On the concept of Energy: conservation and transformation versus equivalence

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ABSTRACT

Many studies have shown that the concept of energy is a problem for teaching. It is in general taught that energy can neither be created nor destroyed but only transformed. Based on the original papers of the discoverers of energy, it will be shown in the present paper that these discoverers did not find anything which is indestructible and transformable. In distinguishing between the treatment of phenomena and the theories carried out by the discoverers of energy, it can be concluded that they established equivalences between different domains, such as motion and heat or position and motion. Taking this idea of equivalence, it will be finally shown that some of the problems pointed out by science teaching experts can be overcome.

KEYWORDS

Energy, conservation, transformation, equivalence, history of science

RÉSUMÉ

De nombreuses études ont montré que le concept d'énergie est un problème pour l'enseignement. Il est en général enseigné que l'énergie ne peut être ni créée ni détruite, mais seulement transformée. Sur la base des documents originaux des découvreurs de l'énergie, il sera montré dans le présent document que ces découvreurs n'ont rien trouvé qui est indestructible et transformable. En distinguant entre le traitement des phénomènes et des théories menées par les découvreurs de l'énergie, il peut être conclu que ils ont établi des équivalences entre les différents domaines, tels que le mouvement et la chaleur ou de la position et le mouvement. Prenant cette *idée de l'équivalence, il sera finalement montré que quelques-uns des problèmes signalés par les experts d'enseignement des sciences peuvent être surmontés.*

MOTS-CLÉS

Énergie, conservation, transformation, équivalence, histoire de la science

INTRODUCTION

The most common presentation of the concept of energy in textbooks is: *energy can neither be created nor destroyed but only transformed* (Chalmers, 1963, p. 43; Bueche, 1972, p. 95; Hänsel & Neumann, 1993, p. 222; Young & Freedman, 2004, p. 264). If energy cannot be produced and if there is some energy, it cannot be annihilated, then it must be a real existing thing. If energy can be transformed, it must be a real thing as well: so real that its form can change. The concept of energy as a substance is therefore understandable. Planck (1887/1921), Hertz (1894), Poincaré (1897) and Einstein (Schilpp, 1970) pointed out several difficulties with this concept. Feynman, Leighton & Sands (1966) was more categorical when he said that we have no knowledge of what energy is. This has been corroborated by other physicists (Bergmann & Schaefer, 1998; Dransfeld, Kienle & Kalvius, 2001; Çengel & Boles, 2002; Halliday, Resnick & Walker, 2003). Under these circumstances, it is not surprising that energy has been a difficulty in teaching and learning.

There has been much research on students' misconceptions (Watts, 1983; Duit, 1986; Nicholls & Ogborn, 1993; Trumper, 1997; Cotignola et al., 2002). In order to avoid them, teaching methods have been developed (Solomon, 1985; Prideaux, 1995; Trumper, 1990, 1991, 1997; Papadouris & Constantinou, 2011). Teachers face, however, a special difficulty when they introduce energy (see Galili & Lehavi, 2006), since the problem is above all, *how to teach a concept that is not well defined*. This has also been a problem for textbook writers (Lehrman, 1973; Hicks, 1983; Duit, 1987; Bauman, 1992; Chrisholm, 1992; Cotignola et al., 2002; Doménech et al., 2007).

In nineteenth century textbooks on thermodynamics, we do not find such difficulties. Indeed, authors such as Verdet (1868-72), Poincaré (1892), Preston (1919), Müller and Pouillet (1926) used 'principle of equivalence' instead of 'principle of conservation of energy'. Significant in this context is that these physicists knew the main texts of the discoverers, which is no longer the case.

In the History of Science, we learn that energy was discovered in the 1840s. Mayer, Joule, Colding and Helmholtz are generally considered the discoverers. If we peruse their texts, we can verify that they *did not find anything which is indestructible and transformable*. In distinguishing between the treatment of phenomena and the theories carried out by them, it can rather be concluded that *they established equivalences between different domains*, such as motion and heat, motion and electricity or position and motion. If we understand the principle of conservation of energy as a principle of equivalence, some of those difficulties with the concept of energy can be overcome, as we shall see.

THE DISCOVERY OF ENERGY BY MAYER, JOULE, COLDING AND HELMHOLTZ

Mayer

Concerning phenomena involving heat, the young physician Robert Mayer raises the question of whether a causal relationship between heat and motion can be established. It can be established if there are phenomena in which heat results from motion or heat produces motion. He set up an experiment to prove that motion causes heat: he agitated water in a recipient vehemently and the temperature of the water rose 12 or 13 degrees.[1] The steam-engine exemplifies the inverse relationship: heat produces motion (1842, p. 239). Once admitted that there exists a causal relationship between heat and motion, it follows from Mayer's fundamental proposition "*cause equals effect*" that an equation of the form

cause (motion) = *effect* (heat) or *cause* (heat) = *effect* (motion)

can be written. This leads to the mechanical equivalent of heat, which was determined by him for the first time in 1842.

Mayer bases his calculation of the mechanical equivalent of heat on experimental results known at his time. The specific heat of atmospheric air at *constant pressure* and *constant volume* are considered by him as follows. The latter has as a consequence the increase of the temperature by one degree. The specific heat at constant pressure has two consequences: the increase of the temperature by one degree and the elevation of the column of air. This column of air has a certain weight and is elevated to a certain height. Mayer compares the causes involved and the effects obtained. He takes the difference between the two specific heats equal to the "force" performed in the variation of volume against atmospheric pressure:

$$C_p - C_v = weight \cdot height$$

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[1] "Wasser erfährt, wie der Verfasser fand, durch starkes Schütteln eine Temperaturerhöhung. Das erwärmte Wasser (von 12° und 13°C) [..]" (1842, p. 238). No further details about this experiment are given by Mayer. In reconstructing this experiment, we took 10 ml of water in an isolated glass tube, we agitated it vehemently and verified that the temperature of the water increased by two or three degrees Celsius. Obviously, this value depends on the intensity of the agitation of the water. Due to such an experiment Mayer concludes, motion produces heat.

Since, according to the experimental values known at that time

- C_p-C_v = 0.000103 units of heat,
- the weight of the column of air is equal to 1033 *g*
- and the height is 1/274 *cm*,[2]

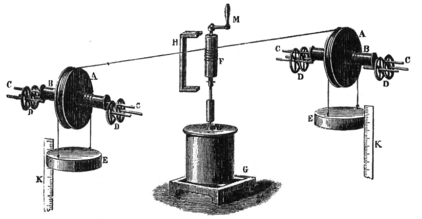
the equation leads to the conclusion: one unit of heat is equivalent to 1 gram raised to 366 metres.[3]

Mayer bases his approach to phenomena on the proposition '*cause = effect*' and developed a theory according to this. 'Cause' and 'effect' are called forces. Thus, heat is considered by him as a force, as well as the effect, the mechanical magnitude. The sides of such equations are very different from a phenomenological point of view: heat and motion. This discrepancy does not matter, since, according to his theory, forces are transformable into each other. He adds, however, that 'transformation of force' does not have ontological meaning (1845, p. 10).

Joule

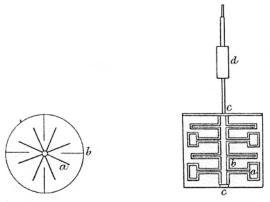
Joule presented several processes to determine the mechanical equivalent of heat. The most important of them consists of a brass paddle-wheel working horizontally in a can of peculiar construction and filled with water.

FIGURE 1



Joule's paddle-wheel experiment, picture taken from Verdet 1868 (p. 42), see also Joule 1884, Plate II

FIGURE 2



Joule's schema: detail of the inside of the can, from Joule's paper, (Joule 1884, Plate II)

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[2] It was known that if one cubic centimetre of atmospheric air at 0A C is heated until 1A C, it raises a column of air of 1/274 cm (see Mayer, 1845, p. 14-5).

[3] In 1845, Mayer did not present 366 m but rather 367 m as the result of that equation. In 1842, he had presented 365 m. If we calculate this height with the values presented in 1845, the result is approximately 366 m.

At the beginning of the experiment, the weights are at a certain height and the water has a certain temperature. At the end, the weights are completely down and the temperature of the water is higher. Due to the measurement of these magnitudes, the following relationship is established:

$$\textit{weight} \cdot \textit{height} = \beta \textit{ units of heat.}$$

If α units of mechanical power correspond to β units of heat, to one unit of heat corresponds x, the value of the mechanical equivalent of heat.[4]

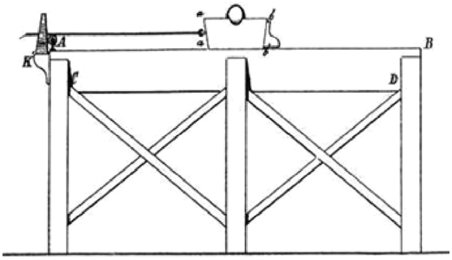
Joule considers the experiment as a phenomenon of conversion from mechanical power into heat.[5] However, if the phenomenon does not consist of a process of conversion, the established relationship between heat and mechanical power is not disturbed. Indeed, the conversion is an interpretation of the phenomenon.

Colding

In 1843, Colding presented a communication "Theses Concerning Forces" to the Science Society of Copenhagen. This paper was published in 1856, when 'energy' was already a significant issue in the science of that time. His thesis is supported by friction experiments with solids, which will be considered next.

Figure 3 gives us an image of Colding's apparatus from the side.

FIGURE 3



From Colding's paper 1856, plate

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[4] Joule ended the paper with the two following propositions:
"1st. *That the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of force expended.* And,
2nd. *That the quantity of heat capable of increasing the temperature of a pound of water (weighed in vacuo, and taken at between 55° and 60°) by 1A Fahr. requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lb. through the space of one foot*" (1884, p. 328).

[5] This idea was expressed in the third proposition of his conclusion (the first two propositions are presented in the previous footnote). This third proposition was, however, suppressed "in accordance with the wish of the Committee to whom the paper was referred" (1884, p. 328). Joule improved his apparatus and carried out a new experiment in 1878. A further development of the paddle-wheel experiment was due to Rowland (see Coelho, 2010).

The apparatus consists of two parallel bars made of tin of about two meters long, on which a small sledge slides (fig. 4).

FIGURE 4

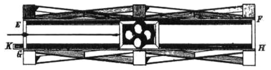

Image of the apparatus from the top, Colding's paper 1856, plate

The weight of the sledge can vary by means of the quantity of balls it carries. The distance covered by the sliding is the same in all experiments; the course is run twice with approximately the same speed. The dilation of the materials in friction gives an indication of the heat produced. This is obtained by means of an instrument that reacts to the difference in length and accounts for the variation in heat.

Colding did 10 series of experiments, from which he only considered 7 as reliable. The first three series were carried out with the same materials but with different weights. He obtained the following results, which are reproduced here in the original units. The average values of force and heat in these series were:

- Moving force: 30.3 19.7 11
- Heat developed: 2.00 1.32 0.72

His reasoning was the following. When the force required for pushing the sledge with the same speed increased by 1.79 (from 11 to 19.7), the heat produced increased by 1.83 (from 0.72 to 1.32). When the force increased by 2.75 (from 11 to 30.3), the heat increased by 2.77 (from 0.72 to 2). Schematically:

- Moving force: 1 1.79 2.75
- Heat developed: 1 1.83 2.77

Taking the average value of the seven series of reliable experiments, the following is obtained

- Moving force: 1.71
- Heat developed: 1.717

Based on his data, Colding concluded that there is proportionality between force used and heat produced.

In consequence of these experiments, as well as others regarding the development of heat through force, Colding defended the thesis that forces which are perceived as vanished appear in a different form. He proposes as a law of nature that when a force has apparently disappeared, it goes through a transformation, becoming effective in a different way. This is conceptually supported by the idea that *forces of nature are imperishable*.

Helmholtz

In 1847, the young physician Hermann Helmholtz presented a communication "On the Conservation of Force" to the Physical Society in Berlin, which was published at his own expense in the same year. The title reflects his thesis: there are two fundamental forces in nature, 'living force' and 'force of tension', whose addition is constant. '*Living force*' was known at that time as the product of mv^2. Helmholtz took $1/2mv^2$ as living force. A body at a certain height is an example of '*force of tension*', which in this case is given by the product of the body's weight and height. Since force of tension is *weight · height*, one expects that an equation of the form

$$\textit{force of tension} = \textit{living force}$$

is written by Helmholtz. However, in the conceptual framework of the science of that time, a justification was required to equate both 'force of tension' and 'living force'. This justification was drawn from Carnot and Clapeyron's statement: it is impossible to have a durable force out of nothing. This proposition is transformed into a principle by Helmholtz: it is assumed that a moving force and its resulting motion are equivalent. Thus, his equation

$$\frac{1}{2}mv^2 = mgh$$

is justified.

In its general form, the principle of conservation of force is stated as follows: the sum of the living forces and of the forces of tension is constant. This principle is then applied to the other domains of physics: heat, electricity and magnetism.

In the case of phenomena involving heat and motion, Helmholtz made recourse to Joule's experiments of 1843 and 1845 to defend a quantitative relationship between mechanical force lost and heat appeared.[6] He further argues that heat cannot be matter, in showing that the concept of heat as a substance is not adequate to explain thermal phenomena in general. Heat obtained by friction is an example of this. Finally, Helmholtz defends that heat is a kind of motion. This kind of motion is not further characterised. It is enough, according to him, that the phenomena of heat can be thought of in terms of motion.[7]

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[6] One of the experiments referred to by Helmholtz (1882, p. 253) is the paddle-wheel experiment, which was firstly presented by Joule in 1845 (Coelho, 2009, p. 970).

[7] Helmholtz's approach to electrical and magnetic phenomena will not be considered in the present paper (see Bevilacqua 1983, 1993).

AN OVERVIEW OF THE DEVELOPMENT OF THE TERM 'ENERGY'

In 1851, William Thomson introduces the concept of "mechanical *energy* of a body" to refer to the 'mechanical *activity* of a body'. As heat had been understood as motion, it became meaningful to speak of the mechanical activity of a body due to its heat. The idea that the quantity of this mechanical activity does not change in the Universe is defended by Thomson (1852) by means of a non-physical argument: only the "Creative Power" can create or annihilate mechanical energy. Presupposed that there is no intervention of the Creative Power in natural phenomena, the quantity of the mechanical activity is conserved. The "stores" of this mechanical activity available for men are then distinguished into two classes: static and dynamic.

In 1853, Rankine defends the conservation and transformation of energy and systematizes it into two sets: "actual or sensible" and "potential or latent". 'Actual energy' was replaced by 'kinetic energy' by Thomson and Tait in 1862. The meaning of energy changed, however, towards the end of the century.

Lodge (1879) criticised the definition of energy as the capacity of a body of doing work, which stems from the 1850s. He argues that a body has some energy and this does not necessarily mean that it can do work. Hence, he proposed understanding energy as the work already done upon a body. The conservation of energy is then expressed in the form: energy is neither produced nor destroyed but only *transferred*.

In 1884, Poynting defends that the energy existing in the space flows into the conductor through the lines that are perpendicular to the lines of the electrical and magnetic field. Based on this paper, Lodge (1885) defends the reality of energy: energy exists in space, in bodies as well as in the ether and it can be transferred between them. This concept of energy as a substance raised some objections.

Planck (1887/1921) pointed out that, even though the energy of an isolated system remains constant, it is impossible to localise it in the system. Hence, he considered the concept of energy as a substance as a concept which, one day, should be overcome. Hertz (1894) criticised the concept of energy as a substance for several reasons. He pointed out that the characteristics of potential energy contradict the concept of substance.[8]

William Thomson, who had introduced the concept in 1851, said, in 1906, that he suspected that the people who claimed that energy is a real, existing thing do not know what it really is (Smith, 1998, p. 289).

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[8] For details, see Smith (1998), Guedj (2000, 2006) and Coelho (2009), on which the present overview is based.

CONCLUSION

All the discoverers, Mayer, Joule, Colding and Helmholtz, put mechanical units and thermal units into an equation and justified this equivalence theoretically.

Mayer wrote

$$Cp\text{-}Cv=Wh$$

and calculated the mechanical value for the thermal unit. He bases this equation on the statement "cause equals effect". In his theory, the 'cause' and the 'effect' in phenomena are called forces and these are indestructible and transformable. As the quantity of force, which is the cause, is equal to the quantity of force, which is effect, his equation is justified. The sides of this equation are very different from a phenomenological point of view: heat and motion. This does not matter, since forces are transformable. He pointed out, however, that 'transformation' of heat into mechanical power does not explain what is going on in the physical processes. Therefore, Mayer did not find an entity which is transformable and cannot be destroyed. The transformability and indestructibility of force serve instead to justify the relationship that he established between domains which were separated until then, such as motion and heat.

Based on the paddle-wheel experiment, Joule wrote an equation of the type

$$Wh = C$$

and determined the mechanical equivalent of heat. For him, heat is a kind of motion. Therefore, his equation consists of magnitudes which concern motions: the motion of the weights and another kind of motion, which is heat. The thesis, 'heat is motion' renders, therefore, homogeneous what, by observation, is diverse: heat and motion. Once this homogeneity is accepted, the equation is considered as an expression of conversion. It serves to determine the factor of conversion: how many units of mechanical power correspond to a thermal unit.

Colding formalised his law of nature - when a force has apparently disappeared, it goes through a transformation, becoming effective in a different way – as follows. If a given moving force q has a totally lost effect, the new action, in which the force is manifested, is to take equal to q. This holds for the relationship between moving force and heat (1972, p. 1-2). He did not write such an equation to determine the mechanical equivalent of heat. Based on his experimental data, he concluded that

$$\Delta \text{ moving force} \approx \Delta \text{ heat.}$$

He defended the homogeneity of heat and motion by means of the concept of 'force of nature': both motion and heat are forces of nature. The phenomenological diversity between them is overcome by the idea of 'transformation': motion is transformed into heat.

Helmholtz did not write an equation as Mayer and Joule did but accepted the equivalence between motion and heat. He knew Joule's experimental work, accepted the concept of a mechanical equivalent of heat and used it. He defended two ultimate forces, which influence each other reciprocally: if the quantity of one of them increases, the quantity of the other decreases. Hence, the quantity of force is conserved. *Conditio sine qua non* of this conservation is that heat is a kind of motion. This is necessary because heat is thought of as living force and force of tension. The heat connected *a priori* with living forces would correspond to the so called 'free heat'. The heat connected with forces of tension of the atoms would be the so called 'latent heat'.

Even though the most common definition of energy - energy cannot be created no destroyed but only transformed - reminds us of Mayer's theory, the notion of energy as a material thing resulted from the semantic development of the concept. Indeed, Mayer pointed out in 1851 that the relationship between heat and motion is quantitative not qualitative. If this point of view is adopted, in approaching the paddle-wheel experiment, for instance, we are previously aware that we establish equivalence between certain magnitudes: weight and height on one side and units of heat on the other. This justifies an equation of the form $Wh=C$.

Since this equation is explained in this way, we can dispense with that real something which is 'indestructible' and 'transformable'. Indeed, the 'indestructibility' served to justify that those magnitudes can be put into an equation. 'Transformability', in turn, served to lead us to accept the equation despite the phenomenological difference between heat and motion. Thus, the difficulties in teaching and learning energy due to the material concept of energy, which has been criticised by physicists and science teaching experts (see sect. 1), can be overcome.

The arguments for the thesis that 'equivalence' has advantages over the material concept of energy, are now based on the history of science:

- The discoverers did not find any material thing with the properties of energy;
- The hypostatising of energy was a consequence of the semantic development of the concept;
- The 'principle of equivalence' was used in textbooks on the theory of heat published about a century ago, where there are no such conceptual difficulties as in the modern ones.

How to use the concept of 'principle of equivalence' regarding energy phenomena and problem solving is a work in progress.

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