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The Conflict Between Theory and Intuition in Contemporary Thermodynamics and Its Historical Causes

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Conflict Between Theory and Intuition

Thermodynamics is generally regarded as conceptually difficult. In its structure it differs strongly from other parts of classical physics, so that mutual support and clarification through analogy and comparison are difficult. Whereas elementary mechanics and electromagnetism are founded upon intuitively grounded concepts such as space, time, force, body, mass, and charge, thermodynamic literature is dominated by abstract and colorless terms such as entropy, enthalpy, state function, cyclic process, potential, system, reversibility, and so forth. Even familiar words such as heat or quantity of heat mean something fundamentally different in ordinary language from what they mean in physics, so that thermodynamics becomes harder rather than easier to understand when one seeks support in intuition.

Let us consider an example. In everyday speech one speaks of the heat contained in a heated room, generated in the stove and flowing out of the room with the air when a window is opened. If, however, one adheres strictly to the physical definition, one can speak neither of heat contained in the room, nor of heat generated in the stove, nor of heat transported by the air current. In theoretical physics the word “heat” denotes only the energy transferred to a body from its surroundings through irregular molecular motion. It does not denote any fraction of the energy already present in matter or generated there. Thus heat, like work, signifies a mode of transfer of the energy rather than a storage form of energy. Mathematically this is expressed by the fact that the quantity Q, just like work, is not a state function and that dQ is not a total but a partial differential. The widespread view, even among scientifically educated people, that the kinetic energy of molecules in a gas constitutes the heat content of the gas is incompatible with the conceptual definitions of modern thermodynamics.

Although this situation has been known for one hundred and twenty years, the conviction stubbornly persists outside theoretical physics that a body not only can receive heat but also contains it. Undoubtedly this conception is well suited for understanding the propagation of heat, temperature changes when liquids are mixed, the cooling and heating of bodies, and many other processes, and therefore it is repeatedly invoked consciously or unconsciously. Certain expressions are intelligible only on the basis of this conception, such as heat capacity, heat storage, and heat conduction. Even the introduction of enthalpy as a heat function is ultimately a concession to intuition. Here the intellectual conflict of thermodynamics is especially evident: on the one hand the insight that there is no such thing as heat content, and on the other the inability to free oneself completely from this idea.

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Proposals for Eliminating the Conflict

One can understand that doubts arise concerning the internal logic of thermodynamics when these inconsistencies become apparent. To have such reservations about a science long regarded as clarified may seem excusable; however, to express them may seem presumptuous. Yet since no one these days is any longer burned for his convictions, I should nevertheless like to venture to voice these doubts.

One may rightly ask what a self-consistent theory of heat would look like if it were not split between the desire for intuitive clarity and the demand for the simplest possible and most powerful formalism. The answer cannot be given in a few words. The most obvious idea would be to construct the theoretical framework consistently according to one of the two conflicting demands while temporarily disregarding the other entirely. There are two possibilities. Either one attempts, beginning with the everyday conception of heat, to construct an intuitive thermodynamics without regard for established definitions, or else one begins with the familiar conceptual system of thermodynamics and eliminates every variable that is in any way dispensable.

Renunciation of Intuition

This is not the place to develop such ideas in detail, and I can only briefly sketch the result of these considerations. At first glance the second path appears more promising, namely to begin with conventional thermodynamics.[1]

If one examines the effectiveness and mutual replaceability of the various variables, it becomes apparent that alongside purely mechanical and electrical quantities only temperature, entropy, amount of substance, chemical potential, and a few derived concepts are sufficient for the description of thermal phenomena. None of the energetic variables is necessary — neither heat nor work nor any of the characteristic functions. On the contrary, every additional variable complicates the calculations. For all quantities employed, methods of measurement can readily be specified, so that the formalism and observable phenomena can be mapped onto one another. This is necessary if the result is to be a physical theory rather than a mathematical game.

The most striking result is that thermodynamics is by no means the science of the transformation of energy; rather, this is merely one possible mode of representation, and not even a particularly useful one.

The Other Possibility

Surprisingly, the first of the two paths mentioned above also leads to the goal[2]. As a starting point I have chosen a procedure unusual for the physical sciences. I have asked a number of people — housewives, students, office employees, and others — what they imagined heat to be. Among the answers given, the one selected as richest in intuitive content was the conception that heat is an imponderable something present in every body in varying quantities, causing it to appear more or less warm, that can be transferred from one place to another, generated by friction or combustion, yet cannot be destroyed. In essence, then, heat was conceived as an imponderable something that can be produced but cannot be annihilated.

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[1] *Georg Job:* Vorschlag zur Vereinfachung thermodynamischer Begriffsbildungen. Eine Kritik der herkömmlichen Wärmelehre. (Not published)

[2] *Georg Job:* Anschauliche Wärmelehre. Ein Vorschlag zur Neugestaltung der Thermodynamik. (Not published)

On this basis it is in fact possible to construct a self-consistent thermodynamics encompassing all thermal phenomena. Temperature can be introduced as the potential of this heat and interpreted intuitively as a kind of pressure or tension. This tension is at the same time the cause of heat striving to spread and pass from one body into another. In a similar way one can define potentials or tensions for substances or amounts of substance which govern the distribution, phase and reaction equilibria, as well as diffusion and ion migration. It is even possible, following the model of electrodynamics, to define force fields associated with these potentials and to understand equilibria as the result of compensating forces. Thus one obtains a theory related to mechanics and electrodynamics that appears formally and conceptually much simpler than conventional presentations.

Comparison of the Two Solutions

Since the two conceptual systems of thermodynamics discussed above — the purified abstract one and the intuitive one — are representations of the same macroscopic phenomena, one should expect them to be translatable into one another. Indeed, a comparison of the mathematical structures yields the simple correspondence:

Heat — Entropy
Heat tension — Temperature
Amount of substance — Amount of substance
Substance tension — Chemical potential

This comparison shows that the heat commonly thought to be contained in a body corresponds to entropy S. This is extraordinarily surprising, since S is generally regarded as one of the most difficult and elusive variables of thermodynamics. To convince ourselves that this result could be correct, let us briefly compare the properties of the two concepts in question in more detail; specifically, let us examine whether the properties that heat would possess if we were actually to equate it with the quantity S are reasonable.

To begin with, heat would be a state function. Intuitively this means that every body possesses a definite heat content S. That is what we are aiming for. At 0 K, according to Nernst's theorem, one can generally set $S = 0$; to put it figuratively, this would mean that a completely cold body, or more generally a system at absolute zero, would no longer contain any heat. This, too, is entirely reasonable. The phenomenon of zero-point entropy, that is,

$$S > 0 \text{ for } T = 0,$$

could easily be explained by the assumption that heat transfer from certain material structures is severely inhibited at low temperatures, so that the heat remains trapped as in a thermos flask. Now, without contradicting the theory, we could also speak of the heat contained within a room and of the fact that it flows out of the window along with the air when we open it. If a gas is compressed or expanded adiabatically, that is, at constant S, the temperature can change very significantly. We can easily explain this phenomenon by the fact that temperature apparently depends not only on the total amount of heat contained in the matter, but also on whether that heat is concentrated in a small region or spread over a larger one.

All of this sounds quite plausible. However, we must now go on to require that heat is generated in all irreversible processes, i.e. those that increase entropy. Processes of this kind include, for example, friction, combustion, plastic deformation, viscous flow, the passage of a current through a resistor, etc.—in essence, all processes in which we somewhat carelessly speak of heat generation anyway, even though, according to thermodynamics, we ought not to do so. But what about the following irreversible processes: the Gay-Lussac experiment, the diffusion of two gases into one another, and heat conduction?

Let us first turn to the first question. In Gay-Lussac's experiment, for example, a gas isolated from its surroundings is allowed to expand into an evacuated vessel, with the average temperature usually changing only slightly. If the process were performed reversibly, the isolated gas would have to cool down significantly. To explain the actual result, one can simply argue that the heat generated during this irreversible process precisely compensates for the cooling. A similar approach can be taken in the case of the diffusion of two previously separate gases into one another: the cooling that would be expected in the reversible process, i.e. with a fixed S, is exactly balanced by the heat generated, so that no effect is noticeable externally. Consequently, no contradictions are found here either.

The case of heat conduction is more difficult. The idea that heat should be generated here is, according to previous understanding, completely alien to us. But where does the conviction come from that heat is conserved during conduction? Even the old calorimetric definition of heat is based on the tacit assumption that the amount of heat transferred from a hotter body to the calorimeter by conduction does not change. But how can we know this? The assumption is arbitrary. With equal justification, we could, for example, stipulate that, in order to measure it, heat should be transferred to the calorimeter not by conduction but by a Carnot process. If one does so, however, then according to this modified procedure, it is no longer heat in the conventional sense that is measured calorimetrically, but entropy. The heat defined in this way would, however, actually—that is, in a truly measurable way—increase during conduction through a temperature gradient. This generation of heat becomes quite clear when we compare it with Joule's heat during the flow of an electric current through a resistor. The heat flow meets resistance, the overcoming of which generates heat, just as in the electrical case.

The question remains as to whether the quantity S precisely increases for a system when we speak of heat input or heat generation. We have just ascertained that this holds true for generation. Let us now consider the other case, and for the sake of simplicity, only reversible processes in which no entropy is generated. Then

$$dS = \frac{dQ}{T}$$

and we see that dS is positive precisely when dQ is positive. Since the quantity Q has, in our view, so far described the heat input correctly in qualitative terms, the quantity S does so as well.

In summary, we can conclude that entropy correctly reflects what we understand as heat in everyday life.

Temperature as potential and tension

We should briefly discuss yet another noteworthy result, as it is important for what follows: namely, that temperature can be regarded as the potential of intuitive heat, or as a tension on it. This gives rise to a range of ways of speaking and thinking that are reminiscent of those found in mechanics and electromagnetism. For example, the equalization of temperature in a heat-conducting body left to its own resembles the equalization of voltage in an electrical conductor. Heat, or entropy, can be regarded as a quantity conceptually related to electric charge. However, whilst a law of conservation applies to electric charge e in closed systems – the total charge can neither increase nor decrease – this is only partially true for 'thermal charge'; it cannot decrease, but it can increase:

$$de = 0, \qquad dS \geq 0.$$

The work done by a heat engine operating between two reservoirs at temperatures T_2 and T_1 is, as in the theory of electricity, given by the product of the potential difference and the charge transferred:

thermal: $W = (T_2 - T_1)\ S$ electrical: $W = (u_2 - u_1)\ e$

(u = electric potential). We can easily see that this result agrees with the equation for the Carnot efficiency

$$W = (T_2 - T_1)\ S = \frac{T_2 - T_1}{T_2} \cdot T_2 S = \frac{\Delta T}{T_2} \cdot Q_2$$

This result, which is otherwise difficult to derive, follows directly from the intuitive picture presented here.

When heat—that is, entropy—is supplied to a body, it must be forced in against a thermal potential T. As with forcing a gas into a container against the pressure prevailing there, the work required for this should be proportional to the amount supplied and to the potential:

thermal: $dW = T \cdot dS$ mechanical: $dW = p \cdot dV$

(Here, V denotes the volume of gas supplied, not the volume of the container). However, the term $T \cdot dS$ is identical to heat in the conventional sense, and thus correctly describes the energy absorption during heating, that is, the supply of entropy. Thus, the energy quantity Q would simply to be understood as work, comparable not only to the mechanical work involved in pumping a gas into a container, but also to the electrical work required to charge a body against the voltage u that builds up:

electrical: $dW = u \cdot de$

A question to history

At this point we must terminate our considerations in order to turn to a question that gradually imposes itself: If thermal phenomena can be described so much more easily using a differently defined heat, why did historical development simply pass by this insight? What caused the unfortunate development of thermodynamics that led to an irreconcilable conflict between theory and intuition and to a flood of abstract concepts making the science so difficult to understand?

I will try to give an answer to that.[3]

The caloric substance

In the seventeenth century heat was imagined as the motion of the smallest particles of matter. No distinction was made between intensity and quantity, as is still the case in ordinary language. Under the influence of chemistry people later tended increasingly to regard heat as a substance and, like the chemical elements, as indestructible.[4]

This conception readily explained the propagation of heat and the behavior of temperature in mixing experiments if temperature was taken proportional to the concentration of heat. Melting and evaporation were interpreted as reactions of this heat substance with the heated material. When friction occurs, heat should not be generated, but rather released from the abrasion. It was only then that more nuanced concepts such as amount of heat, de-

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[3] See also *Stephen F. Mason:* Geschichte der Naturwissenschaft. German edition in collaboration with *Klaus M. Meyer-Abich*, edited by Bernhard Sticker. Stuttgart (1961); *Max von Laue*: Geschichte der Physik. Bonn (1946); *Ernst Mach*: Prinzipien der Thermodynamik. 2nd ed. Leipzig (1900).

[4] See also: *Paul Walden:* Geschichte der Chemie. Bonn 1947; *Joseph Black:* Lectures on the elements of chemistry. Edited by *John Robinson.* Edinburgh (1803); *Johann Heinrich Lambert:* Pyrometry, or On the Measures of Fire and Heat. Berlin (1779); *Leopold Gmelin:* Handbuch der theoretischen Chemie. Vol. 1. Frankfurt am Main (1817).

gree of heat and heat capacity began to emerge, though it took many more decades before a rigorous distinction between these thermal concepts became common knowledge.

Sadi Carnot

In 1824, Sadi Carnot laid the foundations of modern thermodynamics.[5] His reasoning was based on the insight that, due to thermal expansion resulting from a change in the shape or volume of a sample, work can always be extracted whenever there are temperature differences. Since the possible gain in work increases with the temperature difference and the amount of heat transferred, he arrived at the following analogy:

> Based on the concepts established so far, it is entirely appropriate to compare the driving force of heat with that of falling water… The driving force of falling water depends on its height and the amount of liquid; the driving force of heat likewise depends on the amount of heat applied and what might be called its 'falling height', namely the temperature difference ...[6]

He concludes that for the useful work of a lossless process – examples of which include his well-known cyclic processes –:

> The motive force of heat is independent of the agent used to generate it; its quantity is determined solely by the temperatures of the bodies between which the transfer of heat ultimately takes place.[7]

His line of reasoning is rigorous and independent of the underlying concept: for if that were not the case, then the heat transfer caused by a particularly efficient process could be completely reversed by a second, reversible process requiring less energy, leaving a net positive amount of work. "Such a creation, however, stands in complete contrast to currently accepted ideas, to the laws of mechanics and sensible physics ..."[8]

Carnot thus demonstrates – by invoking the impossibility of a 'perpetual motion machine' (the French Academy had not accepted any proposals of this kind since 1775) – that temperature acts as a level value when the caloric substance remains constant. In 1848, *William Thomson* proposed dividing the temperature scale in such a way that transferring a unit of heat between any two bodies with the same temperature difference would always yield the same amount of work. This would define temperature as a potential of the caloric. *Hermann von Helmholtz* offered a slightly different interpretation of Carnot's line of thought. In his view, *Carnot* saw heat as though '… at a higher temperature it possessed, so to speak, a state of greater elastic tension and expanded, when it passed to a lower temperature, whereby the elastic tension of the heat-bearing substance was converted into external work'.[9] We find such a dynamic conception expressed as early as 1800 by *Marc Auguste Pictet:* "Bodies at higher temperatures contain heat in a state of greater tension. The equalization through radiation is an equalization of thermal tensions"[10], or even earlier in *Johann Heinrich Lambert:* "... heat, regarded as a force, can now also be in equilibrium with itself and is so whenever a body ... is equally warm or hot in all its parts."[11] Both a potential and a stress conception of temperature were thus fundamentally established long

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[5] *Sadi Carnot:* Réflexions sur la puissance motrice du feu(1824). Paris, Chez Bachelier, Libraire

[6] *Sadi Carnot:* Réflexions… p. 28.

[7] *Sadi Carnot:* Réflexions… p. 38.

[8] *Sadi Carnot:* Réflexions… p. 21.

[9] *Hermann v. Helmholtz*: Vorlesungen über theoretische Physik. Bd. 6. Theorie der Wärme. Herausgegeben von Franz Richarz. Leipzig (1903), S. 207.

[10] Quoted from *Mach* (1900), 128.

[11] *Lambert*, (1779), 8.

before, and the heuristic value of such analogies is recognizable in the work of *Carnot*.

The law of energy conservation

In the forties of the last century, the law of conservation of energy was formulated as the culmination of a long process of development.[12] Put simply, it states that every individual process possesses a specific amount of work and that, in every event, the sum of these equivalents of work remains constant. *Julius Robert Mayer's* formulation is: 'In all physical and chemical processes, the given force remains a constant quantity'[13], if one regards work as the exchange form of a quantity—'force' or energy—assigned to every body or system of bodies in a specific amount. This law drastically restricts the processes possible in nature. If, for example, two processes are coupled, this can only occur in such a way that their equivalent values *W* mutually compensate each other:

$$W + W' = 0.$$

James Prescott Joule's experiments clearly demonstrated that heat can be generated and that, per unit, the same amount of work is always expended at the expense of the process that produces it; in other words, the law of conservation of energy also applies to the generation of heat. Whilst *Joule* regarded heat as a form of energy on the basis of his experiments, it was only after many years of hesitation that *W. Thomson*, who had worked with him on some projects, was persuaded to accept this view by *Rudolf Clausius's* early publications.

Rudolf Clausius

Until well into the mid-nineteenth century, the motion theory and the substance theory of heat remained at odds, despite the friction experiments conducted as early as before 1800 by Count *Rumford* (*Benjamin Thompson*) and Sir *Humphry Davy*, which clearly contradicted the substance theory.[14] It was believed that there were good reasons for both views:

> Just as the ordinary conduction of heat unmistakably bears the imprint of the gradual absorption of a material substance . . ., so too do the phenomena of heat radiating from reflective surfaces or from elsewhere bear an unmistakable resemblance—or indeed, an identity—to the wave motion of light and sound.[15]

When the previously so convincing theory put forward by the French engineers *Carnot*[15] and *Émile Clapeyron*[16], which presupposed an unchanging heat substance, came into conflict with the experimentally well-established equivalence of heat and work, it became necessary to rethink the entire conceptual framework. *Clausius* proposed a first solution.[17]

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[12] *Hermann v. Helmholtz*: Über die Erhaltung der Kraft (1847) (Ostwalds Klassiker Bd. 216). Leipzig 1926; *Julius Robert Mayer*: Die Mechanik der Wärme (1842) (Ostwalds Klassiker Bd. 180). Leipzig 1911; Mechanik der Wärme. Stuttgart 1874

[13] Mayer (1842 [1911]), 31; (1874), 49.

[14] *John Tyndall*: Die Wärme, betrachtet als eine Art der Bewegung. Edited by *Hermann Helmholtz* and *Gustav Wiedemann*. Braunschweig 1867. 71-75 and 120-126.

[15] *Johann S. Gehler:* Physikalisches Wörterbuch. Revised by *Gmelin*, *Littrow*, *Muncke* and *Pfaff*. Vol. 10, Part 1. Leipzig 1841. pp. 54–103, in particular p. 97. See also the same author: Physikalisches Wörterbuch. Vol. 2. Leipzig 1789. pp. 207–210.

[16] *Émile Clapeyron:* Treatises on the Motive Power of Heat (1834). Translated and edited by K. Schreber (Ostwald's Klassiker, Vol. 216). Leipzig, (1926).

[17] *Rudolf Clausius:* Abhandlungen über die mechanische Wärmetheorie. Braunschweig (1864).

He introduced two fundamental processes, as a compromise between the two conflicting views:

1. The conversion of a quantity of heat *Q* at temperature *t* into an equal quantity of heat at the lower temperature *t'* without the performance of work – achieved, for example, by heat conduction *(a process in which heat is conserved)*.
2. Conversion of work into an equivalent amount of heat *Q'* at a constant temperature *t'* – caused, for example, by friction *(a process in which heat is not conserved)*.

Each of these processes proceeds spontaneously in only one direction. In a reversible *Carnot* process, however, the two transformations should be coupled in such a way that the progression of one forces the reversal of the other, and vice versa. To measure the progress of the fundamental processes, he used the quantities

$$S = \frac{Q}{T'} - \frac{Q}{T} \quad \text{or} \quad S' = \frac{Q'}{T'}$$

and called them equivalence values of the transformations, because these measures were designed in such a way that, when coupled, they exactly compensate each another, just like the work equivalents in the law of conservation of energy:

$$S + S' = 0$$

He demonstrated that *T* can depend only on temperature. (In modern terminology, *S* is, for example, the entropy generated by heat conduction and *S'* that generated by friction; *T* is identical to the absolute temperature.) Later, Clausius took apart his first law of transformation and introduced the expression *dQ/T* for each quantity of heat supplied. For the sum of all these equivalent values, he found the well-known result

$$\oint \frac{dQ}{T} \geq 0 \,.$$

He was unable to make it comprehensible: 'Although the necessity of this theorem … can be proven strictly mathematically, the theorem nevertheless retains its abstract form, in which it is difficult to grasp…'[18] He called the integral

$$S = \int_A^B \frac{dQ}{T} \,,$$

referred to a fixed initial state A, the 'content of transformation'; later, he termed it the 'entropy of the body', deliberately alluding to the word 'energy' in order to emphasize the similarity between the roles of the two quantities. He demonstrated that all results could be deduced from the two laws, that heat and work are equivalent, and '…that heat cannot pass spontaneously from a colder to a warmer body.'[19] It was no longer possible to divide the total energy of a body into a heat content and a non-thermal component without arbitrariness. *Clausius* had attempted a definition as a concession to common sense and conventional thinking, but this failed to gain acceptance.

W. Thomson, inspired by *Clausius*, arrived at very similar conclusions. He introduced the concepts of 'loss of work' and 'dissipation of energy', as well as the modern definition of absolute temperature. Both he and *Clausius* turned to the kinetic theory of gas after abandoning the concept of a 'thermic substance'. The identification of heat with the energy of atoms, and thus the first law of thermodynamics, must have seemed entirely natural on

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[18] *Rudolf Clausius:* Abhandlungen über die mechanische Wärmetheorie. Braunschweig (1864), p. 246.

[19] *Rudolf Clausius:* Abhandlungen über die mechanische Wärmetheorie. Braunschweig (1864), p. 20, 50.

this basis. Entropy remained a mystery. *Clausius's* approach was fiercely criticized at the time, as he himself reports.[20] The criticism was fuelled above all by the fact that the concept of heat content lost its meaning and that *Carnot's* lucid description of the work output of a heat engine was devalued.

What Clausius Overlooked

In fact, alongside *Clausius's* solution discussed above, there is a second solution available—one that is seemingly similar but conceptually much simpler—which avoids the shortcomings that have been criticized. Once the substance theory had been abandoned, the question of under what circumstances heat is conserved remained entirely open. *Clausius's* assumption that its quantity does not change during conduction is arbitrary. With equal justification, this property can also be attributed to the *Carnot* process. For example, following his two types of transformation, one can introduce the following basic processes:

1. The transfer of a constant amount of heat from a higher temperature to a lower one, accompanied by a gain in work W (i.e. $W < 0$) – exemplified, for example, by the Carnot process (*a process that conserves heat*).
2. The generation of heat through the expenditure of work W' – caused, for example, by friction (*a process that does not conserve heat*).

Unlike the first process, the second process is assumed to be possible in only one direction. In the case of heat conduction, the two processes are assumed to be coupled in such a way that their work equivalents exactly cancel each other out:

$$W + W' = 0$$

This is already required by the law of conservation of energy, since in this case no other processes involving the supply or consumption of work are involved.

A first conclusion would be that heat increases during conduction. Therefore, heat transfer to a calorimeter should only take place via a *Carnot* process, in order to avoid measurement errors caused by heat generated in the process. As already mentioned, however, the heat measured using such a modified procedure would be proportional to the modern entropy and not to the quantity Q.
Instead of reversible processes, conduction appears as a composite process that does not conserve heat. Had one been prepared to accept this fact, further development would probably have inevitably led to the previously mentioned intuitive form of thermodynamics, because the necessary concepts, such as potential and tension, were already in place. *Carnot's* work can be read almost without correction if one replaces the word 'amount of heat' with 'entropy', as *K. Schreber*[21] pointed out as early as 1926. I have found no other evidence that such a solution was ever discussed.

Because *Clausius*, unlike *Carnot*, did not attribute any work value to the transfer of heat from a higher to a lower temperature, he could no longer describe the coupling of his fundamental processes in terms of the law of conservation of energy using work equivalents, but had to introduce a substitute measure: entropy. Although many details of the earlier view have now been superseded, thermodynamics was nevertheless established at that time in a way that precluded any steady development in a different direction.

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[20] *Rudolf Clausius:* Abhandlungen über die mechanische Wärmetheorie. 3rd. edition. Braunschweig (1887), p. 316.

[21] See *Clapeyron* (edited by *K. Schreber*, 1926), p. 41.

Energetics

Although the first law of thermodynamics no longer allowed the heat in a body to be conceived of as a specific quantity of something, this way of looking at things has persisted for a long time—indeed, to this day—as a conditionally correct working concept.[22] *James Clerk Maxwell*, for example, writes: "Heat, therefore, may pass out of one body into another just as water may be poured from one vessel into another…"[23] Whilst conduction processes could be described particularly easily in this way, other analogies were sought to explain energy transformations. *Maxwell* highlights the similarity between the relationship between work, volume and pressure ($A = p \cdot V$) and that between heat, entropy and temperature ($Q = T \cdot S$): just as no work can be absorbed without a decrease in volume, so no heat exchange is possible without a change in entropy; or just as a pressure gradient in 'communicating vessels' causes a flow of fluid, so a temperature difference drives a flow of heat. *Gustav Zeuner* illustrates entropy, which he calls 'heat weight', with the weight of a body, temperature with height, heat with potential energy, and, like *Carnot* before him, compares a steam engine to a water wheel.[24]

All these approaches were superseded in the last century by another development in physics, namely energetics:

> Influenced by the profound impact that the discovery of the principle of conservation of energy has had on it [physics], it tends to treat phenomena within its domain as transformations of energy into new forms, and regards the reduction of these phenomena to the laws of energy conversion as its ultimate goal.[25]

The atom hypothesis, which had been declared metaphysical, was acknowledged as a 'historically necessary stage in the development of science'[26], but was regarded by the majority of scientists as having been superseded – a view that seems grotesque from today's perspective. There was no longer any interest in interpreting the concept of heat. On the contrary, following the example of thermodynamics—regarded as the most distinguished example of a physical theory—attempts were made to reshape the other subfields of physics. A remark by *Mach*, who greatly influenced theoretical physics through his relentless criticism of traditional concepts, is worth mentioning here: it is only thanks to a historical coincidence that the quantity of electricity is measured by charge and not in terms of energy. Had, for instance, the charging of a Leyden jar been discovered before the formulation of Coulomb's law, it would have been more natural to measure the quantity of electricity contained in the jar by its capacity to do work or its work equivalent, as is done with heat, whereby the energy transformations in both fields could be described by similar formulas.[27]

It is probably only by taking into account the mindset of the time that one can understand why the reverse approach was not also considered – that is, defining heat in non-energetic

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[22] See *Mach* (1900), pp. 186, 335; *Wilhelm H. Westphal*: Physics. 7th ed. Berlin (1941), p. 212.

[23] *James Clerk Maxwell:* Theory of Heat. Longmans, Green, and Co, (1902), p.7.

[24] *Gustav Zeuner:* Technische Thermodynamik. Leipzig (1887). p. 41.

[25] *Heinrich Hertz*: Gesammelte Werke, Bd. 3: Die Prinzipien der Mechanik in neuem Zusammenhange dargestellt. Herausgegeben von *Philipp Lenard*. Leipzig (1894), p. 17; see also *Georg Helm*: Die Energetik. Leipzig (1898), p. 20: "Wenn Veränderungen auftreten, so besteht doch zwischen ihnen diese bestimmte mathematische Beziehung [Energiehaltung] - das ist die Formel der Energetik, und gewißlich ist das auch die einzige Formel aller wahren Naturerkenntnis. Was darüber hinausgeht, ist Fiktion."

[26] *Georg Helm*: Die Energetik. Leipzig (1898), p. 144.

[27] *Ernst Mach:* Prinzipien der Thermodynamik. 2nd ed. Leipzig (1900), pp. 330ff.

terms and introducing temperature as a potential, following the example of electrodynamics – especially since there was a clear need for such a definition of temperature:

> The concept of temperature is a level concept, like the height of a heavy body, the velocity of a moving body, electric potential, magnetic potential, chemical potential… Whilst the concept of potential was established from the outset with a clear understanding of its purpose, this is only the case with the concept of temperature by chance and in a rather approximate sense...[28]

Subsequent developments

Since a body can be heated not only by the supply of heat but also by the performance of work—such as friction—it is possible to determine its internal energy as a function of certain state parameters, such as pressure and volume, purely by mechanical means. Based on this line of reasoning, *Max Born* formulated a definition of heat that is independent of calorimetry. The quantity Q absorbed by a body from its surroundings during any process is defined as the excess of the energy gain ΔU over the work W done in the process:[29]

$$Q = \Delta U - W.$$

If one attempts to generalize this definition, which applies to closed systems, to open systems, difficulties arise. If one considers, for example, a porous membrane separating two solutions of unequal temperature and concentration, the question of what proportion of the transferred energy is transferred as heat, what as work, and what is transferred solely by convection is answered very differently by various authors.[30] The question is just as problematic as the division of internal energy into a heat component and a non-thermal component. The logical consequence would be to dispense with any division altogether, especially as such a separation does not seem to offer any decisive computational or conceptual advantages. Nature provides no clear criteria, so that a uniform definition of heat could only be established by mutual agreement.

Concluding remarks

We see that the energetic concept of heat encounters new difficulties when considering open systems. Some physicists therefore avoid including such systems in thermodynamics, whilst others attempt to distance themselves from the concept of heat. *H. D. Baehr's* statement: 'In a logically sound thermodynamics, this concept… plays only a subordinate role'[31], is probably to be understood in this sense. However, a renunciation of clarity would ultimately lead to the abstract conceptual system briefly described earlier, which in turn corresponds mathematically to the intuitive representation. The fact that no such approaches are emerging is mainly due to the entrenched prejudice that heat is a form of energy and that thermodynamics can therefore only be correctly described in the language of energetics. Why this definition of heat—which, in retrospect, is so unfortunate—was able to

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[28] *Ernst Mach:* Prinzipien der Thermodynamik. 2nd ed. Leipzig (1900)., p. 57.

[29] *Hans Dieter Baehr:* Thermodynamik. Berlin, Heidelberg, New York (1966).

[30] See, for example, *Rolf Haase:* Thermodynamik der irreversiblen Prozesse. Darmstadt (1963); *Walter Weizel:* Lehrbuch der theoretischen Physik. Vol. 1. 2nd ed. Berlin, Göttingen, Heidelberg (1949); *Josef Meixner* and *Helmut Gottlieb Reik:* Thermodynamik der irreversiblen Prozesse (Flügges Handbuch der Physik. Vol. 3/2). Berlin, Göttingen, Heidelberg (1959); *S. R. De Groot:* Thermodynamik irreversibler Prozesse (B I-Taschenbücher Vol. 18/18a). Mannheim (1960).

[31] *Hans Dieter Baehr:* Thermodynamik. Berlin, Heidelberg, New York (1966), 56.

gain acceptance at all can probably only be explained by the historical development of the science of heat.

Summary

The present theory of heat represents a compromise between the demand for intuitive clarity and the requirement for formal simplicity. Consequently developed only according to the one or the other of these two conceptions, two varieties of the theory arise. Their formalisms are considerable simpler than that of today's thermodynamics. The mathematical structures of both conceptions are identical in their essential parts, so that the quantities can be arranged by pairs with the following result (above, the quantities of the abstract, below those of the intuitive theory are given):

Entropy,	temperature,	amount of substance,	chemical potential;
heat,	temperature,	amount of substance,	potential of substance.

In order to reconcile the two concepts, it is necessary to equate 'intuitive' heat with entropy. A closer look reveals that this is in fact possible without any difficulty.

Now the question arises why, in the long history of thermodynamics, this possibility has not yet been taken into consideration. The answer, in short, can be given as follows: After the substance theory of heat proved to be wrong, the only real alternative, the kinetic theory, offered itself. Only when taking this into account it can be understood that *Clausius* came to a decision in favor of the second one of the following two possibilities:

1) Conservation of heat during the Carnot process

2) Conservation of heat during heat conduction.

Thereby *Clausius* shifted the points for the development towards the to-day's energetical theory of heat in those days.