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What is heat?

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Abstract

According to Aristole's *Categories*, there are three kinds of concept, i.e. substance, quality and quantity in physics. With the question "What is heat?"we mean : is heat a substance, a quality or a quantity? Historically, heat was referred to a substance caloric. Now, it is prevailed that heat is a quantity Q, also called "the quantity of heat" or simply "heat". In this paper, we propose that heat is neither a substance, nor a quantity, but a quality or a property we perceive. We even conclude that the quantity of heat is not the quantity Q, but the quantity caloric or entropy S.

Keywords: category; heat; quantity of heat; caloric; entropy

1. Introduction

In his famous work *Categories* [1], Aristole（384BC-322BC）listed 10 categories: substance, quality, quantity, relation, place, time, position, state, action, and affection. The first three categories he listed are very important concepts in physics.

Obviously, all the physical quantites, such as force, mass, frequency, entropy, momentum, area and electric charge, etc. fall into the category of quantity, and all the physical laws into that of relation.

We know that the world consists of substances that exist in forms of objects and fields. So all different material objects or particles and immaterial fields come into the category of substance. There are a multitude of substances around us that we give names to such as iron, brass, water, milk, Sun, Earth, magnet, charged body, magnetic field, electric field, gravitational field, etc. We call this kind of concept substantive concept.

A substance has observable properties abstracted by our neuronal sensory systems and brains. So color, heat, motion, inertia, surface, electricity and magnetism, etc. should be categorized into quality or property. Properties are what we can observe [2]. They are qualitative concepts, while physical quantities are quantitative ones.

In physics we should recognize that substantive concepts, qualitative concepts and quantitative concepts are three categories that should be clearly distinguished. A substantive concept is an ontological concept of reality, the material world for what is really there. Our sensory systems and brains can abstract the properties of the material world. Physical properties can be described quantitatively with physical quantities, which are defined or invented by physicists. Physical quantities are tools to be used to measure to find relations between quantities, i.e. physical laws, which fall into the forth category of relation.

With the question “What is heat?”we mean: is heat a substance, a quality or a quantity? Historically, heat was referred to a substance caloric. Now, it is prevailed that heat is a quantity Q, also called “the quantity of heat” or simply “heat”. In this paper, we propose that heat is neither a substance, nor a quantity, but a quality or a property we perceive. We even conclude that the quantity of heat is not the quantity Q, but the quantity caloric or entropy S.

2. Heat is not a substance

Heat as a substance was a theory widely accepted at the end of the eighteenth century [3] (p. 411). The eighteenth century saw a proliferation of theories based on imponderable fluids. The so-called "phlogiston" named by Georg Ernst Stahl (1660-1734) was viewed as a fluid gained and lost by bodies during combustion and other chemical reactions. Electric and magnetic effects were described in terms of fluids. Antoine-Laurent Lavoisier (1743-1794), whose own investigations ultimately demolished the phlogiston theory, gave the fluid of heat the name caloric (from the Latin word *calor*). He thought of heat as a kind of subtle fluid that goes into bodies to warm them or to cause other changes. The idea is called *caloric theory of heat*.

Around 1820, Sadi Carnot (1796-1832) used this idea to create a theory of heat engines that is still valid today [4]. In his view, the mechanical work performed by his ideal engine was due to the fall in temperature of *heat* (*chaleur* in French) absorbed by the engine from the source at the higher temperature and released to that at the lower temperature, in analogy with the mechanical work performed by a water wheel when water falls from a higher place through the wheel to a lower place.

In this analogy, there is a fundamental difference [5]: water is a substance, while heat is not. When water enters a physical system (compared to a chemical or nuclear system), it does not disappear. When heat enters a physical system, it has no existence within the system as a substance "heat". Imagine an ideal gas as a physical system, in contact with a large furnace, undergoing an isothermal expansion. Heat goes in the gas, but there is no new substance in it. Heat as matter disappears, because there is no heat flow out of the gas.

On the other hand, heat can be produced in irreversible physical processes such as rubbing or boring. Here the elevation of temperature takes place at the same time in the body rubbing and the body rubbed. Moreover, they do not change perceptibly in form or nature. If heat is matter, it must be admitted that the matter is created by motion.

We know that a substance can be neither destroyed nor created in physical processes (compared to chemical or nuclear processes). So heat is not a substance.

3. Heat is not a quantity

There is a quantity called amount of substance *n*. Here, the word "substance" is not referred to the concept of substance. In everyday language, we talk about a well-defined amount of gold or something else. But in physics we use different quantities to measure what we call the amount of gold: Mass, volume, number of molecules. According to Aristole's *Categories*, substance does not admit of a more and a less [1]. So strictly speaking, we should not speak about the amount of any kind of substances, but the amount of some kind of properties, such as inertia and surface. A property is what we perceive, observe or even imagine by our sense organs and brains. They fall into the category of quality. They are not quantities, but can be quantified.

There are physical quantities which have the function to measure the amount of "some perception or imagination" [6]. The quantity mass *m* can be considered to be a tool to measure the "amount of inertia" we perceive, and the quantity area *A* can be considered to be a tool to measure the "amount of surface" we observe. The so-called amount of substance *n* is used to measure the size of the number of particles we imagine.

Similarly, in the name of the "quantity of heat", heat is neither a substance, nor a quantity, but a property we observe by our touch organs.

4. Heat is a quality

As we have discussed above, heat is a property, or a quality we perceive. We call phenomena related to heat thermal phenomena. There are many different thermal phenomena. The basic thermal phenomena we can observe in everyday life are *heat production*, *heat transfer* and *storage of heat*. We can describe these phenomena by using the word heat as well as other related words, e.g. hotness. Because heat and hotness are words to be used to describe phenomena we perceive, this kind of description is also called phenomenological interpretation, or qualitative interpretation.

Here is an example:

Thermal phenomena. A copper rod AB is connected to a section of a copper bar C at its one end B. The copper bar C is inserted into cold water in a glass. The rod AB is heated by a candle at its end A. Over time, the water become warm.

Qualitative interpretation. Heat is produced by the candle and transferred through the copper rod AB into the copper bar C, and then into the water (*heat production* and *heat transfer*). The flame is very hot, the copper rod AB is pretty hot at the heated end A and cooler at the end B connected to the bar C and the water. The copper rod AB transfers the heat produced by the candle to the water (*heat transfer*). Heat accumulates in the water and as a result, the water become warm, or even hot (*storage of heat*).

Here, we have heat and hotness as the two primitive qualitative concepts for describing thermal phenomena. We should distinguish between the sensation of heat and hotness [7] (p.109). The term heat is often used in the sense of something being hot. In the above example, we assume that the water contains some heat in some time. Divide the water into two same parts. What can we say about the heat contained in each part, and the sensation of hotness of the parts? Experience tells us that their hotness are the same as that of the original body of water. However, the heat has been divided into two equal parts. Therefore heat and hotness are clearly two different qualitative concepts that describe two different sensations: heat is an extensive property or a bulk one, while hotness is an intensive property or a local one.

5. Quantifying heat

As our intuitive perceptions of motion, time and inertia lead us to construction of the quantitative concepts of mechanics, such as momentum, angular momentum, instant of time, interval of time and mass (or energy), so do our intuitive perceptions of heat, cold and hotness lead us into the development of thermodynamics quantitatively. In thermodynamics, physicists have invented many quantitative concepts. The first one is temperature T. Obviously, temperature T is an intensive quantity to be used to quantify hotness. Because hotness is a local property, the value of temperature T, just like other intensive quantities refers to a point.

Which physical quantity can be used to quantify the extensive property heat? Historically, heat and hotness were used more or less interchangeably. Joseph Black (1728-1799), a Scottish chemist and physician, was the first outstanding figure in the conceptual clarification of thermal phenomena. He for the first time in science history distinguished between the extensive property heat and the intensive one measured by the thermometer. The following explanation of the first of these concepts is found in his *Lectures on the Elements of*

Chemistry (edited by Black's pupil Robison and published in 1803, four years after Black's death):

"*If, for example, we have one pound of water in one vessel, and two pounds in another, and these two quantities of water are equally hot, as examined by a thermometer, it is evident, that the two pounds must contain twice the quantity of heat that is contained in one pound. Undoubtedly, we can suppose that a cubical inch of iron may contain more heat than a cubical inch of wood, heated to the same degree; and we cannot avoid being convinced of this by daily experience.*" [8]

Of course, Black's *quantity of heat* is an extensive quantity. That means it quantifies the amount of heat we perceive. Traditionally, the symbol used for this quantity is Q. Because heat is a bulk property, the value of Black's Q, just like other extensive quantities refers to a region of space.

As an extensive quantity, Q is extremely easy to measure. In regarding to the measurement of extensive quantities like Q, Wilhelm Ostwald (1853-1932) stated in 1908 that "One arbitrarily chooses a piece of it to be the unit and connects so many units together until they equal the value to be measured. If the chosen unit is too rough a measure, correspondingly smaller ones can be created. The simplest way to do this would be 1/10, 1/100, 1/1000, etc. of the original unit."[9] (p.8)

However, the misfortune happened, when James Prescott Joule (1818-1889) and Julius Robert von Meyer (1814-1878) introduced the concept of energy. Of course, energy was a big concept. The misfortune was that the inventors equated the old concept of Q with a so-called form of energy.

In physics, we tend to consider (material) systems as strongly simplified often idealized, parts of the natural world around us in which we have a special interest. We assume that systems can appear in various (physical) states, which can differ qualitatively due to characteristics such as state of aggregation or quantitatively in the values of suitably chosen quantities such as temperature. These quantities are called state quantities, or state variable. A state quantity describes the state of a system or is defined by the instantaneous state of a system. [9] (p.18-23)

Of course, Black's Q is a state variable. According to the first law of thermodynamics, which can be expressed as

$$\mathrm{d}E = \delta W + \delta Q, \tag{1}$$

and Gibbs's fundamental equation

$$\mathrm{d}E = \boldsymbol{v}\mathrm{d}\boldsymbol{p} + \varphi \mathrm{d}q + T\mathrm{d}S + \ldots, \tag{2}$$

we can see that an energy change dE in a system is just equal to transfers of energy δW and δQ; and that an intensive quantity, such as velocity $\boldsymbol{v}$, electrical potential φ and temperature T, determines the magnitude of an energy change dE in a system related to a change of the corresponding extensive quantity in the same system, such as momentum $\boldsymbol{p}$, electric charge q and entropy S. A transfer of an extensive quantity is a process. So, when Black's Q was equated with a form of energy, it was no longer a state variable, but a process one. The new quantity Q, not Black's Q, is used to describe processes in which energy is transferred together with entropy.

Now we know that entropy is just an extensive quantity that can be used to quantify the amount of heat we perceive. It is the quantity that best satisfies the expectations that we have for a measure of the amount of heat [10]. Black's concept of quantity of heat coincides perfectly with entropy introduced into physics by R. E. Clausius (1822-1888) in 1865, which is a resurrection of Carnot's caloric [11].

All extensive quantities share the property of being substance-like, that is, each has a density and a current density. It can be pictured to be contained in a body, like a gas is contained in a bottle, and to flow from one body to another [12].

For each extensive quantity A, a relation of the form

$$\mathrm{d}\rho_{\mathrm{A}}/\mathrm{d}t + \mathrm{div}\boldsymbol{j}_{\mathrm{A}} = \sigma_{\mathrm{A}} \tag{3}$$

exists, where σ_{A} is the local source density of the quantity A. The equation is called the local balance equation of A. The integral form of Equation (3) is

$$\mathrm{d}A/\mathrm{d}t = I_{\mathrm{A}} + \Sigma_{\mathrm{A}}, \tag{4}$$

where I_{A} is the current of A and Σ_{A} is the time rate at which the quantity A is created (negative creation is destruction) in a considered system [13]. [Note: The current density in Equation (3) stands on the right hand side of the equation whereas the current in Equation (4) on the left side. This discrepancy is due to the fact that it has become a custom to count the current positive when it *enters* the system when applying Equation (4), whereas div$\boldsymbol{j}_{\mathrm{A}}$ in Equation (3) is positive when the current *leaves* the system because the directions of the current density $\boldsymbol{j}_{\mathrm{A}}$ and that of the related area vector of the outer surface of the system are the same. Actually, Equation (4) is related to the inner surface of the system, whereas Equation (3) to the outer one.] Thus, the time rate of change dA/dt of A comes about in two ways: by an inflow or outflow, expressed by the current intensity I_A and by production or destruction, expressed by the production rate Σ_A .

Thus, physical processes of a system can be simply visualized in terms of increasing or decreasing, production or destruction of these extensive quantities in a given region of space of the system, and inflow or outflow of through the boundary surface of the system. Pedagogically, this picture helps us to get an intuitive understandings for the meaning of extensive quantities and provides us an analogous method for the learning of different branches of physics.

If for a quantity A the term Σ_A (or σ_A) is always zero, A is a conserved quantity. In this case, the value of A in the region of space of a system can only change by means of an inflow or outflow through the boundary surface of the system.

However, physical quantities are human inventions, not discoveries. We can *imagine* a conserved quantity to be a kind of substance, but can never say that it *is* a substance.

6. Historical Burdens

Physical quantities are tools that scientists invented to measure our intuitive perceptions or imaginations. Although Black invented quantity of heat, equivalent to entropy, more than 200 years ago, even it had some chances to become such a tool [14], it has not been widely used to measure the amount of heat we perceive. What might be the reasons that hinder us to use this tool appropriately? There are some historical burdens. Here are three examples:

Misinterpreting Rumford's experiment

In 1797, Count Rumford (1753-1814) carried out his most famous experiment, the cannon-boring experiment. Using a boring machine with blunt tool, the experiment succeeded in raising cold water to the boiling point by means of friction.

It was common knowledge that doing work against friction produced heat that we can perceive. The advocates of the material theory therefore argued that this heat from friction came from the caloric, a kind of substance that was squeezed out from the surface by the pressure.

The purpose of Count Rumford's experiment was to see if the amount of this substance produced by the boring was always the same independent of how long the cannon was drilled.

If heat were a material substance it should eventually be drained out. But what Rumford showed was that no matter how long the cannon was driven, the length of time it took the dull drill to heat the water to boiling was always the same [15].

We know that friction is *not* a chemical process, but a mechanical one. There would be no new substance created. Heat produced in friction is just a quality, not a substance. The caloric theory of heat will be right, if caloric refers to the quantity entropy. It should not be a surprise to modern readers that entropy obeys only half a conservation law: it can be created, but not destroyed. Caloric is substance-like, but not a substance. We now could imagine that if entropy were conserved Rumford could not have a question whether caloric could be a substance.

Misunderstanding Carnot's principle

The great theoretical work by Sadi Carnot, aimed at establishing the maximum attainable limit in the performance of heat engines, led to his principle of heat engines:

"*La production de la puissance motrice est donc due, …, non à une consommation réelle du* ***calorique****, mais à son transport d'un corps chaud à un corps froid,…*" [14]

(The production of motive power has its cause not in a real consumption of **caloric**, but in a transport from a hot to a cold body.)

Historically, there are misunderstandings which still persist in present day texts. Some people said that Carnot obtained a valid result, but he did so by employing an erroneous theory of heat, namely, the now discredited substantive or so-called caloric theory of heat [16].

However, careful studies and discussions [16, 17, 18, 19, 20] of Carnot's memoir show that Carnot implicitly defined caloric (calorique in French) so as to make it equivalent to entropy. With this interpretation it may be shown that his logic was flawless.

Then, we can understand and rewrite Carnot's principle with entropy:

"The production of motive power has its cause not in a real consumption of entropy, but in a transport from a hot to a cold body."

When we examine the original memoir, we would be impressed by Carnot's almost perfect consistency in usage of three technical terms: *feu*, *chaleur* and *calorique* in French. For example [19]:

"*La puissance motrice de la* ***chaleur*** *est indépendante des agens mis en oeuvre pour la réaliser; sa quantité est fixée uniquement par la température des corps entre lesquels se fait en dernier résultat le transport du* ***calorique***."

The erroneous misunderstandings of Carnot's principle are caused the indiscriminate translation of the French words *feu*, *chaleur* and *calorique* . Obviously, *feu* (fire in English) is a substantive concept. However, it serves to emphasize the need for careful translation and interpretation when we proceed to the more subtle problem of the distinction between *chaleur* and *calorique* . The meaning of the above paragraph of Carnot's statement will be clear if *chaleur* is interpreted as a qualitative concept heat and *calorique* as a quantitative concept entropy. It should be translated as following:

"*The motive power of* ***heat*** *is independent of the agents employed to develop it; its quantity is determined solely by the temperatures of the bodies between which, in the final result, the transfer of the* ***entropy*** *occurs.*"

Thus, the Carnot's principle would attain a complete fundamental agreement with the present representations if we carefully distinct *chaleur* and *calorique* and allow them to be created during an irreversible process. His result is still valid today and the theory he employed is always correct.

As a simple application of this interpretation, we derive the thermal efficiency of a heat engine. In the case of a purely thermal process of a heat engine, Gibbs's fundamental equation, i.e. Equation (2) reduces to

$$\mathrm{d}E=T\mathrm{d}S \tag{5}$$

and we get

$$I_{\mathrm{E}}=TI_{\mathrm{S}}. \tag{6}$$

Because of both energy E and entropy S are extensive quantities, we can say that the absolute temperature T measures how much energy is "carried" by the entropy current I_{S}, or how much energy the entropy current is "loaded with"[21].

Let I_{S} (i) is the absolute value of an entropy flowing into the heat engine through a surface of an input channel i, say, the walls of a boiler. Then the absolute value of the flow of energy I_{E} (i) accompanying this flow of entropy into the engine through i is T (i) I_{S} (i). Here T (i) is the absolute temperature of the hot body, say, the boiler. At the output channel o, say the walls of a condenser, the absolute value of an entropy current I_{S} (o) is leaving the engine along with the energy current I_E (o) = T (o) I_S (o). According to the second law of thermodynamics, the entropy current cannot decrease while flowing through an engine operating steadily. Accordingly, I_S (o) - I_S (i) = I_S (created) ≥ 0. Thus the production of motive power P, i.e. the difference between the flow of energy I_E (i) into and I_E (o) out of the engine along with the entropy current I_S (i) and I_S (o) , respectively, is given by [11, 13]

$P = I_E(i) - I_E(o)$

$= T(i)\, I_S(i) - T(o)\, I_S(o)$

$= [T(i) - T(o)]\, I_S(i) - T(o)\, [I_S(o) - I_S(i)]$

$= [T(i) - T(o)]\, T(i)\, I_S(i) / T(i) - T(o) I_S$ (created).

Then, the efficiency η of the engine is given by

$\eta = P / I_E(i)$

$= P / I_E(i) / T(i)\, I_S(i)$

$$= [T(i) - T(o)]\, T(i) - T(o) I_S \text{ (created)} / T(i)\, I_S(i). \tag{7}$$

The Carnot efficiency is given by the first term on the right side of (7). This is the efficiency of a heat engine operating reversibly, i.e., in the limit that I_S (created) = 0. Equation (7) shows that the actual efficiency of a heat engine is always smaller than the Carnot efficiency by the "dissipated" energy current T (o)I_S (created) divided by the inflowing energy current I_E (i). There are flow and creation of caloric (entropy), but no consumption of caloric (entropy) during the transport of caloric (entropy) from a hot to a cold body of the engine.

It should be pointed out that in a heat engine entropy flows spontaneously from a body with higher temperature to a body with lower temperature, just as mass of water flows spontaneously from a reservoir of higher gravitational potential to a reservoir of lower gravitational potential in a water wheel. If the process runs in reverse, i.e., an energy current flows *into* the "heat engine", entropy will flow from a cold to a hot body and it will become a heat pump, just as the water wheel becomes a water pump.

Misapplying the law of conservation of energy

The years from 1841 to 1847 are usually considered the time interval in which the physical quantity energy was invented and the law of conservation of energy is discovered through the work of Robert Mayer (1814-1878), James Prescott Joule (1818-1889) and Hermann von Helmholtz (1821-1894). Of course, it is a great event in the history of physics. But the misfortune happened in 1850 when the first law of thermodynamics was formulated by R. Clausius (1822-1888) as an application of the law of conservation of energy in science of heat. The formulation of the first law can be written as [10]

$$dU = \delta Q - \delta W, \tag{8}$$

where dU is the change of internal energy of a system, δQ is a contribution to the energy change caused by the supply of heat, and δW is the work done by the system.

The misfortune was that the inventors equated the old concept of quantity of heat with a so-called form of energy. Thus the quantity of heat Q was no longer a state variable, but became a process one, just like the quantity work W.

Why is Q still misused to measure the amount of heat today? The reason is that it acts in a strange double role: an energetic quantity equivalent to work, but also as something fundamentally different [22].

Equations (5) and (6) could answer the question: which of the quantities, S and E coupled with S, namely Q (but not the old one) is the correct measure for the amount of heat. Roughly, any one of them could be used to measure the amount of heat. But strictly, they are different tools: entropy S is only responsible for making a stone warm, or for melting a piece of ice; while Q makes a body both more inert and warmer. So it is better to use entropy S to measure the amount of heat.

A similar scenario had already taken place in 1686, when Gottfried Wilhelm Leibniz (1646-1716) initiated the famous *vis viva* (Latin for “living force” and akin to what we now call kinetic energy) dispute in mechanics [23]. It was about the question: which of the quantities, momentum $\boldsymbol{p}$ and E coupled with $\boldsymbol{p}$, namely kinetic energy E_k is the correct measure for the amount of motion. Today we know that they are different. Kinetic energy E_k is energy coupled with momentum $\boldsymbol{p}$. They are related in a way analogous to Equation (5):

$$dE_k = \boldsymbol{v} d\boldsymbol{p}. \tag{9}$$

Strictly speaking, it is better to use momentum $\boldsymbol{p}$, not kinetic energy E_k to measure the amount of motion.

Now we know that traditionally called heat Q is the transfer of energy coupled with the transfer of entropy through the boundary surface of a thermal system, while traditionally called mechanic work W is the transfer of energy coupled with the transfer of momentum (traditionally called impulse) through the boundary surface of a mechanic system.

7. Conclusions

We think with concepts. Every concept should be categorized in order to get a clear understanding through thinking. There are three categories of concepts in physics: substantive concepts, qualitative concepts and quantitative concepts.

Our sense organs are windows we observe the material world. What we obtain in observation is *not* the material world, but phenomena, or quality. So qualitative concepts are primative concepts what we need necessarily when thinking.

What is heat? Heat is a qualitative concept. It is referred to a quality we perceive with our touch organs. If heat is referred to a substance, we get an erroneous theory of heat, e.g., *the caloric theory of heat*. If heat is referred to a quantity, it is just another name for entropy S, not a form of energy Q. If heat is referred to a quality and caloric is referred to the quantity S to be used to measure the amount of heat, both the Carnot's principle and the so-called caloric theory of heat he employed are valid and right.

Temperature, entropy as well as energy are three main important physical quantities in thermodynamics, just as velocity, momentum and agular momentum as well as energy in mechanics, and electrical potential, electric charge as well as energy in electrodynamics. All physical quantities are quantitative concepts in physics. They are conceptual tools in toolbox of physics. They are invented, not discovered by physicists.

The value of a physical quantity at a given instant of time refers to a geometric form: a point, a line, a surface or a region of space. The value of an intensive quantity, such as temperature, velocity, angular velocity, electrical potential, refers to a point. The value of an extensive quantity, such as energy (or mass), entropy, momentum and agular momentum, electric charge, refers to a region of space. The value of a transfer of an extensive quantity, such as work (transfer of energy), impulse (transfer of momentum), or the value of current of an extensive quantity, such as power (energy current), force (momentum current), torque (angular momentum current), electrical current, refers to a surface. (The value of voltage refers to a line.)

Pedagogically, extensive quantities are particularly important for the teaching of physics. They play a central role in the general structure of physics. Each branch of physics has its own characteristic extensive quantities. For mechanics they are momentum and angular momentum, for electromagnism they are electric charge and magnetic charge, for thermodynamics it is entropy. The handling of these quantities is particularly simple. In thermodynamics, if entropy is introduced as a tool to measure the amount of heat at the begining of thermodynamics, every schoolgirl and every schoolboy could understand heat phenomena and heat processes what happen in their everyday lives easily.

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