Three chances for entropy

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Abstract

Entropy is known to be one of the most difficult physical quantities. The difficulties arise from the way it is currently introduced, which is due to Clausius. Clausius showed that the ratio of the process quantity heat and the absolute temperature is the differential of a state variable, which he called entropy. About 50 years later, in 1911, H. L. Callendar, at that time the president of the Physical Society of London, showed that entropy is basically what had already been introduced by Carnot and had been called caloric, and that the properties of entropy coincide almost perfectly with the layman's concept of heat. Taking profit of this idea could simplify the teaching of thermodynamics substantially. Entropy could be introduced in a way "which every schoolboy could understand". However, in 1911 thermodynamics was already well-established and Callendar's ideas remained almost unnoticed by the physics community. This fact should not be an excuse for ignoring Callendar's idea. On the contrary, this idea should be established, especially since entropy plays an important part not only in Thermodynamics but in the whole of physics. A two-man play is included in the appendix to this paper, written to introduce this history to teachers to encourage them to consider this useful complementary model.

Keywords: Thermodynamics, history of science, entropy.

Resumen

La entropía es conocida por ser una de las magnitudes físicas más difíciles. Las dificultades se derivan de la forma en que actualmente se la introduce, lo que se debe a Clausius. Clausius mostró que el cociente de la cantidad de proceso "calor" y la temperatura absoluta es el diferencial de una variable de estado, a la que llamó entropía. Unos 50 años más tarde, en 1911, H. L. Callendar, en ese momento el presidente de la Sociedad de Física de Londres, demostró que la entropía es básicamente lo que ya había sido introducido por Carnot y había sido llamado calórico, y que las propiedades de la entropía coinciden casi perfectamente con el concepto de calor del lenguaje común. Teniendo en cuenta esta idea podría simplificar la enseñanza de la termodinámica considerablemente. La entropía podría ser introducida de una manera "que un niño pueda entender". Sin embargo, en 1911 la termodinámica ya estaba bien establecida y las ideas de Callendar permanecían casi inadvertidas por la comunidad científica. Este hecho no debe ser una excusa para ignorar la idea de Callendar. Por el contrario, esta idea debería ser establecida, sobre todo porque la entropía juega un papel importante no sólo en la termodinámica, sino en la física entera. Una pieza de teatro para dos actores está incluido en el anexo del presente documento, escrito para presentar esta historia a los maestros para animarlos a considerar este modelo .

Palabras clave: Termodinámica, historia de la ciencia, entropía.

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I. INTRODUCTION

Not many ideas get more than one chance to be accepted, but the idea that entropy can be visualized as a kind of substance has had more than one chance. However, this idea has been almost unnoticed by the physics community. This perhaps explains why it took about 300 years for a great number of renowned scientists to develop thermodynamics. For the teaching of physics, it has been mostly a disaster. Today no one is surprised that the majority of physics teachers believe that entropy is difficult to teach. In one American cartoon a scientist says to another scientist: "If you can live with entropy you can live with anything". [1] What could be in greater contradiction with this sentence than Callendar's idea that entropy can be introduced in a way "which every schoolboy could understand?" [2].

II. FIRST CHANCE — BLACK AND THE 'QUANTITY OF HEAT'

For about 150 years (ca. 1600–1750), scientists had been essentially engaged in the measurement of temperature. Joseph Black (1728–1799) was the first to assert that two physical quantities are needed to describe thermal phenomena. Black, a Scottish physicist and chemist, discovered the latent heat, specific heat, carbon dioxide and magnesium. He was professor for chemistry and medicine at the University of Edinburgh and he became a friend and mentor of his assistant James Watt. Black distinguished between the intensive quantity temperature and the extensive ‘quantity of heat’:

“If, for example, we have one pound of water in a vessel, and two pounds of water 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” [3].

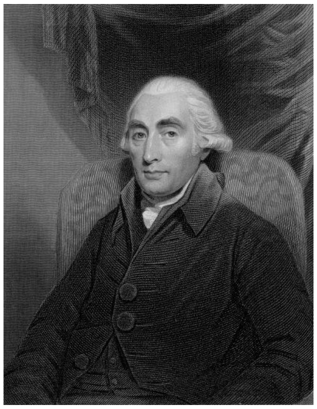

FIGURE 1. Joseph Black.

Black’s idea leads to the conclusion that a temperature difference is the driving force for a flow of the ‘quantity of heat’. Moreover, the ‘quantity of heat’ can be visualized as a kind of substance. It was a general conviction that something that can be visualized as a kind of substance will automatically obey a conservation law. A “creatio ex nihilo” -- a quasi divine act of creation -- was unthinkable at that time. Today, one could believe that Black’s ‘quantity of heat’ is energy. However, his ‘quantity of heat’ is a state variable and thus it must not be confused with heat as a form of energy. Due to this, one can find in recent books about thermodynamics sentences like:

“It is correct, then, to say that a system has a large amount of internal energy, but it is not correct to say that a system has a large amount of heat or a large amount of work. Heat is not something that is contained in a system. Rather, it is a measure of energy that flows from one system to another because of a difference in temperature” [4].

Today we know that Black's concept of ‘quantity of heat’ coincides perfectly with what we call entropy [5]. Count Rumford's experiment using a boring machine with a blunt tool succeeded in raising cold water to the boiling point by means of friction, questioning whether Black's quantity of heat could be a substance. It should not be a surprise to modern readers that the 'quantity of heat' obeys only half a conservation theorem. Back then, the psychological barrier was probably too high, and the production of the 'quantity of heat' could not be accepted. Only one small step was missing to develop a concept of entropy that even a layman could understand.

III. SECOND CHANCE — CARNOT’S PRINCIPLE

Sadi Carnot (1796-1832) asked, “Is there a fundamental limit for the improvement of heat engines?” and “How can the limit be specified?” These led to his principle:

FIGURE 2. Nicolas Léonard Sadi Carnot.

“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,…” [6].

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

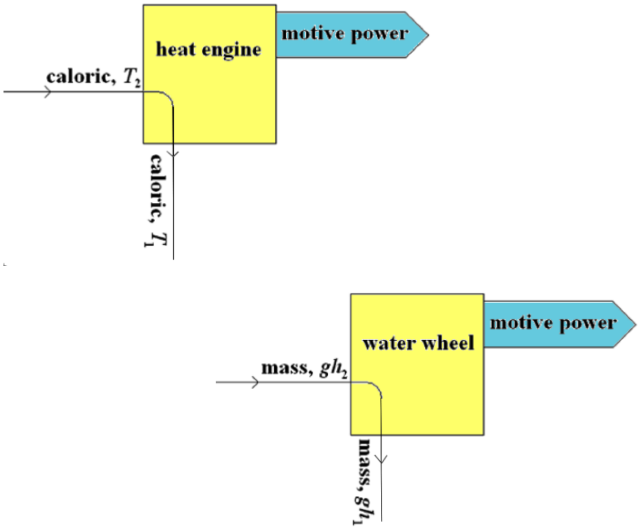

FIGURE 3. Heat engine flow diagram (above) demonstrating Carnot's principle and water wheel analogy flow diagram (below).

Fig. 3 illustrates the meaning of Carnot's principle (top) and describes analogically a water wheel (more exactly mass engines [7]) (bottom). Each machine needs two reservoirs. Heat (caloric) can realize work (motive power) when it is transferred from a reservoir of higher temperature (T_2) to a reservoir of lower temperature (T_1). Mass can realize work when it is transferred from a reservoir of higher gravitational potential (gh_2) to a reservoir of lower gravitational potential (gh_1). At given temperatures and gravitational potentials both machines realize a maximum of work when they work reversibly. To ensure reversibility, Carnot uses cycles. That means that all physical quantities have the same value at the beginning and at the end of the cycle. From today's perspective, Carnot's experiments are correctly described, if we equate heat (caloric) with entropy. The amount of realized work can then be written as $W = \Delta E = \Delta S\ (T_2 - T_1)$ and $W = \Delta E = \Delta m\ (gh_2 - gh_1)$ respectively. Here ΔS is the amount of entropy that is transported from the reservoir with higher to the other with lower temperature. And Δm is the mass that is transported from a place of higher to place of lower gravitational potential.

IV. THE INTRODUCTION OF ENERGY

The misfortune happened, when Joule (1818–1889) and Mayer (1814–1878) introduced the concept of energy. Of course, the introduction of energy was a great idea. The misfortune was that the inventors equated the old concept of heat with a so-called form of energy. ‘Heat’ was no longer a state variable; it has become a process variable. The old concepts of heat (Black, Carnot) were independent of energy; heat (‘quantity of heat’, ‘caloric’) was no form of energy.

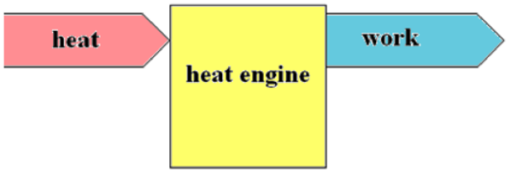

FIGURE 4. A heat engine gets energy as heat and supplies energy as work.

Because of the role-change of 'heat', the heat engine diagram (see Fig. 3) also must change its appearance (see Fig. 4). The old concept of heat as a state variable has disappeared from physics. From now on, it was impossible to make a heat balance. Thus physics has got in an uncomfortable situation. Not only physicists, but also chemists and engineers needed a quantity that measures the heat content of a body.

V. THE INTRODUCTION OF ENTROPY

Clausius (1822-1888) introduced the quantity entropy by an equation relating the change in entropy of the system to the change in heat (form of energy) of the system:

$$\int \frac{\delta Q}{T} = S - S_0\ . \tag{1}$$

where δQ is the amount of heat (form of energy) absorbed in a reversible process in which the system changes from one state to another. According to this definition one cannot see that entropy has a density, that entropy can flow and that entropy can be stored. Entropy has become one of the most difficult physical quantities, which provokes people to make pointed remarks like:

- “The concept of entropy is anyway one of the most occult concepts in physics” [8].
- “Such a definition appeals to the mathematician only” [2].

VI. THIRD CHANCE—CALLENDAR AND HIS PRESIDENTIAL ADDRESS

“The caloric theory of heat is now so long forgotten that we rarely hear it mentioned, except as an example of primeval ignorance; but it was not really quite so illogical as it is generally represented to be” [2]. With these sentences H. L. Callendar (1863-1930) begins his Presidential Address to the Physical Society of London, titled “The Caloric Theory of Heat and Carnot‘s Principle”.

Callendar was Professor of Physics at the Imperial College of Science and Technologies, London. In 1886 Callendar described a precise thermometer based on the electrical resistivity of platinum. He is author of the book “Properties of steam and thermodynamic theory of turbines”.

FIGURE 5. H. L. Callendar.

In his 1911 address, Callendar proves that the concept of entropy, as it had been introduced by Clausius and the concept of heat, as introduced by Carnot are the same. “The main difficulties, which the theory of Carnot encountered, were in explaining the apparent production of heat by friction or compression" [2]. With the addition that heat (caloric) could be produced, both concepts become identical. The conclusion is that entropy could be visualized as a kind of substance, which obeys 'half a conservation theorem': It can be produced but not destroyed. Therefore, entropy could be introduced in a way "which any schoolboy could understand. Even the mathematician would gain by thinking of caloric as a fluid (kind of substance), like electricity, ..." [2]. However, in 1911 thermodynamics was already well-established and Callendar's ideas remained almost unnoticed by the physics community. Another chance has been missed.

VII. ENCORE — JOB AND FALK

Georg Job published in 1972 a book named "A New Concept of Thermodynamics–Entropy as Heat" [9]. As the title suggests, the author talks about entropy in the same way as Black talked about quantity of heat, and as Carnot talked about caloric. Gottfried Falk, who knew Job, proved Callendar's assertion in 1985 once again and added Black's considerations, which Callendar had not taken into account [5].

Falk concludes: "The entropy introduced into physics by Clausius was, contrary to general belief, not a new physical quantity but the reconstruction of the 'quantity of heat' conceived about one hundred years earlier by the Scottish chemist Black. The same quantity was also used under the name 'calorique' by Carnot in his work, which laid the foundations of thermodynamics. That entropy and Black's 'quantity of heat' are only two names for the same physical quantity is not only of historical interest but is of significance to the teaching of thermodynamics as well. It asserts that entropy can be visualised as a kind of substance which obeys 'half a conservation theorem': It can be created but not destroyed" [5].

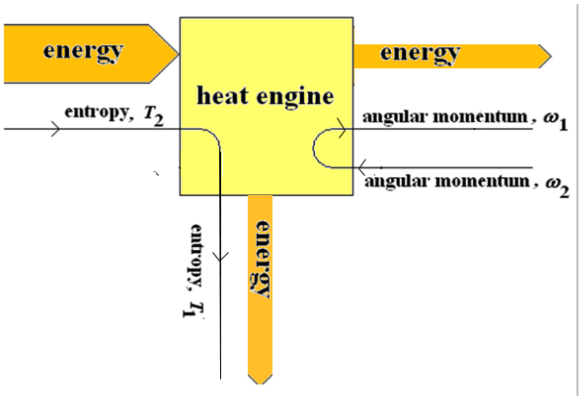

FIGURE 6. Energy-flow-diagram of a heat engine.

Fig. 6 shows the heat engine flow diagram, as it can be found in a recent schoolbook [10]. It shows that the heat engine receives energy with the "carrier" entropy and gives it away with the "carrier" angular momentum. In fact, on the left hand side, entropy arrives at the higher temperature T_2 and leaves at the lower temperature T_1. On the right side, angular momentum arrives at lower angular velocity ω_1 and leaves at higher angular momentum ω_2. Therefore, both "energy currents" are net energy currents.

Now the entropy has the third chance to become well-known in a way, which every schoolgirl and every schoolboy could understand. Let us see.

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APPENDIX A: ORIGINAL SOURCES

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APPENDIX B: THREE CHANCES FOR ENTROPY —

A Play in Honor of the 100 Year Anniversary of Callendar's Presidential Address

By Michael Pohlig & Joel Rosenberg

Slides available here: <http://www.archive.org/details/ThreeChancesForEntropy--Slides>, visited September 4 (2011).

Video of performance available here: <http://www.youtube.com/playlist?list=PL9F6BBC228E902B9B>, visited September 4 (2011).

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Prologue

A Once upon a time, an American cartoonist drew two professors at a cocktail party: "In my opinion, Mrs. Wendell—and I believe Dr. Steinmuth will concur—if you can live with entropy you can live with anything".

Which one of you agrees?

The majority of physics teachers believe that entropy is difficult to teach. And maybe most of you believe that "*The concept of entropy is anyway one of the most occult concepts in physics*".

100 hundred years ago a physicist named Callendar worked out how entropy can be introduced "in a way every schoolboy could understand." Here the American cartoonist, there Callendar. Do they speak about the same thing?

We hope to show you that Callendar's idea was a missed chance for physics education. We will argue that entropy, which was introduced by physicist Clausius, can be visualized as fluid-like, and that entropy and layman's "heat" are only two different names for the same physical quantity. This idea is not new. There were three chances for entropy to be introduced this way.

We will start by going back to the mist of time, to the middle of the 18th century.

***

1st Chance

B *Hello friends. Please let me introduce myself -- I am Joseph Black.*

I was born in 1728 in France, but I'm Scottish by blood. People will later say that I died in 1799. Sorry I must believe that, I cannot check that.

I am a professor of chemistry and medicine at the University of Edinburgh. One of my former students and current collaborators is James Watt. He attended my courses when I was at Glasgow University, and repaired the University's engine. He is a fine man and a fine engineer. Maybe people will remember him while they forget my name and what I have done.

But I have made many contributions to science. For my 1754 thesis to become a Doctor of Medicine, I discovered a kind of air that could be "fixed" by a solid, and released by heating, and also through chemical reactions. I called it "fixed air".

A Today we call it carbon dioxide.

B *"Fixed air" was a very new idea, since at that time many people thought that all gases were the same "air," and that gases could not combine with solids. My work laid the foundation for the pneumatic chemistry of Priestly and Cavendish, leading to the Revolution in Chemistry by Lavoisier.*

I was also the first to establish an improved theory of heat.

A Yes, Professor. That is our subject for today. Can you tell us more about that?

B *First, I differentiated between the intensity of heat, what we call temperature, and a "quantity of heat". So* *"if, for example, we have one pound of water in a vessel, and two pounds of water 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*".

Next, I identified what I called "latent heat", which is the great quantity of heat needed to melt ice or boil water that is not "sensible" by the thermometer. That is, the latent heat is "absorbed and concealed" without changing the temperature, yet can be seen in the fluidity it causes. The ice calorimeter provides a measure of this heat as the volume of water melted.

I also introduced the idea of heat capacity based on an experiment by Fahrenheit using water and quicksilver --

A Also called Mercury

B *-- where he showed that "quicksilver... requires less heat to heat it, than that which is necessary to heat by the same number of degrees an equal measure of equally cold water". I said that quicksilver has less heat capacity.*

And I realized that "equilibrium of heat" will result between objects placed together in an isolated room with no fire and no sun, Heat is communicated from the hotter to colder bodies. At equilibrium they will all be at the same temperature, but the heat will not be equally divided or distributed among them if they have different heat capacities.

A Wow! Heat versus temperature, latent heat, heat capacity, and thermal equilibrium -- that's quite a lot of innovation, all of which we still teach today! But I wonder, what do you mean by heat?

B *Good question. I can't propose with confidence any single theory of heat.*

A But you talk about it as though it is a substance?

B *Well, "when we perceive that what we call heat disappears in the melting of ice, and reappears in the freezing of water, and a number of analogous phenomena, we can* ***hardly avoid thinking it a substance****...*

But since heat has never been observed by us in a separate state, all our notions of this union must be hypothetical".

The French chemists call my latent heat "calorique", based on the theory of Lavoisier, who invented the name. We can see on Lavoisier's "Table of Simple Substances" that he includes calorique as a substance. which replaces old ideas like "chaleur" and "feu" -- heat and fire.

In Lavoisier's scheme, the particles of an object do not touch and the spaces among them are filled with calorique that can flow into and out of the object. The object's heat capacity depends on the size of those spaces. More importantly, calorique is self-repulsive and attracted to matter, and since particles are thought to be attracted to each other like planets, calorique is like an atmosphere around each particle repelling the others.

This explains why adding heat causes liquids and metals to expand, and why latent heat is needed to overcome the attractions and change the state from solid to liquid to gas.

A That is an interesting theory. What do you think of the idea that heat might be motion?

B *Yes, I am aware of that old theory as proposed by Francis Bacon and accepted by some. But I believe that the idea is too vague, and there is not enough evidence to support it as a replacement for the fluid model.*

A Thank you Professor.

Black's ideas let us visualize heat as a kind of substance or fluid that can be stored in or transferred between bodies. But if we look in a modern book like Tipler's *Physics for Scientists and Engineers*, we find this quote:

"It is correct, then, to say that a system has a large amount of internal energy, but it is not correct to say that a system has a large amount of heat or a large amount of work. Heat is not something that is contained in a system. Rather, it is a measure of energy that flows from one system to another because of a difference in temperature".

So what happened to Black's heat?

In Black's time it was the general belief that if something can be seen as a kind of substance it is automatically conserved. "Creatio ex nihilo", a quasi divine act of creation, was unthinkable at that time.

For example, an experiment in 1798 was done by Count Rumford. He bored out a cannon using a blunt tool and showed that cold water could be raised to the boiling point by means of friction, with no change in the original materials. Rumford concluded that "anything which an insulated body or system of bodies can continue to furnish without limitation, cannot possibly be a material substance.

So Black's idea about "quantity of heat" was questioned, and didn't get the opportunity to develop into what today we call "entropy". But if we put entropy into Black's quote -- "It is evident that the 2 pounds must contain twice the entropy that is contained in one pound" -- it is correct. And so the first chance was lost.

This state of confusion was the scientific environment our next guest grew up in.

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2nd Chance

B *Bonjour Messieurs dames. Mon nom est Sadi Carnot.*

Oh I have forgotten, I have to speak English. As you could guess, I am from France. My full name is Nicolas Léonard Sadi Carnot. I was born in 1796, just 7 years after the French revolution started. People say I died as a young man, not older than 38 years. Good that I do not know that yet.

I live in a turbulent time. My father, Lazare Nicolas Carnot, was a master military engineer, politician, and mathematician. His book on the efficiency of traditional machines was very influential for me, since I also became a military engineer.

In the early 1800s, heat engines had just come into fashion, and I was totally fascinated by them. But it seemed to me that their improvement was occurring almost by chance. So I was captivated by two questions. Firstly: Is there a fundamental limit for the improvement of heat engines? And secondly: are there "agents preferable to steam for developing the motive power of heat".

A These are the main questions in your 1824 book. Can you give us a brief summary?

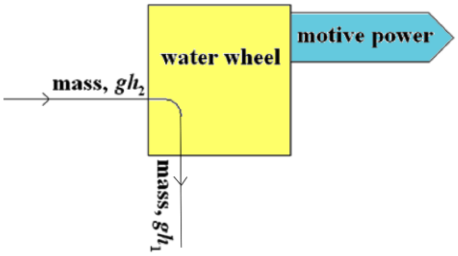
B *Oui. The main idea is that "the production of motive power is...due in steam-engines not to an actual consumption of caloric, but to its transportation from a warm body to a cold body, that is, to its re-establishment of equilibrium".*

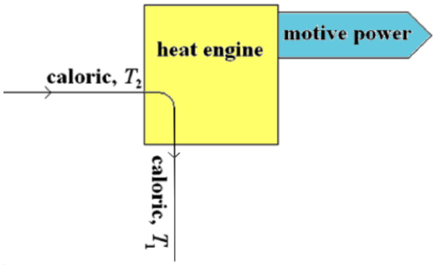
A Sorry, can you explain that in other words? I don't really understand.

B *Well, I will try to explain, using the analogy of a waterfall that I use in my book.*

"The motive power of a waterfall depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what...we will call, the height of its fall". This is my own invention -- to visualize caloric falling from higher to lower temperature and producing motive power.

A So if I draw some diagrams, you're saying that just like water falls from a reservoir of higher 'gravitational-potential' (gh_2) to a reservoir of lower 'gravitational-potential' (gh_1) and produces motive power in a waterwheel, caloric falls from a reservoir of higher temperature (T_2) to a reservoir of lower temperature (T_1) and produces motive power in a heat engine. Is that right?





B *Yes, that is ok.*

A And the more mass transferred, or the bigger the gravitational potential difference, the more motive power is produced. Similarly, the more caloric transferred, or the bigger the temperature difference, the more motive power is produced.

B *Precisely.*

A So this sounds like you believe in the caloric theory of heat as a substance.

B *Well, when I wrote my book I knew that the caloric theory required "the most careful examination". I tried to make my ideas independent of any one theory of heat by focusing on two big ideas: the idea of a heat engine "cycle", and the idea that the cycle is "reversible" when perfect. Here is my diagram.*

A And I can make it a little clearer by adding some colors to represent hot and cold, and also spreading out the four steps of your cycle.

B *Ok. For the engine cycle, we know we can expand a body by adding heat to it, independent of what heat is. And we can use this expansion to produce motive power -- that is the purpose of an engine. We can then remove the heat to contract the body to its original state, ready to go again through the cycle. And this cycle is independent of the body -- steam or otherwise.*

If it is to be a ***perfect reversible cycle*** *that can be run equally well forwards or backwards, there can never be any direct contact between a warmer and colder body, since there can be no useless re-establishment of equilibrium, which is "an actual loss. That's like a waterfall without a waterwheel.*

A Fasinating, Monsieur Carnot. Merci.

Carnot died young in 1832 after a series of illnesses. This second chance to view caloric as entropy was lost, maybe due to the invention of energy.

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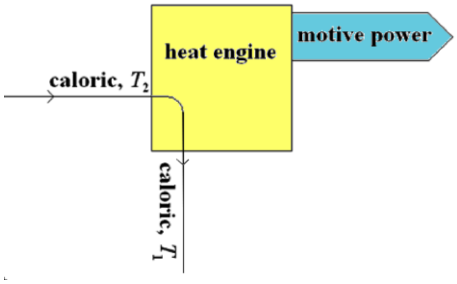
Peripety

A It wasn't until the 1840s that the energy idea really started becoming clear.

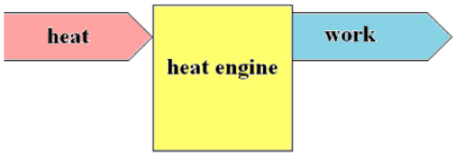
Julius von Mayer (1814-1878) was a German physician with little physical or mathematical training. The story goes that as the ship's physician on a boat to Indonesia in 1840, he realized that after a storm the waves leave the water warmer than when calm. After returning to Germany he dedicated his life to this idea, and by 1842 he published a paper that specified "The warming of a given weight of water from 0° to 1°C corresponds to the fall of an equal weight from a height of about 365 metres". This was the first estimate of the mechanical equivalent of heat.

Independently, a year later in 1843, English physicist James Joule (1818-1889) published his first of several experiments measuring the amount of heat produced by friction. He wrote: "I am satisfied that the grand agents of nature are, by the Creator's fiat, *indestructible*; and that wherever mechanical force is expended, an exact equivalent of heat is *always* obtained".

Based on this model, our diagram changes from this:



to this:



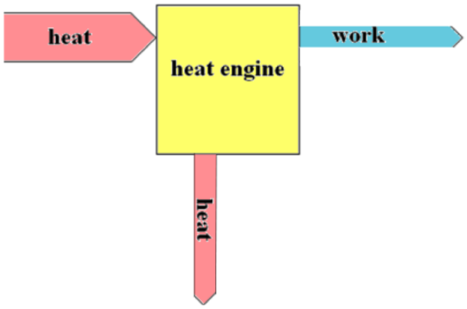
In the Carnot model, motive power appears as caloric falls through a temperature difference. In the Mayer-Joule model, motive power appears as heat disappears. These two models are difficult to reconcile. Is heat conserved? Or does it appear and disappear?

In 1848, British physicist Lord Kelvin published his "absolute thermometric scale". Kelvin based his scale on Carnot's theory, and wrote: "The conversion of heat (or caloric) into mechanica effect is probably impossible*, certainly undiscovered". But wrote in the footnote: "* This opinion seems to be universally held by those who have written on the subject. A contrary opinion however has been advocated by Mr. Joule of Manchester".

In 1849 Kelvin wrote a paper summarizing Carnot's book, and asks: "When 'thermal agency' is spent conducting heat through a solid, what becomes of the mechanical effect which it might produce? Nothing can be lost in the operations of nature--no energy can be destroyed". This is the first modern use of the word energy, and also a very good question about what happens when energy is "wasted" during conduction of heat.

In 1850, German physicist Rufdolf Clausius (1822-1888) did his best to integrate Joule and Carnot, writing: "It is not even requisite to cast the theory of Carnot overboard...It is quite possible that in the production of work...a certain portion of heat may be consumed, and a further portion transmitted from a warm body to a cold one; and both portions may stand in a certain definite relation to the quantity of work produced".

So now the diagram looks like this. Some heat produces work, and some goes from the higher to lower temperature.



By 1851, Kelvin agreed with Clausius that "heat is not a substance, but a dynamical form of mechanical effect", and by 1852, he answered his own question: "As it is most certain that Creative Power alone can either call into existence or annihilate mechanical energy, the 'waste'...cannot be annihilation, but must be some transformation of energy".

And that's how it was decided -- caloric was dead, and heat became energy. Both Joule and Kelvin cited the Creator as the origin of energy. But something was missing.

In his 1854 paper, Clausius defined the relationship between the transformation of heat into work, and heat from higher to lower temperature. "The generation of the quantity of heat [energy] Q of the temperature T from work, has the equivalence-value Q/T". In perfect reversible cycles the transformations cancel each other out and sum to zero:

$$\int \frac{\delta Q}{T} = 0$$

By 1864 Clausius had updated his equation:

$$\int \frac{\delta Q}{T} = S - S_0$$

"I propose to call the magnitude S the *entropy* of the system, after the Greek word [for] *transformation*...to be as similar as possible to the word *energy*: for the two magnitudes to be denoted by these words are so nearly allied in their physical meanings, that a certain similarity in designation appears to be desireable".

So, who among us today recognizes this physical meaning of entropy as Clausius intended? Probably not many. Our next guest might be able to help with this.

***

3rd Chance

B *Let me introduce myself: My name is Callendar, Hugh Longborn Callendar. I am a Professor of Physics at the Imperial College of Science and Technologies in London.*

I began my experimental work in physics with J.J. Thompson. He encouraged me to develop a platinum resistance thermometer for high temperature measurements, and soon I could measure between -160 and 1600 degrees Celsius. Revenue from my thermometer helped make me a wealthy man, but the thermometer itself enabled me to become a great scientist and engineer.

I used this device to study steam, especially in engines. By 1915 I published my first edition of The Callendar Steam Tables, which became famous. But I was not only interested in thermodynamics; I was also interested in "how to teach thermodynamics".

A Yes, Professor. In 1911 -- 100 hundred years ago -- didn't you publish an educational paper?

B *Indeed I did. I was president of the Physical Society of London, and I wrote it for my presidential address. My intention was to re-introduce the old idea of treating caloric as a fluid. "Clausius gave it the name 'entropy,' and defined it as the integral of dQ [over] T. Such a definition appeals to the mathematician only. In justice to Carnot, it should be called caloric...Even the mathematician would gain by thinking of caloric as a fluid, like electricity, capable of being generated by friction or other irreversible processes".*

A That sounds...controversial.

B *Using caloric instead of "entropy" is really just a convenient method of expression. I don't see how there could be serious objection to adopting it.*

A Can you tell us the main idea of your suggestion?

B *"We have become so saturated with the idea that heat is energy...that we...forget that a quantity of heat is not completely specified by its energy equivalent.*

"It is true that we can solve most questions in heat in terms of energy and temperature, without explicit reference to caloric or entropy. We could similarly solve most electrical problems without mentioning amperes. But...everything is greatly simplified and rendered more direct if we adopt caloric as the true measure of heat quantity and regard it as possessing energy in virtue of its temperature".

A That does make it clearer what Clausius meant about the relationship of energy and entropy. Professor, I have to tell you that 100 years later your ideas remain almost unnoticed by the physics community. Do you know why?

B *That is too bad. Perhaps this conception of caloric appears...to run counter to some of our most cherished popular illusions with regard to heat. And it is true that it may be difficult to isolate a particular set of material particles and label them caloric. But the mathematical conception of entropy makes it all the more necessary for our sanity and progress to think and speak of it as a material fluid.*

A Thank you Professor.

It is worth noting that in 1938, Callendar's son published the first paper with experimental evidence of human-induced climate change, now called "The Callendar Effect".

As for entropy, the third chance was missed. So to conclude...

Wait! It looks like we have one more guest.

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Encore

B *Hallo, Ich bin Gottfried Falk -- I am Gottfried Falk, professor of Didactics of Physics at the University of Karlsruhe in Germany. I was a professor of Mathematical Physics before that, but my work to make thermodynamics more axiomatic in the 1950s led me to discover a useful approach to teaching physics. I have been developing that idea ever since, including a children's book with my colleague Friedrich Herrmann.*

It was Herrmann who told me of a 1972 book by Georg Job, a physical chemist from the University of Hamburg, proposing to think of entropy the way we speak of heat in common language, such as "the walls of a house prevent the heat from leaking out".

The physicists will tell you that it is wrong to imagine *that energy is contained in a system as heat. But if we take "heat" to mean entropy, as my friend Job suggests, the common language becomes correct. And as represented in this picture, heat can flow and also be produced.*

A Interesting. Have you published this idea?

B *Ja. In 1985 I wrote a paper arguing that Job's entropy is really just Carnot's "caloric" and Black's "quantity of heat" under different names. Indeed, "entropy can be visualized as a kind of substance which obeys 'half a conservation theorem': it can be created but not destroyed".*

A That is very similar to the argument of Callendar from 1911.

B *Yes, it is funny but Job and I had never heard anything about Callendar's work until a referee for my paper told me about it. I added a note in the proof.*

A So Callendar's work never became well known, let alone adopted.

B *It is astonishing. Despite its unquestionable scientific merit Callendar's work has never been incorporated in textbooks on thermodynamics.*

A Very interesting. Vielen Dank.

***

Exodus

A Now there is a textbook that includes Callendar's idea: The Karlsruhe Physics Course, by Herrmann and Job, which has been translated into several languages.

While Callendar and Falk argued for a "resurrection of caloric", the old caloric theory does have discredited aspects -- it is not the heat atmosphere around each planet-like atom, keeping them all separate. We now have protons and electrons and quantum theory to account for that.

But caloric does give us a model for macroscopic entropy, a concept we don't currently have in physics education. "Macroscopic entropy" ***complements*** the statistical mechanical interpretation. Boltzmann's prized equation for entropy, what he called "the logarithm of a probability of a complexion", is not a great introduction for most students.

And without a solid concept for entropy, is it difficult for scientists and engineers to understand where they are "wasting energy". This is **hugely** important for solving our energy and climate problems.

So on this 100th anniversary of his paper, let us hear once again from Callendar.

We have one more chance. Let us see if we can find a better way to live with entropy.

**** End ****