Problems in the Teaching of Energy: Historical Burdens of Physics

Symposium Overview

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Abstract

If our symposium was in German, its title would be „Altlasten der Physik“. This title meets the content of our contributions very accurately, but is almost untranslatable into any other language. In English it would translate, literally but colorlessly, as „Old Charges of Physics“.

The term „Altlast“ came into being in the early 1990s to describe a phenomenon that showed up after the breakdown of the communist regime in East Germany. The rotten and hazardous industrial plants and other infrastructure remnants that are not only useless, but also necessitate large investments for their rehabilitation, are called „Altlasten“.

In physics there are such infrastructure remnants from the historical development of the subject. We hope that by identifying them, we can begin to make the investment towards fixing them. We have chosen the title „Historical Burdens of Physics“: Like the hazardous sites of East Germany, these concepts once served a purpose, but now they must be cleaned up before further gains can be made.

More of them can be found on our web site
http://www.physikdidaktik.uni-karlsruhe.de
In German: click on „Kolumne: Altlasten der Physik“
In Spanish (in preparation): click on „Publicaciones en Español“

Forms of energy

Subject:

It is common knowledge that energy exists in various forms. Kinetic, potential, electric, chemical energy and heat are examples known to everybody; “converting energy from one form into another” is a common way of speaking.

Deficiencies:

Although we often speak about energy forms, we run into difficulties as soon as we try to define them. We are not consistent in the necessary distinction between the forms of stored and transmitted energy. On the contrary, in our casual formulations we tend not to differentiate the two concepts. While for heat and different types of work certain rules have been established, the classification of storage forms of energy seems vague and arbitrary, with the exception of some mechanical textbook examples. Which part of the energy of a steel spring or of an air molecule is mechanical, thermal, chemical, electric or magnetic? Which part is translational, rotational, oscillatory or electronic? Which part is kinetic or potential? Which part is ordered or unordered? The fact that we obtain reasonable results without knowing the answers to these questions leads to the conclusion that the classification is of no importance for our physical arguments.

Origin:

In order to account for the role of energy within the network of physical phenomena, enumerating energy forms is a means of expression which is difficult to avoid. This can be seen in a citation of F. Mohr (1837) from the time before the discovery of the conservation of energy: "In addition to the 54 known chemical elements there exists in nature yet another agent, the name of which is Force: Under appropriate circumstances, it appears as movement, chemical affinity, cohesion, electricity, light, heat and magnetism, and from each of these forms of appearance, all of the others can be brought into being."

Disposal:

We save many words if we refrain from useless differentiations. It is often comfortable to speak about bottle milk and carton milk. It is completely useless, however, to call the process of transferring or drinking it "milk conversion," or to define the content of a glass or of the stomach as different "forms of milk." The situation is the same when speaking about the energy. The clearest, but perhaps not the most comfortable solution is to refrain from speaking about energy forms completely. Of course, just as for a patient who after a long period of convalescence leaves his crutches for the first time, it takes time until one is acquainted to the newly acquired freedom and also to be able to cover difficult terrain.

Pure energy

Subject:

In textbooks and scientific reviews one often finds statements that say electromagnetic radiation is pure energy. Here is an example of such a formulation [1]: "When a positron encounters an electron, the two particles annihilate each other and produce pure energy in the form of gamma radiation." Or another example [2]: "A massive particle and its anti-particle can annihilate to form energy, and such a pair can be created out of energy." A similar point of view is expressed in the following formulation [3]: "... light can also be described in terms of photons, discretely emitted quanta of energy."

Deficiencies:

It is obvious that an electromagnetic wave is not pure energy. The electromagnetic field is a physical system, i.e. a thing, for which every standard physical quantity has a certain value, and not only the energy. So, in general for an electromagnetic field, apart from just the energy, the extensive quantities momentum, angular momentum and entropy also have non-zero values. But intensive quantities also have certain values, just as is the case for other systems. So the electromagnetic field has a pressure at every point. (The pressure depends on the direction and is therefore a tensor.) In certain states, i.e. in those states that are usually called thermal radiation, the field has a certain temperature and a certain chemical potential. Identifying the radiation with one single quantity is simply not correct. The radiation is a physical system, something that is given to us by nature. Physical quantities on the contrary are products of the human mind. They are tools for the description of systems. Correspondingly, a photon, the elementary portion of the system "electromagnetic field", is more than just a quantum of energy. The photon also carries other extensive quantities in addition to energy, such as momentum and angular momentum.

The confusion between the concepts "quantity" and "system" also manifests in a kind of formulation often encountered in which energy and matter are presented as two concepts on an equal footing [4]: "So if galaxies are all moving away from one another […] it seems logical that they were once crowded together in some dense sea of matter and energy."

Origin:

There are probably two causes for the erroneous identification of the quantity "energy" and the system "electromagnetic field." Apparently, on the one hand the energy was seen as more than just a variable in a theory, and on the other hand, the field was not taken seriously as a system.

After the introduction of the energy in the middle of the 19th century, its comprehensive significance in science was quickly understood. However, the enthusiasm about the importance of the new quantity led to an overestimation and misinterpretation of it. Energy was conceived, in particular in the circle of the "energeticists", as a kind of substance. So, one can read in Ostwald's 1908 book *The Energy* [5]: "Therefore, the energy is contained in all real and concrete things as an essential component, which is never absent, and therefore we can say that the energy embodies the actual reality.”

On the other hand, the electromagnetic radiation was not accepted as what we today understand by the concept. We now know that it is a system like other system, for instance an ideal gas, or the phonon system of a solid. Like other systems, the electromagnetic field consists of elementary portions. What the hydrogen molecules are to the hydrogen gas and the phonons are to the lattice system of a solid, the photons are to the electromagnetic field.

This misunderstanding of the physical quantity “energy”, as well as of the physical system “electromagnetic field”, has left its traces. Although we have known better for a long time, we still easily use sentences like those cited at the beginning.

Disposal:

Instead of saying that pure energy is created in a reaction of an electron and a positron, say that a photon results. And instead of saying electromagnetic radiation is pure energy, say that the radiation carries energy, but besides energy it also carries other extensive quantities such as momentum, angular momentum and entropy.

List of references

[1] Scientific American, December 1993, S. 44

[2] Penrose, R.: The emperor's new mind, Oxford University Press, S. 308

[3] Scientific American, April 1993, S. 2

[4] Scientific American, October 1994 S. 32

[5] Ostwald, W.: Die Energie. – Verlag Johann Ambrosius Barth, Leipzig, 1908, S. 5.

The Energy Mass Equivalence

Subject:

Einstein’s energy mass relation $E = mc^2$.

Deficiencies:

In many schoolbooks and magazines we find the statement that Einstein’s energy mass relation means that mass and energy are different manifestations of the same physical quantity, and energy and mass can be transformed one into the other [1]. If this statement was true, we could distinguish energy from mass. A decrease of energy would be associated with an increase of mass and vice versa. However, it is not true, and it is not what Einstein‘s relation tells us. According to this relation, mass and energy are the same physical quantity, measured with different units.

Origin:

Possibly the culprit is Einstein himself:

"It follows from the special theory of relativity that mass and energy are both but different manifestations of the same thing, a somewhat unfamiliar conception for the average mind. Furthermore, the equation … in which energy is put equal to mass, multiplied for the square of the velocity of light, showed that a very small amount of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned above."
Instead of saying "may be converted into" he should have said "corresponds to".

Disposal:

Teaching should make clear the following:
1. The quantity known before as energy also has the properties of the quantity known before as mass, namely weight and inertia. A charged battery is heavier than an empty one. Hot water is heavier than the same amount of cold water; a moving body is heavier than the same body at rest, and so on. The weight differences in these examples are so small, however, that it is impossible to measure them.
2. The quantity known before as mass has also the properties of the quantity known before as energy. At a first glance, this assertion seems unbelievable. A typical property of energy is that it allows us to do some useful work. So one might expect that with 1 g of sand one should be able to realize a work of $E = 1\ \mathrm{g} \cdot c^2 \cong 10^{14}$ J, what is obviously not true. However, we can never take profit of all the energy contained in a system. With "compressed" air of 1 bar we cannot drive a jackhammer; with "warm" water of ambient temperature we cannot drive a thermal engine. With gasoline alone we cannot run a motor. We also need oxygen. So it should not be surprising that we cannot run or drive anything with 1 g of sand alone. We also need 1 g of anti-sand. But if we had the anti-sand, it would work.

List of references

[1] "…This pair annihilation is the conclusive proof of the famous Einstein's law $E = mc^2$ for the transformation of mass into energy."

Tendency to the energy minimum

Subject:

The common reason given as a cause of a process is that the system reaches a state of minimum energy as a result of this process:

– a pendulum comes to rest at its low point
– a floating board tilts on its side
– a soap bubble forms in a spherical shape

– a sponge sucks up water
– a quantity of electric charge distributes on a conductor
– excited gas atoms emit photons
– positive and negative ions arrange themselves in a crystal lattice
– heavy nuclei decay.

Deficiencies:

Without saying it explicitly, all of these statements assume that each system aims at a state of minimum energy and proceeds to this state, provided it is not hindered by some circumstance. Formulated this way, however, the statement doesn't make sense. If one system reaches a state of minimum energy, then the complementary system, the environment, must reach an energy maximum due to the conservation of energy. The same argument applied to the environment would yield the opposite result. Thus the above assumption cannot be valid generally. So for which system is it valid? The answer comes from thermodynamics. The system must, as W. Gibbs expressed it in 1873, be closed for everything except the energy necessary to keep the entropy constant. The entropy S_p produced by processes occurring within the system appears only in the environment, and with it the energy TS_p coming from the system, where T is the temperature of the environment. Since S_p and T are always positive, the system always loses energy, since any other energy exchange that could compensate the losses is forbidden. Seen in this way, the tendency to the minimum energy is nothing more than a consequence of the entropy principle, applied to a particular class of systems.

Origin:

In mechanics we ignore the thermal properties of things. Levers, pulleys, springs, blocks and ropes are considered objects that cannot be heated, i.e. whose temperature and entropy cannot change. In fact we are tacitly ascribing the entropy created by friction to the environment. Under these conditions, we are allowed to speak of the tendency to an energy minimum. The same applies to systems in many other parts of physics – hydraulics, electricity, atomic and solid state physics and so on. Because we don't mention the production of entropy as the cause for these processes, we get the impression of an independent natural principle.

Disposal:

We can talk about entropy production in systems explicitly. Like so often, our strained relationship to entropy misleads us to questionable surrogates. The fundamental evil, which as a consequence has endless difficulties and opposes itself to any attempt to remedy, is the dogma of the heat as a special form of energy, which for one and a half centuries has been affectionately cared for, and which is anchored in the first law of thermodynamics. Only if we are ready for a revision can a lasting improvement be expected.

Isolated Systems

Subject:

In order to formulate the conservation of energy or of other physical quantities, we often refer to an isolated system. We imagine a region of space whose boundaries are impermeable for a current of the quantity under consideration. The quotations (1) and (2), which refer to the conservation of energy, are taken from books for the secondary high school and are highlighted in these books.

(1) “In a thermally and mechanically isolated system the total energy is constant.”
(2) “In an isolated system the sum of all energies is always constant. The total energy is conserved.

$$E_{\text{total}} = E_1 + E_2 + \ldots + E_n = \Sigma E_i = \text{constant}$$

$E_1, E_2, \ldots, E_n$ different energy forms”

Deficiencies:

The concept of conservation of an extensive or substance-like quantity is not a difficult concept. This has to do with the fact that we can easily represent these quantities pictorially: We imagine them as a kind of fluid or stuff. The conservation of a quantity X can then be stated in the following way: “X cannot be produced and cannot be destroyed.”

Here the exact wording doesn‘t matter. Conservation is something that we can easily express with words of the common language.

A consequence of this statement is that the value of X in a region of space can change only if a current of X flows into or out of the region. Mathematically the statement can be expressed in the following way:

$$\frac{dX}{dt} + I_X = 0$$

Here dX/dt is the rate of change of X in the considered region and I_X is the flow of X through the boundary surface.

A formulation of the principle of energy conservation that refers to an isolated system is a special case of this statement. “The system is isolated” means that there is no flow through the boundary surface. However, the isolation is an unnecessary restriction because the considered quantities are conserved independent of whether the system is closed or not.

To convince myself that the number of my students "is conserved", there is no need to close the door of the classroom. There is no problem if, from time to time, somebody comes in or goes out, as long as I ascertain that the number of students in the classroom increases by one when someone comes in, and decreases by one when someone goes out.

Origin:

The fact that we formulate conservation with reference to an isolated system is a leftover of the troublesome development of the concept of energy as a substance-like quantity. Until shortly before the beginning of the 20th century, the localizability of energy was not acknowledged. It was not yet possible to associate a density, a current and a current density with it. In 1887 Max Planck [1] wrote in a historical survey about the energy:

"... according to this definition the amount of the energy is measured only by these external effects, and if one wants to attribute any imaginary material substrate to the energy, then one has to look for it in the environment of the system; only here the energy finds its explanation and therefore also its conceptual existence. As long as one abstracts completely from the external effect of a material system, one cannot speak about its energy, since it then is not defined... On the other hand, we see from the form of the principle as derived formerly that the energy of a system remains constant, if a process carried out with the system does not cause any external effect whatever the internal effects may be. This observation leads us to conceive the energy contained in a system as a quantity existing independently of the external effects." And later: "Meanwhile it is unmistakable... that with this substance-like interpretation of the energy we get not only an increase in the conceptual clearness but also a direct progress in the comprehension... However, as soon as one enters into this question, the uncertainty, which lay before in the concept itself, takes upon the form of a physical problem which in principle can be solved..."

This solution came a few years later by Gustav Mie [2]. He showed that the principle of energy conservation can be formulated locally, namely in the form of a continuity equation. From then on, the strange separation of the system and the effects that can be observed only in the environment was no longer necessary.

Thus, it took about 50 years to prove the substance-like nature of energy. However, the expectation that the quantity had this property was there from the beginning: Ostwald [3] in his 1908 booklet, *The Energy*, praised the work of Robert Mayer with the following words: "For our general investigation the essential result of Mayer‘s work is the substance-like view of what he calls force, i.e. the energy. For him this was a well-defined entity; the indestructibility and unproducibility are characteristic for its reality.”

Disposal:

We state the conservation law of the substance-like quantity *X* in the following way: “Energy, momentum, angular momentum, electric charge … cannot be produced and cannot be destroyed.”

Just as important are statements about the non-conservation of a substance-like quantity, for example: “Entropy can be produced but cannot be destroyed.”

List of references

[1] M. Planck: Das Prinzip der Erhaltung der Energie. B. G. Teubner, Trennung, 1908, S. 115.
[2] G. Mie: Entwurf einer allgemeinen Theorie der Energieübertragung. Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften. CVII. Band, VIII. Heft, 1898, S. 1113.
[3] W. Ostwald: Die Energie. Verlag Johann Ambrosius Barth, Leipzig, 1908, S. 59.

The energy conservation law

Subject:

The formulation of the energy conservation law does not seem to be trivial. The quotations (1) and (2) are taken from school books, and quotation (3) is from a university book.

(1) “The total energy of a body can be distributed among different forms of energy. – Without the transfer of energy to or from other bodies the total energy of the body remains constant”... “If several bodies are involved in the exchange and transformation without friction being present, the sum of kinetic, elastic and gravitational energy remains constant.” … “If friction is taken into account, the internal energy of the bodies and of the environment are part of the energy sum.”

(2) “Theorem of the conservation of mechanical energy: In an energetically isolated system the sum of the mechanical energies remains constant, as long as the mechanical phenomena take place without friction. Energy is never lost, nor does new energy come into existence; it transforms from one mechanical form into another…. According to this theorem there exists a state variable for an energetically isolated system, called mechanical energy, which can appear in different forms, whose value is always conserved. Therefore, the energy of such a system is a conserved physical quantity.”

(3) “Now the energy law can be formulated as follows: The amount of heat ΔQ supplied to a system from the outside serves to increase its

internal energy ΔU, e.g. its temperature... or its electrical or chemical energy, and serves to realize the work ΔW, which we will consider negative when it is delivered by the system, so that

$\Delta U = \Delta Q + \Delta W$."

Deficiencies:

A simple fact is described in such a way that it is hardly possible to recognize its simplicity. One might argue that before formulating the energy theorem, much has to be taken in consideration. However, one should eventually pronounce it in all clarity: Energy cannot be produced or destroyed. And there should be no qualms with this sentence. Otherwise the idea unavoidably comes up that conservation itself is a difficult concept.

Origin:

See the article "isolated systems" in this paper.

Disposal:

Formulate energy conservation in the same way as the conservation of electric charge, i.e. without any ifs or buts, for instance as follows: Energy can neither be created nor destroyed.

Internal energy and heat

Subject:

If heat is supplied to a body, then the body will contain more heat. If the body delivers heat, then at the end it has less. A person who is not educated in physics will surely not object to these statements. However, physics teaches us that they are incorrect: One can supply heat to a body, but thereafter it has none, and although it does not possess heat, one can extract heat from it. It looks like magic. The top hat is empty, but out of it comes a rabbit. Physics tells us that supplying or extracting heat does not change the heat content of a system; it changes the internal energy or enthalpy, depending on how the heat is supplied. The fact that energy is not called heat as soon as it arrives in the body is more than just a convention. There simply is no means to tell how much heat is contained in a body. In physics text books, this irritating circumstance is expressed in different ways. Some authors express it courageously [1]. Others risk doubtful justifications by maintaining that the internal energy can be divided in fractions, which they themselves would be unable to quantify [2], [3] (see also [4]). Sometimes heat and internal energy are simply taken to be identical [5].

Deficiencies:

I cannot imagine that even a single pupil will understand why it is incorrect to say that the heat supplied to a body remains inside the body. Most of our university students also would be unable to give an explanation. The statement appears to the student either only as sophistry, or it is memorized together with the numerous topics that one does not understand, and does not necessarily need to understand.

Origin:

For the description of the heat supply to a body one would need a quantitative measure of heat. The “heat” of the physicist as a “process variable” [6] is as poorly suited for this as the internal energy or the enthalpy so beloved by chemists. See also [7], [8].

Disposal:

It is particularly simple. One describes the process with the entropy. Entropy corresponds exactly to a non-physicist‘s idea of heat. If one heats something up, one supplies it with entropy, and after the entropy is supplied, the entropy is in it. It is easy to give a value for how much entropy is within a body, and still easier to quantify how much the entropy changes when warming the body up [9].

List of references

[1] Galileo 9 (Oldenbourg 2000) p. 98: “Warning! Differentiate very carefully between heat, internal energy and temperature: An object does not possess heat, but internal energy!”

[2] Spektrum Physik (Schroedel Velag Hannover 2000) p. 17: Under the heading "the portions of the internal energy" are specified: the kinetic energy of the particles; the energy, which is in the co-operation of the particles; chemical energy and nuclear energy.

[3] Galileo 9 (Oldenbourg 2000) p. 93: “The energy of an object, which is not to be described as mechanical energy (potential or kinetic energy), one calls internal energy E_i. The atomic energy, the chemical and the biological energy all belong to the internal energy. A substantial portion is also the energy which is connected with the temperature of the object.”

[4] G. Job, Energieformen in Altlasten der Physik, Aulis Verlag Deubner Köln, 2002, p. 11.

[5] Metzler-Physik (Metzlersche Verlagsbuchhandlung Stuttgart 1988) p. 60: “In all of these cases the bodies are performing frictional work; thereby a part of this mechanical energy is transformed into an energy form that cannot be transformed back into mechanical energy, but is given away as heat energy or internal energy to the environment inside or outside of the system.”

[6] F. Herrmann: State Variables

[7] G. Job: Equivalence of Heat and Work

[8] G. Job: Entropie in Altlasten der Physik, Aulis Verlag Deubner Köln, 2002, p. 85.

[9] F. Herrmann: Die Messung der Entropie in Altlasten der Physik, Aulis Verlag Deubner Köln, 2002, p. 87.