were asked whether a cup of coffee or the room around it (both at the same temperature) have the same heat. More than 50% of the students asked, answered that the cup of coffee and the room have the same heat. One student gave this explanation: "They possess the same heat, the heat which is present everywhere."

Problem 5.1 provides further support for the students' view discussed here. Equal amounts of water and alcohol (both at 20° C) are heated by identical burners. The alcohol reaches 30° C after 2 minutes, water after 4 minutes. When asked which liquid received more heat, 15 out of 34 students (i.e., 44%) did not see that the water received more heat than the alcohol. Even after the intervention of the interviewer, who pointed to the fact that the water was heated for a longer time, 7 students still thought that both received the same heat. Students' explanations may illustrate the interpretation given here, namely, that students view heat not as an extensive but as an intensive quantity:

> "The liquids have been heated with the same temperature."
> "The liquids have been heated with equally hot flames."
> "The liquids have been heated with the same burner."
> "Water only received heat for a longer time."
> "Both liquids are at 30° C."

Heat as a general cause of temperature increase. It is a very valuable everyday schema that the effect is proportional to the cause and inversely proportional to what prevents it (resistance). A number of students also appear to employ this schema to explain thermal processes. Often such a schema is based on the intensity view of heat as outlined above. On the basis of such a schema, it is obvious to the students why bodies of equal masses but of different materials reach different temperatures when they are heated with the same burners: Some materials are difficult to heat; they are more resistant to heating. From this point of view there is no need for the physics concepts of *heat* and *temperature* and hence no need for the physicist's distinction between *heat* and *temperature*.

Furthermore, the cause-effect framework just outlined does not demand thinking in heat balances (i.e., it is not necessary, within this framework, to view heat as something that is transported from one body to another). Students who argued within the cause-effect framework pointed out that more heat is needed to cause a temperature rise in a body that is difficult to heat than in a body that is easy to heat. But this does not mean that the first body has more heat (or energy) after the heating process, something very surprising from the physicist's point of view. In our students' frameworks it does not make sense to ask where the extra heat that was given to the first body is. The last sentence of the following passage from an interview (Problem 5.1) may illustrate this way of thinking:

> I: Has one of the liquids received more heat?
> S: Well it took longer, hence there should be more heat, to warm it, should be away, but may be . . .
> I: That means the alcohol has less heat than the water now?
> S: No, both have the same temperature.
> I: But the water received more heat.
> S: Maybe one can put it like this, more heat has been used to bring water to 30° C than to bring alcohol to 30° C. But the heat both came to is the same. Temperatures are equal, that means they have the same heat, but they used different heat to reach the same heat.

Heat as an extensive quantity, temperature as the amount of heat. It is not surprising that there are also students who viewed heat as an extensive quantity; about 30% of our students appear to have such an idea. But it is striking (from the physicist's point of view) that some students viewed temperature as the amount of heat contained in a body. Some students also viewed temperature as something that passes from one body to another, the degrees indicating the amount of temperature transported.

In Problem 1 students dealt with the thermal interaction of two bodies, one at 20° C and one at 80° C. They were asked (Problem 1.3) whether, at the end of the interaction, the body that had an initial temperature of 80° C may reach 15° C (i.e., a temperature lower than the equalization temperature). The other body, then, has a temperature above the equalization temperature, namely, 29° C. There are some students who argued that the sum of the temperatures has to be the same at the beginning and end of the interaction. Here is an example of the way these students argued:

> S: If nothing can get away, then it must add up to 100° C.
> I: What do you mean?
> S: Now we have 44° C but initially it was 100° C, where have the other degrees gone if nothing gets lost?

Another student comments on the situation in which the initial temperatures of the bodies before the interaction are 80° C and 20° C, and after the interaction 70° C and 95° C (Problem 2):

> This is not possible. Because this would mean that these two suddenly have much more heat than before. If one adds these two together, they come to 100° C and if one adds these two together, one has much more heat.

In passing it is worth mentioning that two students did not view temperature simply as amount of heat but as amount of heat per volume or per mass unit. This view is close to the physicist's when the differentiation between an extensive quantity (heat) and an intensive quantity (temperature) is concerned. However, these two students still did not see temperature as a concept separate from the concept of heat.

Heat, temperature—intensity and extensity. The careful, in-depth analysis of our students' attempts to explain the thermal processes presented in the interview reveals that only a small number of them show explanations that fit a physics framework. Within such a framework, a clear distinction between an extensive energy quantity (heat) and an intensive quantity (temperature) is necessary. Quite often it appears that no distinction is made between heat and temperature in the extensity-intensity framework. Heat is frequently viewed as an intensity, temperature being the measure of this intensity, or heat is viewed as extensity but temperature as extensity too, being the measure of the amount of heat. The importance of our findings with regard to irreversibility ideas will now be discussed.

The Particle Model and Explanations of Thermal Processes

Earlier we presented students' attempts at describing the meaning of heat and temperature. Only a small number of students (21%) gave explanations in terms of the particle model. There are answers to another question in Problem 1, namely, "What happens to a body if it is heated?", that also indicate that the particle model is seldom used. Out of 25 students who were asked this question, only 4 gave an explanation using the particle model on their own, another 8 students only used this model after the interviewer explicitly asked for an explanation using this model. Thirteen students could give no particle explanation, even after the interviewer had asked them to do so.

There are some interesting conceptions among the small number of users of the particle model that appear to be worth mentioning here.

1. In solid bodies particles move at low speed only (due to the structure of these bodies), or they do not move at all.

2. It is much more difficult to set particles of solid bodies into motion than is the case with particles of liquids and gases. Argumentation of this kind sometimes appears to be based on ideas about the structure or about the bonding in solids, liquids, and gases, but also on the idea that the inertia of the particles is different in the three states of matter.

3. Some students are convinced that the particles will not continue to move but will slow down and eventually stop. They explain this by indicating that the particles are hindered in their movement or do not have enough space to oscillate. "Inertia slows the particles down" is also mentioned as a reason why particles slow down after a while.

4. It is known from other studies that students explain the heating of a body by friction in this way: Particles rub against one another and hence become warmer (Manthei, 1980). Four of our students argued in a similar way. The following interview passage illustrates this. It may also point to the mentioned *inertia* idea.

> I: What is the temperature of the water after some time?
> S: 20° C
> I: And the temperature of the metal?
> S: I think it is less than the temperature of the water.
> I: Why is the temperature lower?
> S: Maybe the molecules of the metal have more inertia than the water molecules as time goes on.
> I: What do you mean when you speak about inertia?
> S: They move slowly. They are not inclined any more to be faster and hence to produce greater heat or energy.
> I: You just said they are not inclined any more to produce heat, the molecules.
> S: The inclination to move faster, to dash along.
> I: What happens . . .
> S: Heat is produced.
> I: How is heat produced?
> S: The molecules rub against one another.

5. The explanation of how heat is produced in the last sentence of the previous quotation transfers qualities of behavior in the macroscopic world to the microscopic world. In the macroscopic world, heat is indeed produced by rubbing (i.e., by friction). There are some other findings of a similar kind concerning the transfer of qualities from the macroscopic world to the microscopic world. Some students, for instance,

mentioned that particles expand when heated; others appear to hold the idea that heat is transferred from one particle to another in the process of heat conduction (similar findings are frequently reported in the literature; cf. Rennstrom, 1987).

Energy Conceptions

Students provided explanations using the term *energy* for all the problems posed in the interview. In the following, our main findings will be summarized.

On the meaning of the term "energy". In Problem 7, we probed students' views on whether a pendulum may start oscillating by itself or not. From the students' answers about what energy means, the categories presented in Table 2 emerged.

Similar findings concerning students' attempts to describe what energy is are frequently reported in literature. The pendulum problem that formed a framework for the description triggered slightly more "force" responses than was the case in other studies on the meaning of energy. Associations with electricity that were predominant in another study carried out in Germany (cf. Duit, 1983b) were not visible here.

Students' general energy frameworks. The aspects of transport, transformation, conservation, and degradation (Duit, 1986) are at the very center of the physicist's energy concept. When processes occur, phenomena are usually converted (e.g., heat into motion, motion into heat, light into heat). Viewed in the physicist's energy framework, energy is transformed (i.e., energy changes form) and is usually transported from one place to another. During all of these changes, the total amount of energy does not change (i.e., energy is conserved, but energy is degraded—it becomes less usable).

The general framework that formed the basis for the energy ideas of most of our students is very different from that of the physicist. Briefly summarized, energy was usually seen as something that brings about actions and effects. The effects of energy become visible by the change of intensive quantities (e.g., temperature or height). The change of the extensive quantities that are also involved in the changes was often neglected. In Problem 5.1, for instance, many students regarded just the temperature rise as an indication of the energy contained in the water and alcohol, and not the heat transferred to them. There is another important aspect of students' conceptualization of energy within the cause of actions and effect schema discussed here. Actions and effects are hampered by resistances. If resistances are small, little energy is necessary to overcome them; if they are large, more energy is needed to reach the same state.

Table 2
Students' Understanding of the Word Energy

Categories of responses	Number of students (n = 34)	(Percent of students)
Force	12	(35%)
A cause that brings about effects	9	(26%)
Energy forms mentioned	5	(15%)
Phenomena mentioned	3	(9%)
Energy does not get lost	3	(9%)
Something that is contained in bodies	2	(6%)

When asked for the total energy at the end of the process, students who thought according to that schema only took the resulting effect (measured, from their point of view, only by an intensive quantity) into consideration and not the fact that different amounts of energy had been harnessed to achieve the effect (e.g., because the achieved effect is the same, the energy at the end is the same).

It is interesting that ideas of energy transport, transformation, conservation, and degradation are generally missing in this framework. When asked what all energy forms have in common, most students answered that they can all cause actions and effects. They differ (according to these students' answers) in that they have different effects (e.g., heat energy heats, kinetic energy sets or keeps in motion). That one form of energy may be transformed into a different form (i.e., the physicist's view) was reflected by only 2 students out of 34. The physicist's view of energy conservation was also used very rarely. No student used this idea unequivocally and consistently. The statement that energy is always conserved was made by many students, but it appears that it had only been learned by rote. Some students tried to make sense of this statement within the students' framework discussed here. They argued, for instance, that energy was not lost in processes because energy had brought about an effect (e.g., energy overcame resistances in processes where friction was involved). The energy conservation idea of most of our students may be outlined in this way: Energy is not lost but it is exhausted by bringing about an effect or an action. Here is a quote from an interview to illustrate this.

> I: Does the pendulum's energy become less?
> S: It should, because, if it still contained all energy it should have the force to swing more.
> I: But what happens to the energy? Why does it become less? Is it lost?
> S: No, energy can, as far as I know, not be lost, the principle of energy conservation says so, but . . .
> I: Where does it go to?
> S: Where energy is used up in the pendulum, I do not know. Well, now I know. Gravity, the pendulum has to be pulled up again, energy is needed to do this. The pendulum is pulled down by gravity and it then has to work against gravity, so more energy is needed.

The idea that energy is used up in processes is a common idea. It is in fact at the very center of the energy frameworks of our students. When asked why a pendulum comes to rest after a while, 10 students out of 34 gave an explanation in which they explicitly employed the idea of energy being used up. The reasons given for this energy loss were the force of gravity and air resistance (which have to be overcome). It is obvious, especially with regard to the overcoming gravity idea, that students are far from the physicist's conception of energy degradation.

Energy and heat. In general, students think that heat and energy are closely related. When students explained the temperature equalization processes in Problems 1–6, they frequently employed the word energy. Half of the students, for instance, used the word energy when they explained the meaning of heat in Problems 1.2. But students did not usually view heat as a form of energy in the way that physicists do. First, several students' responses indicated that they also use energy as an intensive quantity. Second, the idea of the transformation of kinetic energy (or, more generally, mechanical energy) to heat energy was not well developed. When the students attempted to explain why a swinging pendulum comes to rest, only 4 out of 34 argued that kinetic energy is transformed into heat energy in the surrounding air (whereas 10 students said that the kinetic energy is simply given to the air with no energy transformation idea involved in their statements). It is important to note that most students who recognized that heating took place during the process did not connect it with an energy transformation or with the loss of energy of the pendulum. The heating was merely seen as an outcome of friction.

Students' ideas about whether or not heat energy may be transformed into kinetic energy were also very limited. Heat energy was often considered only as a cause of temperature changes, and motion only as an effect of kinetic energy. When transformations from heat to motion were considered possible, the emphasis in the explanations was on the concrete mechanisms facilitating the transformation and not on energy considerations (cf. Fedra, 1989).

Students' Conceptions of Temperature Equalization

In Problems 1–3, students' conceptions of temperature equalization were thoroughly investigated. The great majority of the students' responses for all three problems indicated that the bodies involved will have the same temperatures at the end of the processes (in Problem 1, 29 students out of 34; in Problem 2, 24 out of 34; in Problem 3, 25 out of 28). But 18 of the 34 students (i.e., 53%) used alternative conceptions in at least one problem. For example, they were of the opinion that temperature differences may remain or that they may occur by themselves after equalization. They usually pointed out, however, that these differences will be small.

The most frequent reason given for the occurrence of temperature differences was the different qualities of the materials which interact. In Problems 1 and 2 (where different materials interacted), 15 out of 34 students gave this reason at least once. The explanations why different materials are influential were (a) the ease with which heat enters or leaves different materials varies, (b) different materials attract heat or retain heat differently, and (c) the particles are not equally close to one another; they have different qualities (e.g., different inertia or speed).

There was another interesting explanation as to why temperature differences may occur. Six students were of the opinion that the process of temperature change may continue in the same direction even after temperature equalization due to heat inertia. Some of the students drew an analogy with the oscillations of mechanical bodies here.

Although the great majority of the students arrived at the same conclusion as physicists would (namely, that temperatures of bodies in thermal interaction will ultimately become the same), the frameworks on which this conviction was based are far from those of physicists. These frameworks have previously been outlined. The students' responses reveal some uncertainty as to what is equalized: temperature, heat, or energy. This is sometimes due to the idea that two bodies have the same energy or heat if they are at the same temperature. An indication of this insufficient distinction between heat, energy, and temperature is the idea of energy equilibrium. For instance, this idea was employed by students to explain why nothing happens when alcohol and water of the same temperature are brought into contact (Problem 5.2): The temperatures are the same; hence the energy is the same; hence the tendency to cause an effect is the same; hence no temperature changes occur.

Students' attempts to make sense of the presented temperature equalization processes also differed from those of physicists in the following respect. Where the situation of

Problem 1 is concerned, physicists focus on the interaction between the hot metal and the cold water (i.e., on the interaction of the bodies that are in direct contact). Interactions between these bodies and their surroundings are initially neglected. In contrast, it is striking that several students did not even view this process explicitly as an interaction. Some students appeared to be unaware that every cooling process requires an interaction partner. It appears that they held the idea that bodies may cool spontaneously without other (colder) bodies being involved.

Students' Conceptions of Irreversibility

The findings presented thus far form the basis of the following summary concerning students' conceptions of irreversibility. Two irreversible processes are involved in this study, namely, temperature equalization (heat conduction) and a pendulum's oscillations dying out after some time.

Irreversibility of temperature equalization. As has been reported before, most of our students did not think that the temperature equalization process may be spontaneously reversed (i.e., they did not think that temperature differences may occur by themselves). Viewing the idea of irreversibility as self-evident, as teaching approaches to the second law in lower grades usually do, thus appears to be justified (cf. Duit, 1983a; Haber-Schaim, 1981). However, our study has revealed that this idea of irreversibility is not rooted in a physicist-like framework, but in very different everyday frameworks.

Within the framework of heat as intensity, irreversibility is an idea that is certainly close at hand. A temperature difference that would occur by itself would require a higher intensity to occur from a lower intensity by itself. This is an idea that is rejected by most students. It is interesting that some students explained this by pointing out that nothing can be created from nothing. This is an argument that is commonly seen as an indication of the idea of the conservation of extensive quantities like matter or energy. However, there it is used to support the idea of irreversibility.

The idea that differences in intensities tend to equalize and cannot occur by themselves appears to be the prevailing idea underlying students' conceptions of irreversibility. Of course, this idea may also fit into the physicist's framework, but here it is based on a framework that is much vaguer as far as distinguishing between extensive and intensive aspects is concerned.

Irreversibility of the pendulum's oscillations. Similarly, most students did not have the idea that the pendulum's oscillations may be reversed spontaneously (i.e., that the pendulum may start oscillating by itself by cooling the surrounding air). But the framework on which this correct conviction (from the physicist's point of view) is based is far from that of physicists. Instead, students simply harbor the idea that something of this kind does not happen. Most students did not learn physics conceptions that would facilitate a deeper understanding of their conviction. A prerequisite for the understanding of the irreversibility of the pendulum's motion (which almost no students hold) is the idea of the transformation of heat energy to kinetic energy.

Irreversibility as a general feature of all processes. In the concluding problem of the interview (Problem 8), we wanted to find out whether students were aware that processes always take place by themselves in one direction only. Here the findings are more basic than the ones just presented because there was not enough time in the interview to discuss this issue in sufficient detail. The discussion turned out to be rather difficult because what is meant by *by themselves* and by *direction of processes* has to be clarified. Here, most students (23 out of the 27 we asked this question) were also of the opinion that processes occur by themselves in one direction only. But the frameworks on which students tried to base their explanations were the ones just presented and were far from those of physicists.

Cause-effect thinking was dominant. The cause of the process that occurs in a natural direction is inherent in nature; if the process runs backwards the cause has to be arranged in some way. A stone, for instance, falls due to gravity (it is in the nature of the stone to fall), it will not go back to the initial height, because the cause—here an upward force—is missing. It is interesting that once again processes were not seen as interactions and they were not viewed in terms of energy balances.

Students sometimes explained their ideas that processes occur by themselves in one direction only in the following way: Processes strive to achieve certain aims that influence them (e.g., they aim at the states of equalization or of rest). Analogies from everyday human behavior were employed to explain why processes do not run by themselves in the opposite direction: It is pointless to work against one's own aims and intentions.

Discussion—Learning Basic Ideas of the Second Law

Did Our Students Learn Basic Ideas of the Second Law during Traditional Physics Instruction?

Our study is restricted to a few of the basic ideas of the second law listed in Figure 1. It focuses on irreversibility and also devotes some attention to energy degradation and the tendency toward disorder. The answer our study provides to the question in the title of this paragraph is clearly negative. Where irreversibility and energy degradation are concerned, most students were convinced that processes occur by themselves in one direction only and that energy is used up. But these ideas were mainly based on intuitive everyday conceptions and not on the physicist's framework taught in school. Where the tendency toward disorder is concerned, students' ideas about the particle model were very limited. An understanding of irreversibility in terms of the tendency towards disorder cannot, therefore, be expected.

Have Our Students Acquired a Sound Framework that Enables Them to Understand Irreversibility Ideas?

The above results point out that a considerable proportion of the students we studied did not develop such a framework during their physics instruction, on the basis of which irreversibility ideas could be directly developed. The students did not learn to conceptualize processes that take place in the natural direction within the physicist's framework. Thus an understanding of the idea that it is impossible for processes to take place by themselves in the reverse direction cannot be expected.

First, most students have not acquired the necessary physics concepts for heat and temperature. If, for instance, they do not describe thermal interactions with an extensive quantity (heat) that is transferred from one body to another, then they cannot ask about the conditions required for such a transfer to occur. The same holds also for students who think that bodies cool down spontaneously [i.e., without other (colder) bodies interacting with them].

Second, students have difficulties in using the idea of the transformation of kinetic energy to heat energy to explain relevant processes. It is obvious, then, that they cannot explain the reversed processes in terms of the reverse transformation (i.e., the transformation of heat energy to kinetic energy) and to ask about the conditions required for such a transformation to occur.

Third, only a limited number of students gave explanations using the particle model. Students' responses that involve explanations using the particle model point to (mis)conceptions that may hinder their understanding of the ideas of the tendency toward even distribution of matter and energy and of the tendency toward disorder. For instance, when students have the conception that particles slow down by themselves, they imply that energy is lost during this process. From this point of view, it does not make sense to ask if the process of heat conduction can occur in reverse. The (total) energy of the particles is not conserved, so energy from the outside is needed to keep the particles moving or to set them back in motion.

Consequences for Teaching and Learning about Basic Ideas of the Second Law

The conclusion from this study is that a mere enlargement of the traditional physics curriculum by the addition of ideas of the second law will not be successful. Understanding irreversibility within the physicist's framework, for instance, requires an adequate understanding of the temperature equalization and energy transformation processes. Our study revealed that most students did not achieve such an understanding during their traditional physics instruction.

Our findings may lead to a pessimistic view of chances for successfully teaching and learning basic ideas of the second law of thermodynamics in lower grades. However, it should be taken into consideration that our study did not investigate the effects from instruction that explicitly focused on basic ideas of the second law. A study that compared conceptions of students taught in the traditional way against conceptions of students taught in a new way, in which second law ideas were an integral part (cf. Kesidou, 1990), supported our view that it is, in fact, possible to teach basic ideas of the second law of thermodynamics in lower grades. But we believe that this is only possible within a totally new teaching approach to heat/temperature and energy in which these basic ideas are central and integral parts from the outset. We think that our in-depth analysis of students' attempts to make sense of the phenomena presented in the interview point to major learning difficulties and hence will be of value when new approaches are developed. Although it is not possible to detail such an approach here, a few remarks can be made.

From the outset of teaching, students' difficulties in adequately differentiating between heat and temperature should be addressed in the curriculum. First, experiments have to be carried out by the students that provide evidence that, at the end of thermal interactions, the same temperatures of the interacting bodies result. Second, a conceptual framework has to be provided that conceptualizes the thermal interaction as an exchange of the extensive quantity heat (or energy) that runs spontaneously only as long as there is a temperature difference. If ideas of irreversibility were to be introduced here, this would help the student to better understand this conceptual framework because these ideas would stress that temperature differences do not occur by themselves from temperature equalization. If temperature differences did occur by themselves, heat (or energy) would have to flow against the driving force of temperature difference or, more metaphorically, heat (or energy) then would have to flow uphill. Emphasis should be given to explanations of different thermal interaction processes within the sketched framework. A particular focus should be on the interplay of the extensive quantity (heat or energy) and the intensive quantity (temperature). Particular attention also should be given to the two variables influencing the amount of heat transported to a body, namely, the intensive variable temperature and the extensive variable mass. Students have to be convinced that the amount of heat flowing from one body to another is measured by both temperature and mass and not by temperature alone.

The students in our study learned a rather vague energy concept during their instruction. Our findings suggest that science instruction should emphasize the ideas of energy transformation, energy conservation, and energy degradation (which is one of the qualitative ideas of the second law of thermodynamics) rather than providing students with a long list of different energy forms. As noted in the introductory remarks of this article, energy degradation ideas should play a major role in the development of students' energy concepts. Without these ideas, the understanding of everyday experiences, where degradation, not conservation, is the dominant impression, is not very likely. The findings of our study have pointed out some of the deficiencies of the energy concept as learned in traditional physics instruction. We believe that energy degradation ideas, if developed alongside conservation ideas from the outset, will help to remediate them.

Appendix A

Syllabus Contents in the Areas Heat/Temperature, Energy, and Particle Model in the Grades 7–10 of a German Grammar School

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Grade 7

- Heat
  - Heat sources
  - Heat convection
  - Heat conduction
  - Heat radiation

Grade 8

- Particle structure of the bodies
- Heat
  - Temperature increases through energy transfer
  - Temperature variations without change of state
  - Temperature variations with change of state
  - Specific heat capacities for different solids and liquids
  - Explanation of heat using the particle model

Grade 10

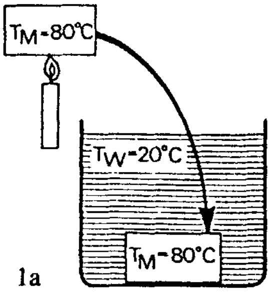
- Energy transformations
  - Energy transformations involving mechanical, electrical, heat, chemical energy
  - Energy transformation processes at power stations
  - Efficiency of combustion engines, hydroelectric power stations, thermal power stations

Appendix B

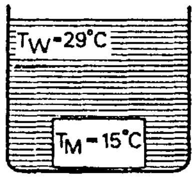
The Problems of the Interview

In the following the problems used in the interview are presented. In the boxes an abbreviated version of the interview guide we used is given. The questions asked are printed in italics. The pictures were presented to students on cards during the interview.

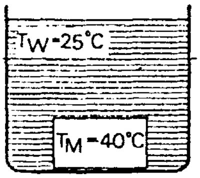
1. A hot piece of metal is put into cold water
   - 1.1 A piece of metal is heated to 80° C. It is then put into water of 20° C. *What happens?*
     If the student predicts a temperature difference at the end of the process: *What happens then?*
   - 1.2 If the student uses the terms heat and temperature in 1.1:
     What do you mean when you speak about heat/temperature? What has heat to do with temperature?
   - 1.3 Some students carried out this experiment and got different results. Some of them are correct, others are not. One group, for instance, presented this result: After a while the temperature of the water is 29° C and the temperature of the piece of metal 15° C.
     What do you think about this result? Is it possible? Why/why not?
   - 1.4 Here are the results from another group of students who carried out the experiment in 1.1: They say that temperatures equalize (say at 29° C) but that after equalization the piece of metal becomes warmer, and the water becomes colder. After a while the piece of metal has a temperature of 40° C, the water a temperature of 25° C.
     Is this result possible? Why/why not?



1a

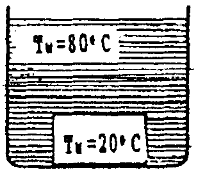


1b

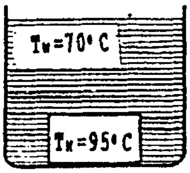


1c

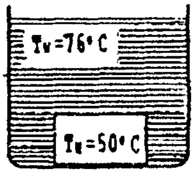
2. A cold piece of metal is put into hot water
   Here a piece of metal at 20° C is put into water at 80° C. In principle the interview follows the same sequence of questions as in 1.1, 1.3, and 1.4. The situations presented are given in 2a, 2b, 2c.



2a

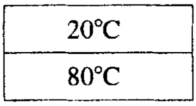


2b

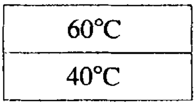


2c

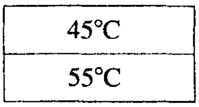
3. Two metal plates are brought into contact
The heat exchange/temperature equalization of two identical metal plates is discussed. The interview follows the same order of questions as in 1.1, 1.3, and 1.4. The situations presented are given in 31, 3b, 3c.



3a



3b

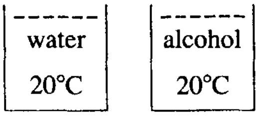


3c

4. Does coffee heat up again by itself after it has cooled?
   4.1 You put hot coffee in a cup on your desk. You leave the room. After about ten minutes you come back.
   What has happened to the coffee? Why? Is there any change in the air temperature?
   4.2 Imagine there is a cup of coffee at room temperature. You leave the room for a while. When you return the coffee has become warm.
   Is this possible? Why/why not? Why is the reverse process possible? Did the surroundings receive heat (energy) when the coffee cooled down? If so, why do the surroundings not give this heat (energy) back to the coffee?

4

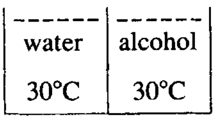
5. Heating of water and alcohol
   5.1 There are two identical containers filled with equal amounts of water and alcohol at 20° C. Tom heats them with two identical burners. After 2 minutes the temperature of the alcohol is 30° C; the water has this temperature after 4 minutes.



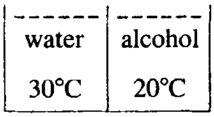
5a

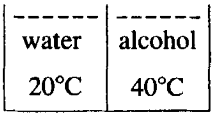
Please explain this. What do you think? Has one of the liquids got more heat (energy)? Has one of the liquids stored more heat (energy)?
[In the interview the interviewer uses the vocabulary (terminology) that the student uses. If, for instance, the student has so far used the word *energy* to describe the temperature equalization processes the interviewer uses the word *energy* for his question.]

   5.2 What happens when Tom brings the two containers with alcohol and water (both at 30° C) into contact?
   Do the temperatures stay the same? Why/why not?
   5.3 Tom has the following idea: I shall use water at 30° C to heat alcohol which is at 20° C. The water has a great deal of heat energy. If I bring the water and the alcohol containers into contact then the alcohol will heat up to 40° C and the water will cool down to 20° C.
   What do you think about Tom's idea?



5b





5c

6. Heat never travels by itself from a colder to a warmer body
   In some textbooks you may find this sentence:
   "Heat never travels by itself from a colder to a warmer body."
   What does this sentence mean to you?
   Please give examples to support the statement.
   Please give examples which are not in accordance with it.
   Has the sentence something to do with the processes discussed in the previous problems?
   What is the meaning of "by itself" in the sentence?
   Are there any conditions in which heat may travel from a colder to a warmer body?
7. Does a pendulum start swinging by itself?
   7.1 Here is a pendulum. It is hanging on a string. It does not move. Suddenly it starts moving and oscillates more and more.
   Is this possible? Why/why not?
   7.2 Now let us have a look at the normal behavior of a pendulum. We set it in motion.
   What happens then? Why?
   Are there any changes involved when the oscillations become smaller and smaller?

7

   7.3 *Is energy involved in the process discussed?*
   Does the pendulum have energy? Which form of energy?
   What happens to the pendulum's energy when the oscillations become smaller and smaller? Does it disappear? Where does it go?
   Is there any heating involved in the process?
   7.4 OK, let us come back to the pendulum starting moving "by itself" (7.1).
   Do you now have an idea as to what would be necessary to cause the pendulum to start oscillating?
   Is it possible that the pendulum receives heat energy back from the surroundings and starts moving?
   Why/why not?
   Does the surrounding air contain any heat/energy?
   Is it possible to set the pendulum in motion by heating it with a burner?
   Is it possible to transform heat into motion? How? Why is it impossible to set the pendulum in motion in this way?
   7.5 *What does energy mean to you? Has energy anything to do with heat? What do you mean when you say that heat is a form of energy? Is there any difference between heat energy and other forms of energy? What are the similarities between the different forms of energy?*
   If heat is a form of energy then shouldn't it be possible to set the pendulum in motion by using heat?
8. Processes take place by themselves in one direction only.
   8.1 *Have you noticed whether the problems we discussed before have anything in common?*
   8.2 All of the problems had to do with the fact that processes take place by themselves in one direction only. (Interviewer gives three examples: examples from problems 1 and 7 and the distribution of ink in water.)

Please give other examples of processes which occur by themselves in one direction only!

8.3 *What about processes around you? Do they take place in one direction only? Or are there processes which can take place both forwards and backwards? Do you have any idea why processes occur by themselves in one direction only? Is it possible for them to take place in the reverse direction?*

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