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On the concept of energy: History and philosophy for science teaching

Ricardo Lopes Coelho*

Faculty of Science, University of Lisbon, Campo Grande C4, Lisbon, P-1749-016, Portugal

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Abstract

Some physicists have pointed out that we do not know what energy is. If there is no clear idea of energy, teaching the concept must be a problem. There has been much criticism concerning explanations of energy in textbooks and research literature about students´ misconceptions is ample. In the History of Science, one learns that Mayer and Joule discovered energy. A study of their experiments, calculations and interpretations of phenomena shows that they did not find anything which is indestructible and transformable but rather a methodology of dealing with phenomena. How to understand energy thanks to their works is the central subject of the present paper.

Keywords: Energy; mayer; joule; conservation; transformation; conversion; equivalence.

1. Introduction

"It is important to realize that in physics today we have no knowledge of what energy *is*", said Richard Feynman in his *Lectures* in the sixties. "Nobody knows what energy really is" can be read in Bergmann and Schaefer's *Experimental Physics*, 1998. If we do not know what energy is, it is difficult to explain it in the best way. Many studies have shown that the concept of energy is a problem for teaching (Watts 1983, Solomon 1985, Duit 1986, Trumper 1990, Barbosa & Borges, 2006, De Berg 2008, and many others). Concepts of energy presented in high-school and university textbooks have been criticised (Lehrman 1973, Sexl 1981, Duit 1981, Hicks 1983, Duit 1987, Bauman 1992, Chrisholm 1992, Cottignola, Bordogna, Punte & Cappannini 2002, Doménech *et al.*, 2007). Empirical educational research shows alternative ideas such as 'Energy is fuel' or 'Energy is stored within objects' (Nicholls &

*Ricardo Lopes Coelho.
E-mail address; Rlc@fc.ul.pt

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Ogborn 1993, p. 73, Prideaux 1995, p. 278). There is much confusion with energy, says Beynon, "because it is not treated as an abstract physical quantity but something *real*, just like a piece of cheese" (1990, p. 315). According to Feynman, energy is not a concrete thing and energy conservation is a mathematical principle, which is also corroborated by Arons 1999. A study on the history of the concept of energy has however shown that the discoverers did not find anything which is indestructible and transformable but rather a methodology of dealing with phenomena. Let us consider Mayer's and Joule's work: their calculations and experiments, which usually appear in introductory textbooks on physics, and their own interpretations of phenomena. What follows is based on Coelho 2007.

2. Robert Mayer

Mayer considered the falling of bodies in the following way. The weight and height of a body form together the cause of falling. The value for the cause is calculated by the product of the mass and the height of the body. The height is equal to the square of the velocity, thanks to Leibniz's principle (1686). Taking the product of mass and square of the velocity as the effect of that cause and admitting that cause equals effect, Mayer writes $mh=mv^2$. Let us move on to phenomena which involve motion and heat.

Mayer 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. Motion can also be produced by heat. The steam-engine is the example given for this. Mayer admits then that there exists a causal relationship between heat and motion. If there is a causal relationship, an equation of the form "cause=effect" connecting both heat and motion can be written. To write such an equation, he used the specific heat of atmospheric air at constant pressure and constant volume. As the specific heat at constant pressure, C_p, is greater than the specific heat at constant volume, C_v, but in the first case there is some motion and in the second there is none, Mayer considers the difference, C_p-C_v, equal to the "force" performed in the variation of volume against atmospheric pressure. This "force" is calculated by the product of the weight of the column of air, W, and that variation of volume, the height h. Writing C_p-C_v=Wh and introducing into this equation the experimental values known at that time, Mayer reaches the result: the fall of a weight from the height of about 365m corresponds to the heating of an equal mass of water from 0° C to 1° C.

The connection between electricity and motion is exemplified by an electrophorus. An electrophorus can produce an electric effect at its original position. Raising the upper part, a second effect can be obtained. Coming back down to the original position, another electric effect can be obtained and raising the upper part once more, yet another effect can be obtained. Mayer concludes that for each time a mechanical effect is made and an electrical effect is earned, the mechanical effect is transformed into electricity. Let us move on to Mayer's theory.

Forces are causes, is its basic statement. This is used to apply to forces the classical saying '*causa aequat effectum*', ***c=e***. If the effect ***e*** becomes a cause of an effect ***f***, then ***e=f***. Mayer writes ***c=e=f…=c***. The quantity of force holds therefore constant. Mayer expresses this in the form: force is indestructible. As ***c=e***, Mayer says that ***c*** is transformed into ***e*** because at the end, no part of ***c*** can exist, and at the beginning no part of ***e*** exists. He pointed out, however, that, for instance, 'transformation of heat into mechanical effect' expresses a fact and does not explain the physical process. We also say, he exemplifies, that ice is *transformed* into water and this is not dependent on *how and why* it happens. He adds that these kinds of questions are useless and typical of poets and philosophers of nature (Mayer 1978, p. 52). 'Transformation' does not explain therefore what is going on in a physical process. The concept was instead used to connect observable data.

3. James Joule

Joule´s first result concerning energy was achieved thanks to experiments carried out with a "magneto-electric machine". This machine consists of three elements which are theoretically relevant: 1- a magnet or an electro-magnet; 2- a rotated electro-magnet; and 3- a crank, which brings element 2 into motion.

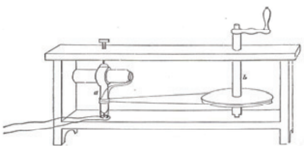

Fig. 1. From Joule's paper: elements 2 and 3.

With the magneto-electric machine, Joule researched the calorific effects of the electric current, which is produced thanks to motion. In order to achieve a numerical relation between the "mechanical power" used in the motion of the machine and the heat derived from the electric current, he replaced the crank with the system represented in fig. 2.

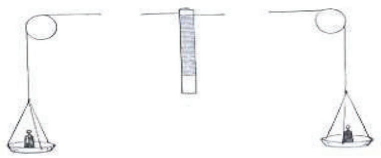

Fig. 2 From Joule's paper.

Thanks to this experimental configuration, he determined the "mechanical power" used. This is the product of the weights on the scales and the distance they cover. Taking this value equal to the heat produced by the electric current, Joule determined the "mechanical equivalent of heat". Joule´s results can be summed up by the following equation:

$$(Weight_{\,mag.\text{-}elec.} - Weight_{\,mec.}) \times Height = Heat_{\,mag.\text{-}elec.} - Heat_{volt\text{-}elec.},$$

where '$Weight_{\,mag.\text{-}elec.}$' and '$Weight_{\,mec.}$' symbolize the weight used in moving the machine as a magneto-electric one and as a mechanical one alone, 'Height' the distance covered by the scales and '$Heat_{\,mag.\text{-}elec.}$', '$Heat_{volt\text{-}elec.}$' the heat evolved by the induced current and by a battery. If

$$(Weight_{\,mag.\text{-}elec.} - Weight_{\,mec.}) \times Height$$

is positive, Joule says that the mechanical power has been converted into heat; if it is negative, he says that heat has been converted into mechanical power. Thanks to the equation, which states that

$$\alpha \text{ units of mechanical power} = \beta \text{ degrees of heat},$$

he calculates how many mechanical units correspond to one degree of heat, i.e., the mechanical equivalent of heat.

In 1845, Joule presented for the first time the paddle-wheel experiment. The apparatus consists of a brass paddle-wheel working horizontally in a can of peculiar construction and filled with water. This paddle-wheel moves by means of weights thrown over two pulleys working in opposite directions. In the 1850 article, a schema of the paddle-wheel and of the construction of the can for the fluid is presented.

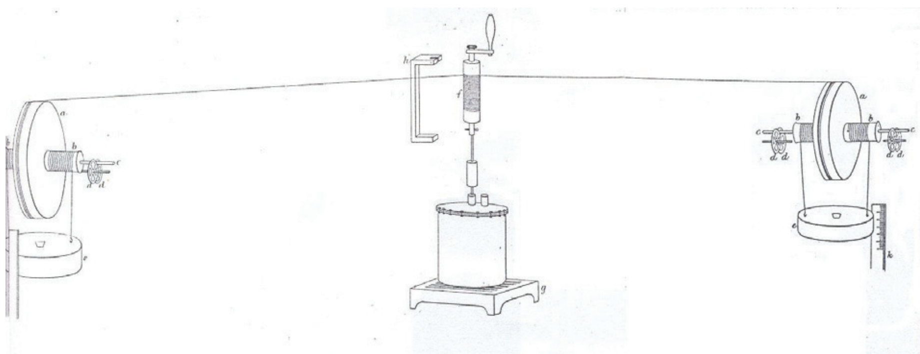

Fig. 3. Joule's schema of the mechanism.

From an experimental point of view, Joule measured the weights on the scales, the distances these covered in moving and calculated the heat thanks to the increase of the temperature of the water in the can. Thanks to these data, he established α *units of mechanical power = β units of heat*. This enables him to calculate the mechanical equivalent of heat.

Let us move on to his interpretation of the experiments. Joule was faced with the dichotomy: heat is either a substance or a kind of motion. From the experiments which were performed with the magneto-electric machine, he inferred that heat must be a kind of motion, since it could be created or destroyed through motion. Since heat is motion, the experiments were interpreted as conversion from mechanical motion into another kind of motion or vice versa. The conversion factor is called mechanical equivalent of heat. The interpretation of the paddle-wheel experiments is analogous. He defended that friction consisted in the conversion of mechanical power into heat. This statement was not published in accordance with the wish of the Committee to whom the paper was referred (Joule 1884, p. 328).

4. Conclusion

Energy is usually presented in the following way: 'energy can neither be created nor destroyed but only transformed'. If energy cannot be destroyed, it must be a real existing thing. If its form changes, it must be something real as well. Thus, that statement can easily lead to the concept of energy as something material. The German physician Robert Mayer did not find, however, anything like a substance but rather a methodology for dealing with phenomena. Using observable or measurable elements, he established *equivalences* between different domains, such as those which concern heat, motion, position or electricity. Let us suppose that we use Mayer´s methodology for dealing with phenomena. In this case, we know in advance that an equivalence is established by us between certain quantities. Hence, we do not need the 'indestructibility' of an entity to express that the quantity does not change. As we also know that we establish equivalences between mechanical, thermal, electrical quantities, we do not need to suppose the 'transformability' of the same entity. Thus, we understand energy conservation and transformation as a consequence of our dealing with the phenomena. Some difficulties with the concept of energy as something material can be overcome.

Concerning Joule, who was neither a physicist, it could be said that he found *experimental methods for determining the mechanical equivalent of heat.* He measured the "mechanical power", the heat evolved, established a numerical relation and determined the mechanical equivalent of heat. The justification of this, as conversion from the observable motion of the weights into the unobservable motion of which heat would consist, is interpretation. In textbooks on the theory of heat published towards the end of the nineteenth century or the beginning of the following century, the concept "principle of equivalence" is used and not "principle of conservation of energy" (Verdet 1868, Poincaré 1892, Müller & Pouillet 1926).

This way of teaching science, based on exhibition of original experiments and presentations of their interpretations by the discoverers, is being tested within the framework of the European Project "History and Philosophy in Science Teaching". Problem solving strategies based on the concept outlined above are being developed.

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