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The left and right sides of the equation $\Delta S = Q/T$

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Abstract

Heat Q and entropy S are two central quantities in thermodynamics. At first glance, Q seems to be the simpler and more intuitive concept, while S is reputed to be difficult. We argue that this impression is misleading: heat Q is, in fact, an insidious quantity. Entropy, on the other hand, has been given its bad reputation unjustly. Once it is recognized that entropy almost perfectly describes what we colloquially mean by ‘heat’, one discovers that it is actually one of the most intuitive physical quantities of all.

Keywords: entropy, heat, process variable, state variable

1. Introduction

In this paper, we are concerned with the introduction of two quantities when teaching physics: heat Q and entropy S .

As is well known, these quantities are related through the equation

$$\Delta S = \int_{\text{rev}} \frac{dQ}{T} \quad (1)$$

as formulated by Clausius, who is regarded as the inventor of entropy. T is the absolute temperature. In textbooks, the equation is often found in the

simplified form [1, 2, p 428, 3]

$$\Delta S = \frac{Q}{T}. \quad (2)$$

It is used to define entropy, meaning that heat Q and absolute temperature are introduced beforehand.

When introducing a new physical quantity, one always has a choice: either to define it operationally, i.e. by specifying a measurement procedure, or to derive it from other quantities. If it is derived, it is assumed that the initial quantities are already known, meaning that one knows how to measure them and has a good intuition about them. The hope is that the definition will then also provide intuition for the new quantity.

In the present case, the decision was made to first introduce the form of energy called heat and the absolute temperature, and then to define entropy by means of equations (1) or (2). We intend to show that, from today’s perspective, this approach is problematic.

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Our observation applies to teaching at every level, from junior high school to university.

2. Judgments and prejudices

We first ask which of the two quantities, S or Q , is the simpler and more intuitive one.

At first glance, one might choose heat. Heat is energy, and students are familiar with energy from other contexts. Heat is that ‘form of energy’ which has to do with a body being warm or cold. If one remains with this idea, heat seems to be an intuitive quantity.

Entropy, by contrast, appears difficult. Equation (1) already reveals this. One has to evaluate an integral under a peculiar condition: the contributions to the integral must correspond to a reversible process.

In addition, students learn—in chemistry classes as well—that entropy is a measure of disorder. It seems that one can only properly understand entropy if one describes the world on the microscopic–statistical level. But how does this statement fit with equation (1)?

There is yet a third approach to entropy: entropy is said to be a measure of the irreversibility of a process. But entropy also has a value if a reversible process takes place—or even if no process at all occurs. What then should entropy represent in these cases?

Entropy therefore seems to be a tricky quantity. Here is a typical statement from a textbook [4]:

‘There is no concept in the whole field of physics which is more difficult to understand than is the concept of entropy, nor is there one which is more fundamental.’

3. A different judgment about heat Q

We turn to a reconsideration of the concept of heat. In fact, the physical quantity Q , to which the name ‘heat’ has been given, is a conceptually demanding one. The reason is that it is what is called a process variable. Only heat and work belong to this category.

What does it mean to be a process variable? A ‘normal’ physical quantity has a definite value for a given physical system, at a given

time. Especially in thermodynamics, one emphasizes this fact by calling such normal quantities state variables. But the criterion of being a state variable also applies to all non-thermodynamic quantities: electric field strength, electric charge, electric current, momentum, angular velocity, to name just a few. The designation ‘state variable’ is therefore unnecessary, as it describes what is actually the normal case.

The two process variables, heat and work, differ from state variables, i.e. from all other quantities, in that they do not have a value in a given state of a physical system. Consider some object in front of you: the heat (in the physical sense) has no value for it. This does not mean that its value is zero. It also does not mean that it has some value that we do not know. It means something more radical: if one asks for its value, one asks a ‘non-sense question’.

Even for someone who is familiar with physics, it is difficult to understand that heat is not a state variable. What would one say about the following process: We supply heat to a body, for instance a block of metal, let us say 10 kJ. The body’s temperature rises. One would now like to return it to its initial, cooler state. The only way is to withdraw the same amount of heat—10 kJ—that was supplied. Why then should it not be allowed to say, that 10 kJ of heat were contained in the body?

From our own experience, most physics students, even at the end of their bachelor’s studies, cannot answer this question.

That it makes no sense to speak of a ‘heat content’ becomes clear only when, instead of a solid (where thermal and mechanical variables are practically decoupled), one considers a gas. A gas can be supplied with 10 kJ of heat, returned to its initial state, and in the process only 6 kJ of heat are withdrawn. (What we have described here is essentially a heat engine.)

Let us look at how textbooks handle this problem. Heat is typically defined as follows [2, p 391]:

‘Thus, heat is energy transferred from one object to another because of a difference in temperature.’

This statement is not wrong. But how will it be understood by learners? When something is

transferred from object A to object B—does one not understand it to mean that this ‘something’ was previously located in A and afterwards is located in B?

Or in another context [5, p 368]:

‘The amount of heat gained when water changes phase from a solid to a liquid at 0°C is $Q = mL_f$, where m is the mass of water and L_f is the latent heat of fusion.’

If something is ‘gained’ by the water, does this not mean that it is then contained in the water?

Or again [6]:

‘When heat is removed from a gas at the boiling temperature, the gas returns to the liquid phase, or condenses, giving up to its surroundings the same quantity of heat (heat of vaporization) that was needed to vaporize it.’

If something is removed from a system, does this not mean that the system previously possessed it?

And let us check Wikipedia [7]:

‘Latent heat (also known as latent energy or heat of transformation) is energy released or absorbed by a body or a thermodynamic system during a constant-temperature process—usually a first-order phase transition, like melting or condensation.’

If something is released or absorbed, does this not mean that it was in the releasing system beforehand and afterwards in the absorbing system?

The authors of the following two quotations have at least recognized that the natural expectation based on normal language usage does not apply, and have added a warning [5, p 360, 8]:

‘It is correct to say that the internal energy of a system has increased, but it is not correct to say either that the work of a system has increased or that the heat of a system has increased.’

‘Heat is energy that flows from a higher-temperature object to a lower-temperature object because of the difference in temperatures... it is not correct to say that a substance contains heat.’

It would not be quite so bad if the quantity Q had been given some neutral name, e.g. a Greek one, that is not used colloquially. But the designation ‘heat’ is so suggestive that it is hard to accept that the question for the ‘heat content’ of a body makes no sense [9].

In summary: Heat Q is a tricky quantity. The impression that it is intuitive arises only if one does not look closely.

4. A different judgment about entropy S

If entropy is introduced as described above—via equations (1) or (2), or as a measure of microscopic disorder, or as a measure of the irreversibility of a process—then it indeed appears as a challenging concept.

In contrast, entropy can be introduced in a way that highlights its intuitive character. It then turns out that entropy is not only not difficult but can become one of the most intuitive physical quantities of all.

As early as 1911, Calendar [10] pointed out that entropy is nothing other than the concept of ‘caloric’ (chaleur/calorique) introduced by Carnot. This is a state variable, and—as Calendar emphasized—it is so intuitive that ‘any schoolboy can understand’ it.

Of particular help to us, however, is a surprising observation made in 1972 by Job [11, 12]: entropy is a measure of something for which even a layperson has a very good and clear intuition, namely of what is colloquially (not in terms of physics) called ‘heat.’ It is interesting that this insight came so late. One could almost say: people did not see the forest for the trees.

In table 1, we have formulated in the left column some colloquial and plausible statements in which the word ‘heat’ occurs. If one replaces the word ‘heat’ by ‘entropy’ (see the right column), these statements remain physically correct.

Table 1. Entropy and the colloquial concept of heat.

Everyday statements with ‘heat’ ^a	Equivalent statements with ‘entropy’
An object contains more heat ^a when it is hot than when it is cold.	An object contains more entropy when it is hot than when it is cold.
At the same temperature, a large object contains more heat ^a than a small one.	At the same temperature, a large object contains more entropy than a small one.
Heat ^a flows spontaneously from places of higher to places of lower temperature.	Entropy flows spontaneously from places of higher to places of lower temperature.
A heat pump conveys heat ^a from outside into the house.	A heat pump conveys entropy from outside into the house.
In the combustion of wood in a stove, or of a candle’s wax, heat ^a is produced, i.e. heat ^a is generated that was not there before.	In the combustion of wood in a stove, or of a candle’s wax, entropy is produced, i.e. entropy is generated that was not there before.
Heat ^a is also generated by mechanical friction and in an electrical resistor.	Entropy is also generated by mechanical friction and in an electrical resistor.

^a To avoid confusion between the colloquial meaning of ‘heat’ and the physical quantity Q , we have marked the colloquial term with an asterisk.

Thus, while one can replace the colloquial word ‘heat’ by entropy, this must not be done for the physical concept of heat Q .

If this insight is conveyed, students can deal comfortably with entropy. It is sufficient to explain: What you colloquially call ‘heat’ is what physicists call entropy.

We ourselves have introduced entropy in this way in a large-scale school experiment with grade 8 and grade 11 students, involving about 30 000 students. All teachers involved were surprised at how smoothly this worked.

There are now a number of textbooks for both school and university that present thermodynamics in this way [12–14].

Finally, a more general remark about handling the concept of heat: one should by no means ask the question ‘What is heat really?’ There is nothing in the real world that we could claim *is* heat. Rather, we construct theories by which nature can be described mathematically. To the variables of the theory—that is, the physical quantities—we give names which, if well chosen, help us form a picture of them. This holds for all physical quantities.

5. Concluding remarks

The process variable heat Q is a variable that not only school students have problems with and that is easily misunderstood. In our experience, even

most university students cannot explain why it makes no sense to talk about the heat content of a system.

If entropy is introduced starting from this quantity, the well-known impression arises that entropy is a particularly difficult concept. In fact, however, entropy—if introduced in a suitable way—can become one of the most accessible and intuitively meaningful physical quantities of all, namely when it is presented as a measure of what is colloquially called ‘heat’. This perspective may help reduce conceptual barriers in teaching thermodynamics and foster a more accurate and intuitive understanding of entropy among students.

Data availability statement

No new data were created or analysed in this study.

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