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Thermodynamics: A Misconceived Theory

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ABSTRACT: Children and physicists alike conceive of heat as being contained in physical systems, even though the “heat” of the physicists’ thermodynamics does not allow for this interpretation. In my opinion, the misconception does not lie with the children but with the particular structure of the theory of thermodynamics. Rather than exorcizing basically sound ideas, I prefer to construct a new approach to teaching thermodynamics based on the notion of heat acquired in everyday life (which is rendered formal by a modern version of the caloric theory of heat). On the basis of didactic considerations we should reject any theory of heat which does not allow for heat to be contained in bodies.

I Introduction

M.Wagenschein[2] tells the story of how he observed a little girl sitting on a park bench in the sun. The girl placed her hand on the hot bench just to withdraw it quickly after some time and hold it in her other cooler hand. According to some recent investigations[3] we can safely assume how concepts about heat form in this little child (see also Section II). The heat of the sun goes into the bench and makes it hot. It is possible to withdraw some heat with a hand, and then let a part of the heat flow into the other hand. Heat is a “thermal fluid” which flows between objects and is stored in them.

Wagenschein then goes on to tell us how these ideas have to be given up to make way for the more profound knowledge gained by those physicists who developed thermodynamics more than a hundred years ago. Wagenschein, who places much emphasis on unifying prescientific and scientific knowledge,[4] finds nothing wrong with this. And indeed, why should he? We all know beyond a shadow of a doubt that the idea of a thermal fluid is wrong:[5] heat is energy, or a form of energy, and not a kind of “fluid”.

Obviously we are confronted with a new case of a misconception which provokes the usual reaction in teachers. While we might be sorry that there is another discrepancy between physics on the one hand, and concepts formed in everyday life on the other, we do not see how we could do anything else but exorcize the misguided notions. The suggestion that we comfort students by mentioning that scientists before Mayer, Joule, and Clausius, erred on the same count,[6] does not change the fact: we are determined to undo what nature has put into students’ minds.

Here I shall propose a completely different solution to the problem of how to deal with the misconception. There is good reason why we should reject the usual form of thermodynamics rather than force our students to change their intuitive concepts. The reason is simple: *Thermodynamics does not allow for heat to be contained in bodies* (Section III). This is not a matter we can pass over lightly. Texts on physics often create the impression that nothing is wrong with the concept of a “heat content”.[7] It seems that even we teachers desperately need to believe that heat can be stored in bodies. This is unacceptable. A theory which makes writers of textbooks succumb to a fundamental misconception should be rejected. We should search for a form of a theory which allows us to retain our intuitive notions regarding heat. If we achieve this goal it will become clear that the usual version of thermodynamics is misconceived. It is not the concept of a thermal fluid which is at fault.

There are still other reasons for investigating the structure of a theory before deciding that, as usual, the intuitive notions are misconceived. Forcing students to give up concepts would certainly be alright if the theory of thermodynamics (as it is being taught) was worth it, and if we did not have a choice. However, a critical analysis of the theory shows that neither one of these possible reasons carries much weight.

(1) *Thermodynamics is not worth giving up intuitive concepts for.* Thermodynamics is considered to be one of the most difficult and abstract disciplines of the physical sciences. Usually we try to excuse this problem by claiming that we are paid for our efforts by one of the most beautiful and most general theories. I do not know whether thermodynamics is beautiful, but I do know that the theory we are taught in school is not as general as we are made to believe. Clausius’ famous words that the energy of the world stays constant while the entropy of the world can only increase, are quoted as proof of the breadth and depth of thermodynamics. In fact they only serve to cover up the weaknesses of the theory. Thermodynamics is little more than glorified thermostatics. A form of mathematics unknown to any other branch of the sciences is used and made to look profound. The theory does not provide us with the means of calculating general initial-boundary-value problems as we know them from mechanics and electromagnetism. And finally, entropy is not understood even though it is the fundamental thermal quantity (Section III). All these reasons make thermodynamics the odd man out among physical theories. They do not make it worth the effort. We should look for a theory which prepares us for modern thermodynamics.[8] Only this expanded version of thermal physics would make it worth giving up intuitive ideas for.

(2) *It is not necessary to give up intuitive concepts formed in everyday life in order to create a theory of thermodynamics*. There is an alternative. It has been demonstrated [9,10] that thermodynamics can be built upon the notion of heat as we acquire it in everyday life (Section V). There

is no need for giving up the intuitive concept of a "thermal fluid" which is contained in bodies and which can flow from one body to another. If it is rendered precise, this notion can be made the basis of a simple understanding of thermal phenomena: the heat of everyday experience is the thermodynamicist's entropy. Such a theory makes thermal physics structurally analogous to electricity and mechanics.[11,12] In this way it becomes the natural introduction to advanced modern thermodynamics of irreversible processes.[8] And what is most important for us: *There is no misconception on the part of the student* (and the teacher) who formed the image of the thermal fluid.

II Heat in Everyday Life

A good number of investigations[3] have demonstrated that students have their own ideas regarding the nature of heat. Here I would like to add some observations concerning concepts formed before much formal schooling in thermodynamics has occurred. I shall use material gathered in my classes at ZHW. I let my first-year engineering students write a short essay on what they believe heat to be before I introduce thermal physics. I always stress that I would like to know what images they have formed of heat irrespective of what they have learned in school. All of them, however, have been told by previous teachers that heat is energy. It will be interesting to investigate the influence of this pre-college teaching. This study is complemented by a second one in which junior and senior engineering students answered some specific questions regarding heat.

It is clear that students believe that heat is contained in bodies, and that it can be created (Fig.1). Indeed, in the second study, 29 out of 31 students (who have had some college thermodynamics) answered in the affirmative the direct question of whether or not heat was contained in physical systems. Compared to this, the belief that heat and temperature are the same has been voiced rather infrequently. Indeed, at this level, students usually distinguish between an intensive and an extensive thermal quantity. The extensive quantity is called heat, and it is believed to be something like a "medium" which is stored in bodies, and which can flow from body to body. Again, the question of whether or not they picture heat to be a sort of invisible medium which is stored and which can flow (rather like electrical charge and water), was answered in the affirmative by 27 out of 31 juniors and seniors. Explanations of the phenomenon of heat in terms of energy play a minor role (Fig.1). If at all, energy only has been mentioned in passing in most cases. More detailed results show that the concept of energy is used incorrectly most of the time: students' knowledge does not extend beyond the superficial notion that heat is energy.

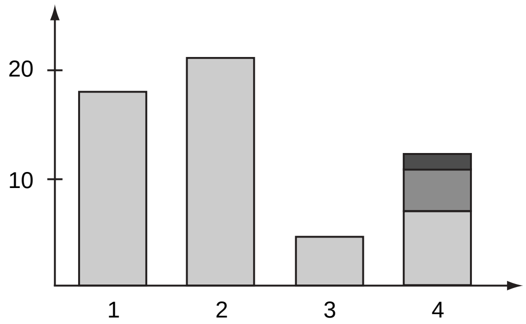

Figure 1: Results of the analysis of 42 essays on heat. Different opinions are given. Numbers of answers are plotted vertically. 1: heat can be created; 2: heat can be stored; 3: heat and temperature are the same; 4: heat is energy (light: energy mentioned in passing; darker: energy mentioned more often; black: energy is an integral part of the explanation).

All in all, we can conclude that *students picture heat to be an extensive quantity with all its attributes: it can be stored, and it can flow.* Often, we associate with the term "extensive" a quantity which is conserved. The study shows that students do not spontaneously assume heat to be conserved. However, if they are asked directly, they usually resort to an explanation in terms of conversion of energy. Their intuitive knowledge of the one-sidedness of heat (none of the students mentions that heat can be destroyed[13]) collides with the belief of the conservation of a quantity which is imagined to be something like a "fluid". This type of reaction is the same in electricity and in mechanics where charge and momentum often are assumed to be converted out of other forms of energy.

The concepts formed obviously are similar to those held in the caloric theory of heat. Like the physicists who used this theory, students show an ambivalence as to the conservation of this quantity, and they solve the problem in the same way as was done more than 100 years ago (Section IV): they resort to the use of the concept of energy. However, they do not do so spontaneously.

III Heat in Classical Thermodynamics: The Dynamical Theory of Heat

In order to see why believing heat to be an extensive quantity is a misconception in thermodynamics, we have to understand the theory as it is commonly presented. This theory, which was first developed around 1850 by

R.Clausius, is based on the so-called dynamical theory of heat.

Ever since Clausius, heat has been an exchange form of energy. Clausius built his theory on the assumption that heat and work should be universally and uniformly interconvertible in cyclic processes. If W is the work done by a heat engine in one cycle, and Q is the difference between heat absorbed Q^+ and heat emitted Q^- in this cycle, then

$$W = JQ = J\left[Q^+ - Q^-\right] \quad (1)$$

where J is the mechanical equivalent of a unit of heat. This is the expression of the dynamical theory of heat.

This does not mean that heat is energy. In particular, heat is not internal energy. Heat is the name for energy exchanged in thermal processes, no more, no less. As such, it has to be strictly distinguished from internal energy. Thermodynamics needs this distinction: otherwise it is left impotent when it comes to formulating the First Law. We have to make perfectly clear to students that the first law

$$\Delta U = Q + W \quad (2)$$

may not be read as follows: the (internal) energy of a body is the sum of heat and work, suggesting that at any given moment we could say how much heat and how much work the body contains. The quantity Q in (2) has a totally different meaning. The problem is that even physicists do not always grasp this meaning,[7] since the words used mask it completely (Section IV). We have to conclude that the majority of students, including those who have had physics and engineering thermodynamics, plus a good number of teachers, are victims of a misconception (Section II): in the dynamical theory of heat, *heat is not contained in bodies!*

There is a simple way by which we can demonstrate that we may not believe heat to be contained in bodies. Take a compressed gas in a cylinder with a piston, with values of temperature and pressure higher than those of the surroundings. How much heat is contained in this gas? Obviously, this question is senseless. If a heat content existed, we should be able to measure changes of this quantity. Different processes can be envisioned which lead to such a change. We can let the gas expand adiabatically, or we can let it cool through heat conduction. Now, since the amount of heat exchanged is different in the two processes, we cannot say by how much the heat content has changed. Therefore, there is no such thing as a “heat content”.

IV Historical Development

Why is there such a dichotomy between intuitive concepts and the theory of thermodynamics? The historical development can cast some light on this question. On the one hand we will see that there are some reasons and some prejudices which explain why thermodynamics developed the way it did; on the other hand it will become clear that only a small step separated S.Carnot from finishing the theory of thermodynamics on the basis of the caloric theory of heat. In other words, only a small step was needed to found thermodynamics on the basis of intuitive concepts rather than anti-intuitive ones.

The historical development roughly went along the following lines.[10,14] The caloric theory of heat was widely accepted during the period before 1850. In mathematical terms, it simply meant that for the fluids used there exists a heat function (Section V). It was assumed that heat (caloric) was conserved which, for the cases treated by Carnot and by later thermodynamicists, was acceptable. However, the main problem with the caloric theory of heat can be traced to irreversible processes in which, as Davy’s experiment (melting two blocks of ice by rubbing them) had demonstrated, heat must be generated. Today we know that heat cannot be caloric if we accept that the usual calorimetric measurements determine amounts of heat. In these experiments heat would be generated.

The concept of caloric and a heat function led Carnot to propose the following analogy for the functioning of heat engines: heat falls from a higher to a lower level (temperature), thereby driving the engine just like water drives a water wheel. Carnot proceeded to derive the motive power of heat. However, the result which was based on the caloric theory required the heat capacities of the ideal gas to be inversely proportional to the ideal gas temperature. If we measure “heat” in the usual calorimetric devices, we get a different answer: the capacities should be constant. Carnot did not decide between this and another solution he proposed, thus forgoing the simplest form of a theory of thermodynamics (Section V).

However, measurements were not accurate enough for deciding if the caloric theory of heat was still tenable. Also, the often cited experiment by Rumford, which is supposed to have demonstrated that heat could not be caloric, did not even prove that caloric was not conserved. Even Joule’s experiments did not show that heat is an energy form: the range of temperatures employed by him was too small for the motive power of heat to be determined experimentally. His experiments simply supported a completely new idea: there is a quantity called energy associated with different types of processes (electrical, mechanical, and thermal) which remains constant during such processes.

Something else was needed for deciding between the two concepts concerning the nature of heat.[10] It was the prejudice of physicists "that heat is not a substance, but consists in a motion of the least parts of the bodies" (Clausius), which suggested that the heat (energy!) capacities of the ideal gas should be constant. Now, nothing in the world of experiment could have suggested such a belief at the time. Still, Clausius sought, and found, a theory which both determined the motive power of heat and allowed for the capacities to be constant. It is irony indeed that Clausius' solution does not permit us anymore to think of heat as the "motion of the least particles of the bodies", since this would equate heat and internal energy!

We conclude that Carnot could have finished his theory of the motive power of heat on the basis of the caloric theory if he had accepted that heat (caloric) can be generated in irreversible processes (which would have told him that calorimetric devices do not measure caloric[10]). The dynamical theory of heat triumphed not because of nature, and not because of pure reason, but because we want heat to be the irregular motion of the atoms.

Here is the point to say a few words about the usage of terms and expressions in thermal physics. The very word heat, like electricity and motion, suggests an extensive quantity. The term "heat capacity" and "latent heat" make us think of a quantity which is contained in bodies. "Absorption of heat", and "emission of heat" do the same. Why should heat, which has been absorbed, not reside in the body which absorbed it? No wonder that we have such difficulties with thermodynamics if the simplest and most intuitive things are not true anymore. Take mechanics. There we have a different, and neutral, word for the energy exchanged in mechanical processes: it is "work", and not "motion". If we want to learn from other fields of physics, we should call the extensive thermal quantity heat (and not entropy), and "heat" (thermal energy) should be called thermal work. The trouble with thermodynamics is that *the words which make sense in the caloric theory have been transferred to a context where they simply do not belong*. As Kelvin put it in 1878 ("Heat", Encyclopedia Brittanica, 9th ed.): "Now that we know heat to be a mode of motion, and not a material substance, the old 'impressive, clear, and wrong' statements regarding latent heat, evolution and absorption of heat by compression, specific heats of bodies and quantities of heat possessed by them, are summarily discarded. But they have not yet been generally enough followed by equally clear and concise statements of what we now know to be the truth. A combination of impressions surviving from the old erroneous notions regarding the nature of heat with imperfectly developed apprehensions of the new theory has somewhat liberally perplexed the modern student of thermodynamics with questions unanswerable by theory or experiment…".

V Thermodynamics on the Basis of the Caloric Theory of Heat

The way we think about heat, even after much formal schooling, resembles the old caloric theory of heat. Heat is something like a "thermal fluid" which can be stored, and which can flow from body to body. Intuitively, we also know that heat is not conserved (Section II). This suffices for building thermodynamics on an extended version of the caloric theory of heat.[10]

We start with a specific theory of calorimetry for a particular type of fluid.[14] This theory served as the basis of just about all the investigations regarding heat from the beginning to Clausius and Kelvin. Only the theory of the conduction of heat was excluded from it. The theory will be outlined briefly. The bodies used in this theory are those which (1) obey a thermal equation of state relating pressure, volume, and temperature:

$$p = p(V,T) > 0 \tag{3}$$

and (2) for which two further constitutive quantities exist, namely the latent and specific heats (Λ_V and K_V):

$$\Lambda_V = \Lambda_V(V,T) > 0 \quad , \quad K_V = K_V(V,T) > 0 \tag{4}$$

The index V refers to the latent heat with respect to volume, and the specific heat at constant volume. [The first inequality in Eq.4 excludes water in the range of temperatures from 0°C to 4°C from our considerations.] This means that the bodies can be fully described by the values of two variables, namely volume and temperature. The latent and specific heats are related as follows to the heating:[15]

$$\dot{S} = \Lambda_V \dot{V} + K_V \dot{T} \tag{5}$$

The heat (caloric) exchanged in a process P is then given by

$$\dot{S} = \int_P \dot{S}\,dt \tag{6}$$

Note that nothing has been said about what heat "really" is. A few consequences of the theory of calorimetry are particularly interesting. First, the bodies subsumed by this theory can only undergo reversible changes.[10] Second, the latent and specific heats with respect to volume and pressure are related by

$$\Lambda_p = \Lambda_V \left(\frac{\partial p}{\partial V}\right)^{-1} \quad \textbf{(7)}$$

$$K_p = K_V - K_V \left(\frac{\partial p}{\partial T}\right) \cdot \left(\frac{\partial p}{\partial V}\right)^{-1} \quad \textbf{(8)}$$

Finally, we can derive the Poisson-Laplace Law of adiabatic change (*dS/dt* = 0) for the ideal gas with constant ratio of the specific heats:

$$pV^{\kappa} = const \quad , \quad \kappa = \frac{K_p}{K_V} = const > 1 \quad \textbf{(9)}$$

The inequality follows from Lapace's explanation of the speed of sound. This speed is always higher than that calculated if the oscillations of the gas were isothermal. The observation that the ratio of the specific heats must be constant will prove to be crucial when we determine the motive power of heat.

We need two assumptions plus the theory of sound (Eq.9) in order to derive the motive power of heat. This development simply finishes what Carnot had left open. The first assumption is that the caloric theory of heat is valid. In the context of our theory of calorimetry his means that there exists a "heat function" $S(V,T)$. As a consequence, the latent and specific heats are related to the heat S by

$$\Lambda_V = \frac{\partial S(V,T)}{\partial V} \quad ; \quad K_V = \frac{\partial S(V,T)}{\partial T} \quad \textbf{(10)}$$

Also, if we consider a fluid body to undergo a (Carnot) cycle, the heat absorbed (S^+) and the heat emitted (S^-) in one cycle must be equal:

$$S^+ = S^- \quad \textbf{(11)}$$

This means that a heat engine can do work without any consumption of heat. (Compare this with Eq.1, the expression of the dynamical theory of heat.) Heat simply is the driving agency like water in the case of a water wheel.

The second assumption concerns the validity of Carnot's Axiom.[14] It states that the work done by a heat engine undergoing Carnot cycles only depends on the temperatures of the furnace (T^+) and the refrigerator (T^-), and on the heat absorbed from the furnace (S^+). These two assumptions together with the observation that the ratio of the specific heats must be constant (Eq.9) suffice to determine the relationship between the heat "falling" from the higher to the lower temperature and the work done by it:

$$W = \left(T^+ - T^-\right)S^+ \quad \textbf{(12)}$$

The result is analogous to what we know from gravitation. Heat corresponds to the mass of water falling, and the difference of temperatures is compared to the difference of the gravitational potential. The heat capacities of the ideal gas turn out to be inversely proportional to the (ideal gas) temperature T:

$$K_V \propto \frac{1}{T} \quad , \quad K_p \propto \frac{1}{T} \quad \textbf{(13)}$$

which still allows for their ratio to be constant as required by the theory of the speed of sound. Finally, there exists a function E of the body (which we call its internal energy) such that:

$$\dot{E} = T\dot{S} - p\dot{V} \quad \textbf{(14)}$$

This should now be compared to the theory of thermodynamics based on the dynamical theory of heat. We find that heat in the caloric theory is the enigmatic entropy of classical thermodynamics.

VI Conclusion: What is a Misconception

There are three points we should keep in mind: (1) students and teachers alike need a quantity which they call heat and which they can believe to be contained in bodies; (2) thermodynamics can be built on the basis of the caloric theory of heat (in this form it is structurally analogous to electricity and mechanics); and (3) the classical form of the theory is too limited (it does not prepare students for modern non-equilibrium thermodynamics). These three reasons call for a modern version of introductory thermodynamics.

If we build thermodynamics on the caloric theory of heat (suitably extended by the requirement that heat is created in irreversible processes), an interesting reversal of the roles of intuitive concepts and accepted theory results: it is not the concepts which are wrong, it is the theory which, unnecessarily, makes sound intuitive notions unacceptable. A similar situation exists in mechanics with regard to forces.[16] Fig.2 shows that most students have formed correct concepts if heat is accepted as entropy. Indeed, 17 essays can be taken as a lucid explanation of the concept of entropy, while only two describe the dynamical theory of heat in an acceptable way.

Thermodynamics therefore is a case which forces us to investigate the structure of the theory before we conclude where the misconception lies. In this case we are allowed to say that the form of the theory is misconceived. The theory disregards valuable information contained in intuitive concepts formed before formal schooling has taken place. For didactic reasons it should be rejected. In an analogous case we would not hesitate to discard such a theory. If we develop electricity along lines we know from thermodynamics, we get a structure which, according to taste, is either unacceptable, or ridiculous, or both.[11]

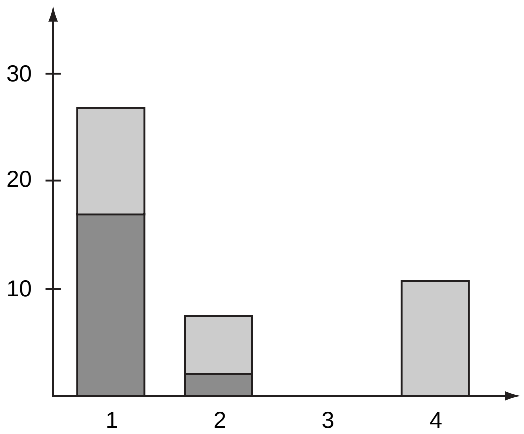

Figure 2: Results of the analysis of 42 essays on heat. In the essay, heat can be 1: only entropy (light: only entropy if a reference to energy is dropped); 2: only energy (light: only energy if a reference to storage of heat is dropped); 3: both entropy and energy; 4: neither entropy nor energy, or too vague.

This is not to say that a new structure will present us with a brave new world in which all is well. My experience in the teaching of several different subjects suggests that students resort to the wrong use of the concept of energy when they are confronted with the task of recognizing the role of so-called substancelike quantities like electrical charge (electricity), momentum (motion), and entropy (heat). At first sight, it seems that electricity, motion, and heat, can all be created. Since they have an apparent aversion to such a conclusion, students resort to the cure-all: energy. To give an example: charge, which has been used to introduce electrical phenomena, is not created; students rather say that it is converted out of other forms of energy. The real remaining problem thus is the failure to understand the role of energy and its relationship to the substancelike quantities in physical processes.[17] Whether this failure has its roots in experience outside of formal schooling, or whether it is a result of the teaching of physics, I cannot decide at this point. However, since the concept of energy and its conversion is a result of teaching rather than a self-evident notion, I suggest that we should look to how we teach physics if we want to solve the problem.[17]

Notes and References

[1] This is the slightly reworked version of the paper presented at the Second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics held at Cornell University in July 1987. It was Published in the Proceedings (J.D.Novak, ed.). I have changed some of the references. I have dropped references to reports no longer available and replaced them by more recent and more useful ones. The rest of the paper is essentially unchanged.

[2] M.Wagenschein: Ursprüngliches Verstehen und exaktes Denken. Vol.2. Klett Verlag, Stuttgart, West Germany, 1970; p.101-108.

[3] E.Engel Clough and R.Driver: Secondary students´ conceptions of the conduction of heat: bringing together scientific and personal views. Phys.Educ. 20,176-182, 1985. And references therein.

[4] M.Wagenschein: Die pädagogische Dimension der Physik. Klett Verlag, Stuttgart, 3rd ed. 1971.

[5] The following quote is typical for our belief: “...[Carnot] had grasped the real nature of heat and its equivalence to work.” (J.B.Fenn: Engines, Energy, and Entropy. Freeman and Company, New York, 1982. p.86).

[6] Reference 2, p.182.

[7] While a recent text on introductory physics calls heat the energy of the irregular motion of atoms and molecules, its accompanying Study Guide calls heat a form of energy exchange. (H.Ohanian: Physics. W.W. Norton & Company, New York, 1985. Van E.Neie and P.Riley: Study guide, Ohaninan’s Physics. W.W.Norton, 1985.) S.Strauss and R.Stavy (Educational-developmental psychology and curriculum development: the case heat and temperature. In H.Helm, J.D.Novak eds.: Proceedings of the International Seminar on Misconceptions in Science and Mathematics, Cornell University, Ithaca, N.Y. 1983, p.292) express the same misconception differently: they call heat the extensive thermal quantity.

[8] I.Müller: Thermodynamics. Pitman, Boston, 1985. C.Truesdell: Rational Thermodynamics. Springer-Verlag, New York, 1984.

[9] H.U.Fuchs: Entropy in the teaching of introductory thermodynamics. Am.J. Phys. 55,215-219,1987.

[10] H.U.Fuchs: *The Dynamics of Heat*. Springer-Verlag, New York, 1996.

[11] H.U.Fuchs: A surrealistic tale of electricity. Am.J.Phys. 54, 907- 909,1986.

[12] J.U.Thoma: Bond graphs for thermal energy transport and entropy flow. J.Franklin Inst. 292(no.2),109-120,1971. J.U.Thoma and H.Atlan: Network thermodynamics with entropy stripping. J. Franklin Inst. 303,319-328,1977. J.U.Thoma and H.Atlan: Osmosis and hydraulics by net-

work thermodynamics and bond graphs. J.Franklin Inst. 319,217-226,1985.

[13] One student expressed his concept succinctly: “Heat can be created, but it cannot be destroyed anymore; all we can do is distribute it in colder places.”

[14] C.Truesdell: The Tragicomical History of Thermodynamics 1822-1854. Springer-Verlag, New York, 1980. C.Truesdell and S.Bharatha: The Concepts and Logic of Classical Thermodynamics. Springer-Verlag, New York, 1977.

[15] S is the heat (caloric) of the body which we take to be a function of volume and temperature. The dot denotes the time rate of change of the heat content. By heating we might mean the current of heat (caloric) entering or leaving the body. If heat (caloric) is conserved, as it must be for the fluids treated here, then the heat flow and the time rate of change of the heat content are equal.

[16] H.U.Fuchs: Do we feel forces? In J.D. Novak ed.: *Proceedings of the Second International Seminar on Misconceptions in Science and Mathematics*, Vol.III, p. 152–159. Cornell University, Ithaca, New York.

[17] H.U.Fuchs: The continuum physics paradigm in physics instruction I. Images and models of continuous change. ZHW, 1997.