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Abstract Some physicists have pointed out that we do not know what energy is. Many studies have shown that the concept of energy is a problem for teaching. A study of the history of the concept shows that the discoverers of energy did not find anything which is indestructible and transformable but rather that the concept of energy underwent a change of meaning and energy was considered a substance towards the end of the nineteenth century. In distinguishing between the treatment of phenomena and the theories carried out by Mayer and Joule, it can be concluded that they established equivalences between different domains, such as motion and heat, motion and electricity or position and motion. This complies with the interpretation presented in textbooks published about a century ago and enables us to overcome some difficulties with the concept of energy.

1 Introduction

The Nobel Laureate, Richard Feynman, said in his *Lectures* in the sixties, "It is important to realize that in physics today we have no knowledge of what energy *is*". In Bergmann and Schaefer's *Experimental Physics*, 1998, one reads, "nobody knows what energy really is". Dransfeld et al. (2001), Çengel and Boles (2002), Halliday et al. (2003), among others, pointed out the difficulty in defining energy. If there is no clear idea of what energy is, teaching the concept of energy must be a problem.

Research literature about students' misunderstandings is ample: Watts (1983), Duit (1986), Nicholls and Ogborn (1993), Cotignola et al. (2002), De Berg (2006), Barbosa and Borges (2006), and many others. Teaching methods have been developed in order to avoid misconceptions: Solomon (1985), Prideaux (1995), Trumper (1990, 1991, 1997). For decades, there has been much criticism concerning explanations of energy in high-school and university textbooks: Lehrman (1973), Sexl (1981), Duit (1981), Hicks (1983), Duit (1987), Bauman (1992), Chrisholm (1992), Cotignola et al. (2002), Doménech et al.

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(2007). Some of those authors but also Valente (1999), Greenslade (2002) Hecht (2003) or Roche (2003) made historical approaches to the concept of energy. Recourse to the past of science will also be made in the present article, though in rather a different way.

In the history of science, we learn that energy was discovered in the 1840s: Mayer, Joule, Colding and Helmholtz are generally considered the discoverers.[1] None of them were physicists at that time and, in some important aspects, their theories do not comply with each other. Textbooks on physics usually use calculations or experiments from Mayer and Joule to introduce energy.[2] Physicists and historians of science agree, therefore, on this point: Mayer and Joule discovered energy. To try to understand *what they discovered*, how Mayer and Joule dealt with the phenomena and how they interpreted them will be considered in this paper.

The discoverers did not speak of conservation or transformation of energy. This term was introduced later on by William Thomson (1851). Towards the end of the nineteenth century, the concept underwent a change in meaning: energy was understood as a substance by some physicists. An outline of this development will be given in order to clarify some difficulties with the concept nowadays. Finally, some educational implications will be considered.

2 Robert Mayer

In 1842, Mayer published an article in Liebig's *Annals of Chemistry and Pharmacy* with the title "Observations on the Forces of Inorganic Nature". First of all, Mayer speaks on forces, what forces are and how they are related to each other.[3] Afterwards, he deals with phenomena. The answer to the question what forces are, tells us only that forces are causes. This statement is not proved. It serves, however, to apply to forces the classical saying '*causa aequat effectum*'.[4] If a cause $\boldsymbol{c}$ originates an effect $\boldsymbol{e}$, and this becomes a cause of an effect $\boldsymbol{f}$, then $\boldsymbol{e} = \boldsymbol{f}$ or, as he writes, $\boldsymbol{c} = \boldsymbol{e} = \boldsymbol{f} \ldots = \boldsymbol{c}$. On account of these two equations, Mayer justifies two properties of force.

As $\boldsymbol{c} = \boldsymbol{e} = \boldsymbol{f} \ldots = \boldsymbol{c}$, the quantity holds constant. Mayer says force is indestructible.[5] As $\boldsymbol{c} = \boldsymbol{e}$, Mayer says that $\boldsymbol{c}$ is transformed into $\boldsymbol{e}$ because when there is $\boldsymbol{e}$ at the end, no part of $\boldsymbol{c}$ can exist, and when there is $\boldsymbol{c}$ no part of $\boldsymbol{e}$ exists.[6] In his own synopsis, forces are quantitatively indestructible, qualitatively transformable and imponderable.[7]

[1] See, for instance, Breger (1982), Schirra (1989), Smith (1998), Guedj (2000) or Caneva (1993), Cardwell (1989), Dahl (1963) and Bevilacqua (1983).

[2] See, for instance, Preston (1919, p. 288), Müller and Pouillet (1926, p. 110), Hund (1956, p. 50), Allen and Maxwell (1962, p. 284), Tipler (2000, p. 554), Cassiday et al. (2002, p. 255), Young and Freedman (2004, p. 653).

[3] "Der Zweck folgender Zeile ist, die Beantwortung der Frage zu versuchen, was wir unter 'Kräften' zu verstehen haben, und wie sich solche untereinander verhalten" (p. 233).

[4] "Kräfte sind Ursachen, mithin findet auf dieselbe volle Anwendung der Grundsatz: *causa aequat effectum*" (p. 233).

[5] "In einer Kette von Ursachen und Wirkungen kann, wie aus der Natur einer Gleichung erhellt, nie ein Glied oder ein Theil eines Gliedes zu Null werden. Diese erste Eigenschaft aller Ursachen nennen wir ihre *Unzerstörlichkeit*" (p. 233).

[6] "Hat die gegebene Ursache c eine ihr gleiche Wirkung e hervorgebracht, so hat eben damit c zu seyn aufgehört; c ist zu e geworden" (p. 234).

[7] "Kräfte sind also: *unzerstörliche*, *wandelbare*, *imponderable* Objecte" (p. 234). "Ursachen sind (quantitativ) *unzerstörlich* und (qualitativ) *wandelbare* Objecte" (p. 234).

The third property of forces, imponderability, is understandable in the context of the physics of his time: light, heat, electricity and magnetism were called imponderables.[8] The two other properties, indestructibility and transformability, are important for us for they are the root of many formulations of the principle of energy conservation or definitions of the concept in modern textbooks: "energy can neither be created nor destroyed but only transformed". Let us consider Mayer's dealing with the phenomena.

The first kind of phenomena Mayer deals with is the falling of bodies. At that time, weight was considered the cause of falling. Mayer argues, however, weight is not enough for falling, for a body cannot fall without height.[9] Hence, he defends that the weight and height of a body form together the cause of falling. To calculate a value for the cause, Mayer proposes the product of the mass and the height of the body.[10] On account of the relationship between height and velocity of falling, which was used in Leibniz's conservation principle (1686), the height is equal to the square of the velocity.[11] Mayer takes the product of mass and square of the velocity as the effect of the cause referred to. Admitting that cause equals effect, he writes mh for the cause equals mv^2 for the effect.

The next kind of phenomena Mayer deals with are those where motion and heat are involved. The first question he raises is if 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.[12] He speaks of other observations, in which motion has been made and heat has appeared. The steam-engine gives an example of the inverse relationship: heat produces motion.[13] He argues that he prefers to admit that heat produces motion or motion heat, instead of admitting that there is a cause without effect or an effect without cause.[14] Once admitted that there exists a causal relationship between heat and motion, Mayer tries to measure cause and effect to write an equation of the form "cause = effect".

To write an equation relating heat to motion, Mayer made recourse to the specific heat of atmospheric air at constant pressure and constant volume. As the first quantity of heat referred to is greater than the second one, but in the first case there is some motion and in the second there is none, Mayer considers the difference of the quantities of these heats equal to the force performed in the variation of volume against atmospheric pressure. With

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[8] Textbooks of that time are often divided into two parts, where the first one deals with matter which has weight and corresponds to mechanics; and the second one deals with optics, electricity, magnetism and heat and has 'imponderables' in the title, like 'on the fundamental imponderable substances of bodies' (Suckow 1813) or 'on imponderable powers' (Muncke 1829).

[9] "Um daß ein Körper fallen könne, dazu ist seine Erhebung nicht minder notwendig, als seine Schwere, man darf daher auch letzterer allein den Fall der Körper nicht zuschreiben" (p. 236).

[10] "Die Größe der Fallkraft v steht [...]—mit der Größe der Masse m und mit der ihrer Erhebung d, in geradem Verhältnisse; $v = md$" (p. 236).

[11] "Geht die Erhebung $d = 1$ der Masse m in Bewegung dieser Masse von der Endgeschwindigkeit $c = 1$ über, so wird auch $v = mc$; aus den bekannten zwischen d und c stattfindenden Relationen ergiebt sich aber für andere Werthe von d oder c, mc^2 als das Maß der Kraft v" (p. 236).

[12] "Wasser erfährt, wie der Verfasser fand, durch starkes Schütteln eine Temperaturerhöhung. Das erwärmte Wasser (von 12° und 13°C.) [..]" (p. 238).

[13] "umgekehrt dienen wieder die Dampfmaschinen zur Zerlegung der Wärme in Bewegung oder Lasterhebung" (p. 239).

[14] "Ist es nun ausgemacht, daß für die verschwindende Bewegung in vielen Fällen (*exceptio confirmat regulam*) keine andere Wirkung gefunden werden kann, als die Wärme, für die enstandene Wärme keine andere Ursache als die Bewegung, so ziehen wir die Annahme, Wärme entsteht aus Bewegung, der Annahme einer Ursache ohne Wirkung und einer Wirkung ohne Ursache vor" (p. 238).

the numerical values known at that time, Mayer reaches the result: the fall of a weight from the height of about 365 m corresponds to the heating of an equal mass of water from 0 to 1°C. These calculations were explicitly presented in a book that was published at Mayer's own cost in 1845.

To increase the temperature of a given quantity of gas without changing its volume, a quantity x of heat is necessary, says Mayer. To increase the temperature of the same value but with a variation in volume, a greater quantity of heat $x + y$ is necessary.[15] As the difference between them is equal to y, y corresponds to the mechanical effect produced. Let us turn to numerical data, which will serve to make the steps covered explicit.

One cubic centimetre of atmospheric air at 0°C and a barometric pressure of 76 cm weighs 0.0013 g. The specific heat of air is 0.267 (from the work of Delaroche and Bérard). The quantity of heat, which a cubic centimetre of air takes up, in order to go from 0 to 1°C at constant pressure equals $0.0013 \times 0.267 = 0.000347$. Using the ratio between the two specific heats, $C_p/C_v = 1.421$ (from Dulong's work), Mayer calculates the difference between the specific heats at constant pressure and constant volume: $C_p - C_v = 0.000103$ units of heat. This value corresponds to the mechanical action.

If one cubic centimetre of atmospheric air at 0°C is heated until 1°C, it raises a column of air of 1/274 cm. The weight of this column equals the weight of a column of mercury of 1 square centimetre cross-section and 76 cm high, i.e., 1033 g. The mechanical action is therefore equal to $1033 \times 1/274$. As a weight of 1033 grams is lifted 1/274 cm by the expenditure of 0.000103 units of heat, one unit of heat is equivalent to 1 gram raised to 366 m.[16]

The connection between electricity and motion is exemplified by the utensil outlined in the following picture, called an electrophorus. It constitutes a base, a conductor plate and an isolating handle (Fig. 1).

If there has been friction on the base, an electrophorus produces an electric effect (if someone's hand touches it, it gives him a shock). Raising the upper part, a second effect can be obtained. Leaving the upper part to descend to the original position, an electric effect can be obtained again and raising the upper part, a second effect can be obtained once more. Mayer concludes that for each time a mechanical effect is made and an electrical effect is earned, the mechanical effect is transformed into electricity.

The argument is as follows: the electricity from the lower part of the electrophorus is kept constant; on the other hand, a mechanical effect is produced. Then, either it is

[15] "Angenommen, ein Kubikzoll Luft von 0° und 27 Zoll Quecksilber Druck, sey durch die Wärmemenge x bei constantem Volumen um 274°C. erwärmt worden [...] Ein andermal aber werde unser Cubikzoll Luft nicht unter constantem *Volumen*, sondern unter constantem *Drucke* der 27zölligen Quecksilbersäule von 0 auf 274° erwärmt. Diessmal ist eine grössere Wärmemenge erforderlich als zuvor; es sey dieselbe $= x + y$" (p. 12).

[16] "Ein Kubikcentimeter atmosphärische Luft bei 0° und 0 m, 76 Barometer, wiegt 0.0013 Gramme; bei constantem Drucke um 1°C. erwärmt, dehnt sich die Luft um 1/274 ihres Volumens aus und hebt somit eine Quecksilbersäule von einem Quadratcentimeter Grundfläche und 76 Centimeter Höhe um 1/274 Centimeter. Das Gewicht dieser Säule beträgt 1033 Gramme. Die specifische Wärme der atomsphärischen Luft ist bei constantem *Drucke*, die des Wassers = 1 gesetzt, nach ***Delaroche*** und ***Bérard*** = 0.267; die Wärmemenge, die unser Kubikcentimeter Luft aufnimmt, um bei constantem *Drucke* von 0 auf 1° zu kommen, ist also der Wärme gleich, durch welche 0.0013×0.267 oder 0.000347 Gramme Wasser um 1° erhöht werden. Nach ***Dulong*** [...] verhält sich die Wärmemenge, welche die Luft bei constantem Volumen aufnimmt, zu der bei constantem Drucke, wie 1:1,421; hiernach gerechnet ist die Wärmemenge, die unseren Kubikcentimeter Luft bei constantem *Volumen* um 1° erhöht, = 0.000347/1,421 = 0.000244 Grad. Es ist folglich die Differenz $y = 0.000347 - 0.000244 = 0.000103$ Grad Wärme, durch deren Aufwand das Gewicht P = 1033 Gramme auf $h = 1/274$ Centimeter, gehoben wurde. Durch Reduktion dieser Zahlen findet man 1° Wärme = 1 Grm. auf 367 m [...] Höhe" (pp. 14–15).

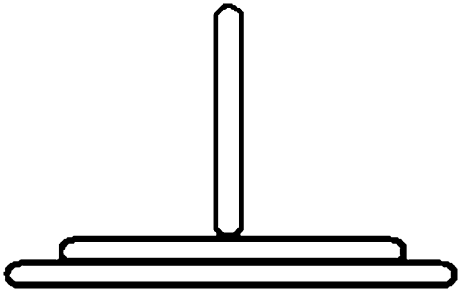


Fig. 1 Schema of an electrophorus

admitted that the mechanical effect does not have any consequence and that the electrical effects come from nowhere or it is concluded that the mechanical effect is transformed into electricity.[17]

In this case, transformation of mechanical effect into electricity, Mayer does not indicate a value to the mechanical equivalent of electricity, as he did concerning the heat-mechanical effect transformation. However, he writes: $z + z' = x$, where z symbolises the first electrical effect, z' the second one and x the mechanical effect.[18]

In conclusion, there are two steps in Mayer's dealing with the phenomena. Firstly, he verifies if a cause-effect relationship can be applied to the phenomena considered. Secondly, he writes an equation, whose sides are constituted by the quantities which characterise the cause and effect involved. Let us move on to the theory carried out by Mayer.

The 'cause' and the 'effect' in phenomena are called forces. 'Force' was a scientific concept and the statement 'forces are causes' was accepted in the science of that time. Nevertheless, Mayer's concept of force is different. He argues against the traditional concept in discussing the meaning of cause. According to his own concept, forces are indestructible in quantity and transformable in quality. This does not mean, however, that he had found an entity which is transformable and cannot be destroyed. The properties of force are instead useful in justifying Mayer's dealing with the phenomena.

As the quantity of force, which is cause in a phenomenon, is equal to the quantity of force, which is effect, an equation of the form

$$\text{force (cause)} = \text{force (effect)}$$

can be written. The sides of these equations can be very different from a phenomenological point of view, as for instance motion and heat or force of fall and electricity. This discrepancy does not matter, if the transformability of forces is admitted. Let us see if this interpretation agrees with the meaning of 'transformation'.

Mayer says, 'transformation of heat into mechanical effect' expresses a fact and does not explain the transformation. We say that ice is *transformed* into water. This is a fact, says Mayer. This fact, he further argues, is not dependent on *how and why* it happens. He adds that these kind of questions are useless and typical of poets and philosophers of

[17] "Aus Nichts wird Nichts. Die Elektrizität des Harzkuchens kann, da sie sich unvermindert erhalten hat, die fortlaufende Summe el. Effekte nicht hervorgebracht haben; der bei jedem Turnus verschwundene mechanische Effekt kann nicht zu Null geworden seyn. Was bleibt übrig, wenn man sich nicht in einem doppelten Paradoxon gefällt? nichts, als auszusprechen: *der mechanische Effekt ist in Elektrizität verwandelt worden*" (p. 24).

[18] "*Während wir also jedesmal einen mechanischen Effekt* $= x$ *aufwenden, gewinnen wir den el. Effekt* $z + z'$. So ist folglich: $x = z + z'$" (pp. 23–24).

nature.[19] In speaking of another transformation, from a chemical process into a mechanical effect, Mayer says that nobody knows how this takes place.[20] He added, 1851, that the relationship between heat and motion is quantitative and not qualitative[21] and that 'transformation from falling force into motion' cannot express anything but a numerical relation between both.[22] According to these statements, transformation does not explain what is going on in a physical process. The concept was instead used to connect observable data in certain circumstances. In fact, Mayer uses what is observable or measurable and thus he does not need to discuss the nature of heat or of electricity, as was usual at that time.

Concerning the question of what Mayer discovered, posed in the introduction, it could be said that he found a *methodology for dealing with phenomena*. This consists of the two steps referred to above and enables us to establish a numerical relationship between domains, which were until then separated, such as motion and heat. Mayer formalised his dealing with phenomena through the concept of force. Knowing the kinds of force[23] and their properties, one is led to dealing with phenomena as Mayer did.

3 James Joule

Joule published an article in the *Philosophical Magazine* of 1843, with the title "On the Calorific Effects of Magneto-Electricity, and on the Mechanical Value of Heat". 'Magneto-electricity' was the name given to the induced electric current, discovered by Faraday in 1831.[24] Joule constructed a magneto-electric machine. In his machine, there are 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. In the following schema, the three elements are represented (Fig. 2).

[19] "Wenn hier eine Verwandlung der Wärme in mechanischen Effekt statuirt wird, so soll damit nur eine Thatsache ausgesprochen, die Verwandlung selbst aber keineswegs erklärt werden. Ein gegebenes Quantum Eis lässt sich in eine entsprechende Menge Wassers verwandeln; diese Thatsache steht fest da und unabhängig von unfruchtbaren Fragen über Wie und Warum und von gehaltlosen Speculationen über den letzten Grund der Aggregats-Zustände. Die ächte Wissenschaft begnügt sich mit positiver Erkenntniss und überlässt es willig dem Poëten und Naturphilosophen, die Auflösung ewiger Räthsel mit Hülfe der Phantasie zu versuchen" (p. 10).

[20] "Näheres über die Art und Weise, ***wie*** das Organ, der Muskel, die Metamorphose einer chemischen Differenz in mechanischen Effekt vollbringt, wissen wir nicht zu sagen. [...] Die scharfe Bezeichnung der natürlichen Grenzen menschlicher Forschung ist für die Wissenschaft eine Aufgabe von praktischem Werthe, während die Versuche, in die Tiefen der Weltordnung durch Hypothesen einzudringen, ein Seitenstück bilden zu dem Streben des Adepten" (p. 88).

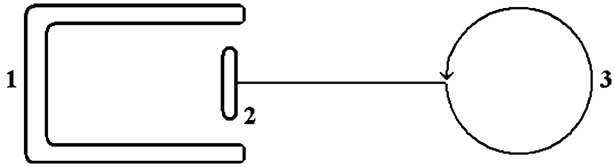
[21] "Der Zusammenhang, in welchem, wie wir gesehen haben, die Wärme mit der Bewegung steht, bezieht sich auf die Quantität, nicht auf die Qualität, denn es sind—um mit Euklid zu reden—Gegenstände, die einander gleich sind, sich desshalb noch nicht ähnlich" (p. 43).

[22] "Diese, zwischen der Fallkraft und der Bewegung bestehende constante Proportion, welche in der höheren Mechanik unter dem Namen 'Princip der Erhaltung lebendiger Kräfte' aufgeführt wird, kann kurz und passend mit dem Ausdrucke 'Umwandlung' bezeichnet werden. [...] Etwas anderes, als eine constante numerische Beziehung soll und kann hier das Wort 'Umwandeln' nicht ausdrücken" (pp. 41–42).

[23] The five kinds of forces are: 1. force of falling, 2. motion, 3. heat, 4. magnetism and electricity, and 5. chemical separation and combination (1845, p. 33).

[24] "The various experiments of this section prove, I think, most completely the production of electricity from ordinary magnetism" (p. 138). "I propose to call the agency thus exerted by ordinary magnets, *magneto-electric* or *magnelectric* induction" (p. 139).

Fig. 2 Schema of the theoretically important elements



With the magneto-electric machine, Joule researched the calorific effects of this current. From the experiments carried out, presented in the first part of the article "On the Calorific Effects of Magneto-Electricity", Joule concludes that heat can be generated or destroyed through the magneto-electric machine.[25] Hence, in the second part of the article, he sets up some of the experiments again but now to find out a numerical relation between the mechanical power used in the motion of the machine and the heat evolved through the electric current. Let us consider first, what Joule experimentally did and second, how he interpreted the results.

In the following image, elements 2 and 3 are represented (Fig. 3).

If axle *b* is cranked, it brings axle *a* into rotation. Perpendicular to this axle, there is a hollow box, in which element 2 is introduced. This element is immersed in a tube with water and thermally isolated. The temperature of the water is measured before the rotation and after it and the heat evolved is determined. From all the experiments set up with this experimental configuration, Joule concluded that motion creates heat. The next experimental configuration gives him the reason for the other part of his thesis: the destruction of heat through the magneto-electric machine.

The second experimental configuration is distinguished from the first one, principally, through the connection of element 2 with a battery. Joule connected element 2 with a battery and measured the heat evolved in this element when it does not rotate and when it does. In one direction, element 2 rotates without external help and in the opposite direction, it must be cranked to rotate. As in the first case, there was less heat than when the element did not move, Joule concluded that some heat was destroyed by the motion of the machine.

As heat could be increased or decreased through the magneto-electric machine and this functions by means of motion, Joule tried to determine a proportion between the heat evolved and the mechanical power used. To estimate the mechanical power, he replaced the crank with the system represented in the following image (Fig. 4).[26]

The product of the weights and the height make up the value of the mechanical power. This value is equated with the value of the heat evolved. The value of mechanical power that corresponds to one degree of heat is termed 'mechanical equivalent of heat'. Let us have a look at the figures.

The machine moves with a velocity of 600 rpm. For this motion, a weight of 5 lb 3 oz in each scale is necessary. If the machine works without electricity production, but as a mere mechanical machine, it needs only 2 lb 13 oz to rotate with the same velocity.[27] Joule took

[25] "*We have therefore in magneto-electricity an agent capable by simple mechanical means of destroying or generating heat*" (p. 146).

[26] "The axle *b* [...] was wound with a double strand of fine twine, and the strings [...] were carried over very easily-working pulleys, placed on opposite sides of the axle [...] By means of weights placed in the scales attached to the ends of the strings, I could easily ascertain the force necessary to move the apparatus at any given velocity" (p. 150).

[27] "when the battery was thrown out of communication with the electro-magnet, and the motion was opposed solely by friction and the resistance of the air, only 2 lb 13 oz were required for the same purpose" (pp. 150–151).

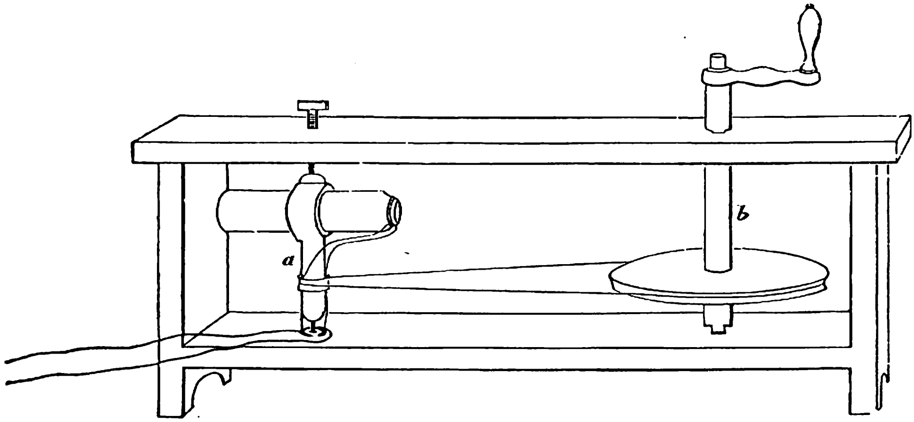


Fig. 3 From Joule's paper

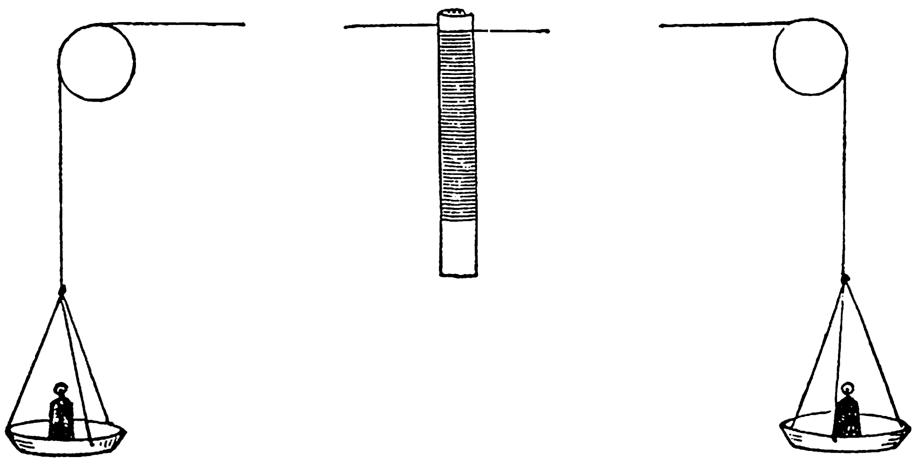


Fig. 4 From Joule's paper

the difference of the two weights as the weight which contributes to the heat produced. The value of this difference is 2 × (5 lb 3 oz – 2 lb 13 oz) = 4 lb 12 oz or 4.75 lb. As each scale covers the distance of 517 feet, the mechanical power is equal to 4.75 lb × 517 ft.[28] The final value of heat evolved was calculated and is equivalent to the heat necessary for heating a pound of water by 2.74 degrees Fahrenheit. If 2455.75 ft-lb corresponds to 2.74 degrees, one degree corresponds to x, where $x = 4.75 \times 517/2.74$. Joule said that the mechanical equivalent of heat is equal to the weight of 896 pounds which fall from the height of one foot.[29] Two other experiments gave the results of 1001 and 1040.[30]

[28] "2°.46 × 1.114 = 2°.74; and this has been obtained by the power which can raise 4 lb 12 oz to the perpendicular height of 517 feet" (p. 151).

[29] "1° of heat per lb of water is therefore equivalent to a mechanical force capable of raising a weight of 896 lb to the perpendicular height of one foot" (p. 151).

[30] "Two other experiments, conducted precisely in the same manner, gave a degree of heat to mechanical forces represented respectively by 1001 lb and 1040 lb." (p. 151).

In the following experiments, element 2 is connected to a battery. First, Joule measured the heat evolved when this element does not move. Afterwards, the machine is moved through the mechanical power of weights by falling and the heat evolved is determined. The difference between the two values of heat is equal to 4.54 degrees. In order to set the machine into motion, 6 lb 4 oz in each scale are required. To work as a mere mechanical machine, 2 lb 8 oz in each scale are necessary. The difference between the weights ($W_1 = 2 \times 6$ lb 4 oz = 12.5 lb and $W_2 = 2 \times 2$ lb 8 oz = 5 lb) is equal to 7.5 lb. As the scales cover the distance of 551 feet, the mechanical power used in producing that quantity of heat is equal to 7.5 lb × 551 ft.[31] The mechanical equivalent of heat is then equal to 910 ft-lb.[32]

In the following experiment, the rotation of the electro-magnet takes place in the opposite direction. In this case, the machine operates like an engine, says Joule.[33] This means that the rotation is not caused through falling weights but caused by the machine itself. In this case, the heat evolved is less than the heat evolved when the magnet did not move. The difference between these two quantities, 1.794 and 1.191, is equal to 0.603. The mechanical power necessary to produce the same motion by mechanical means is equal to 2.25 lb × 275 ft. From these data, it is concluded that the falling of a weight of 1026 lb from the height of one foot is equivalent to the heat necessary to raise the temperature of one pound of water by one degree.[34]

Joule obtained a total of thirteen results, whose values vary between 587 and 1040 ft-lb, and proposed the average of them as the value of the mechanical equivalent of heat, 838 ft-lb.[35]

The following equation subsumes all cases worked out by Joule

$$(\text{Weight}_{\text{mag.-elec.}} - \text{Weight}_{\text{mec.}}) \times \text{Height} = \text{Heat}_{\text{mag.-elec.}} - \text{Heat}_{\text{volt-elec.}}.$$

If

$$(\text{Weight}_{\text{mag.-elec.}} - \text{Weight}_{\text{mec.}}) \times \text{Height}$$

is positive, Joule says that the mechanical power has been converted into heat; if that value is negative, he says that heat has been converted into mechanical power. As the equation 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. This is the value of the mechanical equivalent of heat. Let us move on to the interpretation.

31 "Hence 4°.54 were evolved in the experiment over and above the heat due to the chemical changes taking place in the battery, by the agency of a mechanical power capable of raising 7 lb 8 oz to the height of 551 feet" (p. 152).

32 "In other words, one degree is equivalent to 910 lb raised to the height of one foot" (pp. 152–153).

33 "An experiment was now made, using the same apparatus as an electro-magnetic engine" (p. 153).

34 "Hence 0°.603 has been converted into a mechanical power equal to raise 2 lb 4 oz to the height of 275 feet […] one degree per lb of water may be converted into the mechanical power which can raise 1026 lb to the height of one foot" (p. 153).

35 "At present we shall adopt the mean result of the thirteen experiments given in this paper, and state generally that, *The quantity of heat capable of increasing the temperature of a pound of water by one degree of Fahrenheit's scale is equal to, and may be converted into, a mechanical force capable of raising 838 lb to the perpendicular height of one foot*" (p. 156). Greenslade (2002) indicates some values of the mechanical equivalent of heat in modern units.

At the beginning of the article, Joule asks the question of if the heat of the magneto-electricity is generated or transferred.[36] This question is connected with another one: if heat is a substance or a state of vibration.[37] If the heat determined in element 2 is transferred from another part of the circuit, heat can be a substance; if it is not transferred, then it cannot be a substance but it must be a kind of motion. From the experiments which were performed in the first part, Joule concluded that heat can be created or destroyed. Therefore, heat cannot be a substance. If it is not a substance, it must be a kind of motion. If heat is motion and the calorific effects of the magneto-electricity are produced through motion, then we have a motion that causes another motion. The quantity of one kind is converted into the other. The conversion factor is called mechanical equivalent of heat.

In the meeting of the British Association in Cambridge, 1845, Joule presented a new process to determine the mechanical equivalent of heat. The apparatus used in all experiments 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. The paddle-wheel experiment can be represented by the following schema (Fig. 5).

Joule gave the following description of the experiments:

> "The paddle moved with great resistance in the can of water, so that the weights (each of four pounds) descended at the slow rate of about one foot per second. The height of the pulleys from the ground was twelve yards, and consequently, when the weights had descended through that distance, they had to be wound up again in order to renew the motion of the paddle. After this operation had been repeated sixteen times, the increase of the temperature of the water was ascertained by means of a very sensible and accurate thermometer" (p. 203).

The result was the following: "for each degree of heat evolved by the friction of water a mechanical power equal to that which can raise a weight of 890 lb to the height of one foot had been expended" (p. 203).

In 1850, an article on the same subject was published in *Philosophical Transactions*. The writing opens with a quotation of Locke: "Heat is [...] *motion*" and another of Leibniz: "The *force* of a moving body is proportional to the square of its velocity".[38]

[36] "it must be admitted that hitherto no experiments have been made decisive of this very interesting question; for all of them refer to a particular part of the circuit only, leaving it a matter of doubt whether the heat observed was *generated*, or merely *transferred from the coils* in which the magneto-electricity was induced, the coils themselves becoming cold" (p. 123).

[37] "It is pretty generally, I believe, taken for granted that the electric forces which are put into play by the magneto-electrical machine possess, throughout the whole circuit, the same calorific properties as currents arising from other sources. And indeed when we consider heat not as a *substance*, but as a *state of vibration*, there appears to be no reason why it should not be induced by an action of a simply mechanical character, such, for instance, as is presented in the revolution of a coil of wire before the poles of a permanent magnet" (p. 123).

[38] "Heat is a very brisk agitation of the insensible parts of the object, which produces in us that sensation from whence we denominate the object hot; so what in our sensation is *heat*, in the object is nothing but *motion*"—Locke. "The *force* of a moving body is proportional to the square of its velocity, or to the height to which it would rise against gravity"—Leibniz (p. 298).

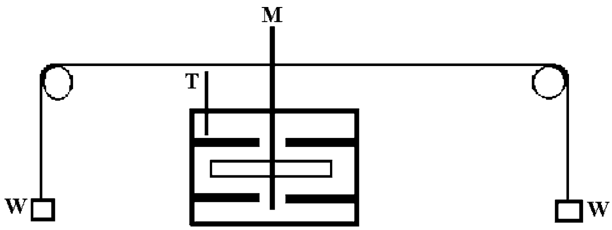


Fig. 5 Schema of the paddle-wheel experiment: W symbolises weights, M the mechanism which produces friction and T a thermometer

Rumford is quoted because he said, heat is motion.[39] Davy's experiment of rubbing two pieces of ice together is also referred to.[40]

In this article, a schema of the paddle-wheel and of the construction of the can for the fluid is presented (Figs. 6, 7).

Joule had ended the paper with three propositions but the third one was suppressed in accordance with the wish of the Committee who reviewed the paper:

> "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 1° Fahr. requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lb through the space of one foot" (p. 328).

In the third proposition, the conversion of mechanical power into heat was defended.[41]

The propositions have different origins: the proportionality between expended force and heat produced comes from the experiments carried out, as well as the value of the mechanical equivalent of heat. The third one cannot be proved by the same experiments. It represents more Joule's interpretation of the phenomena. Let us consider this topic.

At the beginning of the experiment, the weights are at a certain height and the water is a certain temperature. At the end, the weights are down and the temperature of the water has increased. Thanks to these data the following relationship is established

$$\text{weight} \times \text{height} = \beta \text{ units of heat.}$$

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.

Joule considers the experiment as a phenomenon of conversion from mechanical power into heat. The phenomenon of conversion must have taken place within the can. However,

[39] "For a long time it had been a favourite hypothesis that heat consists of 'a force or power belonging to bodies', but it was reserved for Count Rumford to make the first experiments decidedly in favour of that view [...] 'It appears to me', he remarks, 'extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in the manner the heat was excited and communicated in these experiments, except it be motion' [...]" (pp. 298–299).

[40] "By rubbing two pieces of ice against one another in the vacuum of an air-pump [...]" This experiment was the more decisively in favour of the doctrine of the immateriality of heat, inasmuch as the capacity of ice for heat is much less than that of water. It was therefore with good reason that Davy drew the inference that "the immediate cause of the phenomena of heat is motion, and the laws of its communication [...]" (p. 300).

[41] "A third proposition, suppressed in accordance with the wish of the Committee to whom the paper was referred, stated that friction consisted in the conversion of mechanical power into heat" (p. 328).

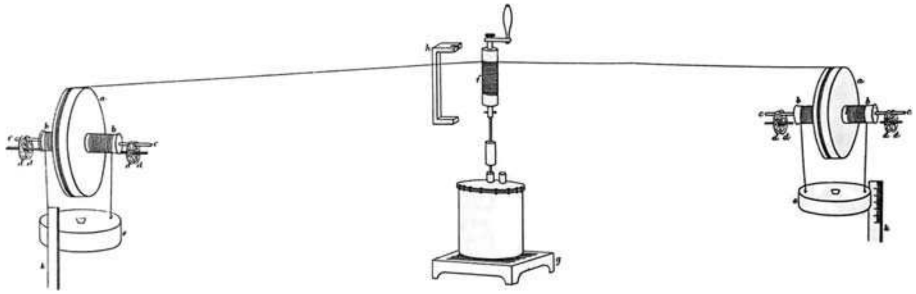
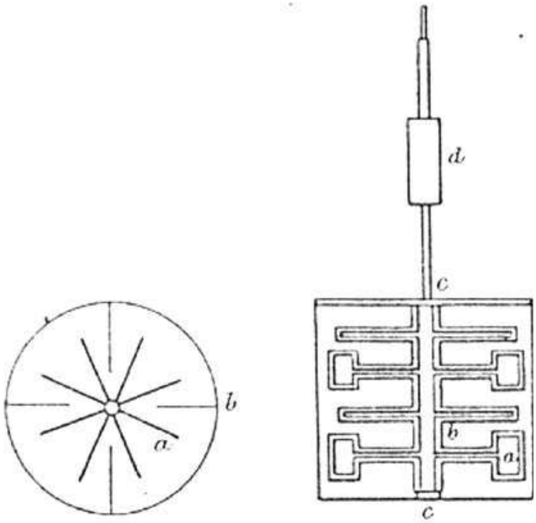


Fig. 6 Joule's schema of the mechanism

Fig. 7 Joule's schema: detail of the inside of the can



no observation is made to verify what happened within it. The temperature of water is read off when the weights are down and there is no conversion anymore. In fact, what really happened within the can is also not important for the final result: no specific information of the process of conversion is used. If the phenomenon does not consist of a process of conversion the established relationship between heat and mechanical power is not disturbed. The conversion is therefore an interpretation of the phenomenon.

Concerning the question of what Joule discovered, posed in the introduction, it could be said that he found *experimental methods for determining the mechanical equivalent of heat.* Joule 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. This is understandable within the science of that time.[42]

[42] There were two main theses concerning the nature of heat. According to Rumford (1798, p. 99) or Davy (1799, pp. 13–14), heat was motion. According to Carnot (1824, pp. 10–11, 28) or William Thomson (1849, p. 315), heat was a substance. Some authors had posed the question, "what is heat?", in connection with their experimental works during the first part of the nineteenth century. This was the case of Haldat (1807, p. 214), Berthollet, in cooperation with Pictet and Biot (1809, p. 447) or Colladon and Sturm (1828, p. 161). Joule's research concerns this question: heat is either a substance or motion.

4 Topics on the Development of Thomson's Concept

Energy, etymologically, means activity. The word was commonly used in the eighteenth century. "Psychological energy", for instance, was in the lexicon in 1798, among other uses of the word (Delon 1988, p. 45). In 1807, Thomas Young used the word 'energy' but only to designate the quantity mv^2.[43] In the first part of the nineteenth century, the word appears in scientific texts meaning 'activity'. Seebeck uses it in his lectures, 1821;[44] Ampère speaks of energy about the same time;[45] Faraday gives us an example of the use of the concept in English, 1831.[46] Mayer uses the word in different contexts: mechanics, chemistry, biology, physiology, among others.[47] William Thomson also uses the word, 1849, in the article "On Account of Carnot's Theory", where he defends that heat is a substance.[48] In 1851, he uses the word to refer to the mechanical activity of a body, i.e., what a body can do mechanically. This is the meaning of his concept of "mechanical energy of a body".

As heat had been understood as motion, thanks to the works of Joule, but also Rankine (1850), and Clausius (1850), (Coelho 2006, pp. 73–76) and there was a conversion factor, the mechanical equivalent of heat, heat could be translated into mechanical units. Thus, it is meaningful to speak of the mechanical activity of a body thanks to its heat. The mechanical activity of a body, which depends on the total heat in it, led to the concept of "total mechanical energy of a body". By this is understood the mechanical value of all effects a body would produce in heat emitted and in resistances overcome, if it were completely cooled.[49] This is, however, impossible to determine.[50] Hence, Thomson defines

[43] "The term energy may be applied, with great propriety, to the product of the mass or weight of a body, into the square of the number expressing its velocity. […] This product has been denominated the living or ascending force, since the height of the body's vertical ascent is in proportion to it; and some have considered it as the true measure of the quantity of motion; but although this opinion has been very universally rejected, yet the force thus estimated well deserves a distinct denomination" (pp. 78–79).

[44] "Aus meinen Untersuchungen [...] hatte sich ergeben, daß die Intensität des Magnetismus dieser Ketten in geradem Verhältniß zu der Energie der durch den feuchten Leiter begründeten chemischen Action stehe" (p. 265).

[45] "[...] ce qu'il est mis en action par une pile de Volta, dont on peut augmenter l'énergie à volonté en augmentant le nombre et l'étendue des plaques" (p. 60).

[46] "It possessed also the power of making magnets with more energy, apparently, than when no iron cylinder was present" (p. 133, § 34).

[47] "Wenn für die *kleine* Raumabstände und Geschwindigkeiten die Energie der mechanischen Effekte, den ausgezeichneteren chemischen Kräften gegenüber, sehr in den Hintergrund treten [...]" (1845, p. 28); "[...] einen Einfluss, durch den im allgemeinen die Energie des Oxydationsprocesses erhöht" (1845, p. 79); "die einzelnen Blutkörperchen nehmen mit verstärkter Energie den Sauerstoff auf" (1845, p. 82); "L'éxtrême énergie avec laquelle la chaleur des rayons solaires pénètre des corps transparents, fait voir […]" ((1846) 1893, p. 265).

[48] "When 'thermal agency' is thus spent in 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" (p. 545).

[49] "The total mechanical energy of a body might be defined as the mechanical value of all the effect it would produce, in heat emitted and in resistances overcome, if it were cooled to the utmost, and allowed to contract indefinitely or to expand indefinitely according as the forces between its particles are attractive or repulsive, when the thermal motions within it are all stopped" (p. 475).

[50] "in our present state of ignorance regarding perfect cold, and the nature of molecular forces, we cannot determine this 'total mechanical energy' for any portion of matter" (p. 475).

the mechanical energy of a body in a given state.[51] By this is understood the mechanical value of the effects the body would produce in passing from that state to a standard one or from this to the given state.

In 1852, Thomson defends the thesis that there is a universal tendency to the dissipation of mechanical energy.[52] He argues: as the phenomena are irreversible, there is an absolute waste of mechanical energy available for man;[53] as only the "Creative Power" can annihilate mechanical energy, a transformation must have taken place.[54] To explain this transformation in a precise way, Thomson introduced a division into two classes of stores of energy: static and dynamic.[55]

In the following year, Rankine proposed a new terminology for the systematization of energy: "actual or sensible" and "potential or latent".[56] In 1854, Thomson adopted Rankine's concepts: actual or dynamic for the energy of motion and potential energy for the other.[57] In 1862, Thomson and Tait published a paper in a non-scientific review, *Good Words*, and introduced the concept 'kinetic energy' instead of 'actual energy'.[58] According to Thomson, 1883, this change was a mere consequence of a terminological reform of mechanics.[59] The expression 'mechanical equivalent of heat' was also changed into 'dynamic equivalent of heat', but this alteration was not successful.

In the 1870s, Maxwell's *Theory of Heat* was published several times. He adopted the theory of energy and defined the energy of a body as its capacity of doing work.[60] Since it

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[51] "the 'mechanical energy of a body in a given state,' will denote the mechanical value of the effects the body would produce in passing from the state in which it is given, to the standard state, or the mechanical value of the whole agency that would be required to bring the body from the standard state to the state in which it is given" (p. 475).

[52] "The following general conclusions are drawn from the propositions stated above [...] 1. There is at present in the material world a universal tendency to the *dissipation* of mechanical energy" (p. 141).

[53] "The object of the present communication is to call attention to the remarkable consequences which follow from Carnot's proposition, established as it is on a new foundation, in the dynamical theory of heat; that there is an absolute waste of mechanical energy available to man" (p. 139).

[54] "As it is most certain that Creative Power alone can either call into existence or annihilate mechanical energy, the 'waste' referred to cannot be annihilation, but must be some transformation of energy" (p. 139).

[55] "To explain the nature of this transformation, it is convenient, in the first place, to divide *stores* of mechanical energy into two classes—*statical* and *dynamical*. A quantity of weights at a height, ready to descend and do work when wanted, an electrified body, a quantity of fuel, contain stores of mechanical energy of the statical kind. Masses of matter in motion, a volume of space through which undulations of light or radiant heat are passing, a body having thermal motions among its particles (that is, not infinitely cold), contain stores of mechanical energy of the dynamical kind" (p. 139).

[56] "All conceivable forms of energy may be distinguished into two kinds; actual or sensible, and potential or latent. *Actual energy* is a measurable, transferable, and transformable affection of a substance, the presence of which causes the substance to tend to change its state in one or more respects […] by the occurrence of which changes, actual energy disappears, and is replaced by *Potential energy*" (p. 106).

[57] "The energy of motion may be called either 'dynamical energy' or 'actual energy'. The energy of a material system at rest, in virtue of which it can get into motion, is called 'potential energy.'" (p. 34).

[58] "[...] It had kinetic or (as it has sometimes been called) actual energy. We prefer the first term, which indicates motion as the form in which the energy is displayed" (p. 602).

[59] "A few years later, in advocating a restoration of the original and natural nomenclature—'mechanics the science of machines,'—'dynamics the science of force,' I suggested (instead of statics and dynamics the two divisions of mechanics according to the then usual nomenclature) that statics and kinetics should be adopted to designate the two divisions of dynamics. At the same time I gave, instead of 'dynamical energy,' or 'actual energy,' the name 'kinetic energy' which is now in general use to designate the energy of motion" (1884, Vol. II, p. 34).

[60] "the energy of a body may be defined as the capacity which it has of doing work" (p. 90).

is impossible to determine the total energy of a body and energy of a body in a given state is determined in relation to a standard state,[61] the value of energy can be negative. Maxwell pointed this out in order to add that negative energy is really impossible.[62] (This topic becomes a critical point when energy is understood as a substance, as we will see.)

Maxwell did not categorically assert that heat is a form of energy but rather that it is better to understand it as such because one can obtain heat through work.[63] For the same reason, he argues also, heat cannot be a substance.[64]

In 1879, Oliver Lodge criticised the definition—energy is the capacity of doing work—due to the following reason.[65] One says that a body has some energy. Nevertheless, it does not mean necessarily that it can do work.[66] Hence, he proposed understanding energy as the work already done upon a body.[67] The conservation of energy is then expressed in the form: energy is neither produced nor destroyed but only transferred.[68] Lodge comes to the subject again due to an article of Poynting.

"On the Transfer of Energy in the Electromagnetic Field" is the title of Poynting's article in *Philosophical Transactions* (1884). If a current goes through a wire—the first example of energy transfer in the article—the vector product of the "electromotive intensity" and the "magnetic intensity" leads to the expression of the heat developed.[69] As heat is a form of energy and from a formal point of view the result of the calculation is a

[61] "we cannot determine experimentally the whole energy of the body. It is sufficient, however, for all practical purposes to know how much the energy exceeds or falls short of the energy of the body in a certain definite condition—for instance, at a standard temperature and a standard pressure" (pp. 183–184).

[62] "If the body in its actual state has less energy than when it is in the standard state, the expression for the relative energy will be negative. This, however, does not imply that the energy of a body can ever be really negative, for this is impossible. It only shows that in the standard state it has more energy than in the actual state" (p. 184).

[63] "The reason for believing heat to be a form of energy is that heat may be generated by the application of work, and that for every unit of heat which is generated a certain quantity of mechanical energy disappears" (p. 93).

[64] "The reason for believing heat not to be a substance is that it can be generated, so that the quantity of it may be increased to any extent, and it can also be destroyed, though this operation requires certain conditions to be fulfilled" (p. 93).

[65] "This definition of energy, as the effect produced in a body by an act of work, is not so simple as the usual one—'the power of doing work' but this latter definition seems a little unhappy" (p. 279).

[66] "energy is power of doing work in precisely the same sense as capital is the power of buying goods. […] money is a power of buying goods. It does not, however, *necessarily* confer upon its owner any buying-power, because there may not be any accessible person to buy from; and if there be, he may have nothing to sell. Just so with energy: it usually […] confers upon the body possessing it a certain power of doing work, which power it loses when it has transferred it" (p. 279).

[67] "Whenever work is done *upon* a body, an effect is produced in it which is found to increase the working-power of that body (by an amount not greater than the work done); hence this effect is called *energy*" (pp. 278–279).

[68] "But in every action taking place between two bodies the work is equal to the antiwork (§ 3); hence the energy gained by the first body is equal to the energy lost by the second; or, on the whole, energy is neither produced nor destroyed, but is simply transferred from the second body to the first" (p. 279).

[69] "Let r be the radius of the wire, i the current along it, α the magnetic intensity at the surface, P the electromotive intensity at any point within the wire, and V the difference of potential between the two ends. Then the area of a length l of the wire is $2\pi rl$, and the energy entering from the outside per second is $\frac{\mathrm{area}\times\mathrm{EMI}\times\mathrm{MI}}{4\pi} = \frac{2\pi rlP\alpha}{4\pi} = \frac{2\pi r\alpha Pl}{4\pi} = \frac{4\pi iV}{4\pi} = iV$ for the line integral of the magnetic intensity $2\pi r\alpha$ round the wire is $4\pi\ \times$ current through it, and $Pl = V$. But by Ohm's law $V = iR$ and $iV = i^2R$, or the heat developed according to Joule's law" (pp. 350–351).

vector perpendicular to the other two, Poynting connected these data in the following way. 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.[70] Lodge wrote a paper in the following year to defend the reality of energy.[71]

According to Lodge, energy exists in space, in bodies and in the ether and it can be transferred between them.[72] With a transference, there is a transformation of energy. Thanks to this new doctrine, it would be possible to give an explanation of potential energy, which had been a problem, according to Lodge.[73] He writes concerning the falling of a stone as follows:

> "the common mode of treating a falling weight, saying that its energy gradually transforms itself from potential to kinetic but remains in the stone all the time, is, strictly speaking, nonsense. The fact is the stone never had any potential energy, no rigid body can have any; the gravitation medium had it however, and kept on transferring it to the stone all the time it was descending" (p. 486).

Two years later, Planck's work on the principle of the conservation of energy appeared. This was his answer to a question from the Faculty of Philosophy of Göttingen concerning the concept and the conservation of energy. One of the problems pointed out by Planck concerns the hypostatising of energy. Energy had been understood as a substance, according to Planck.[74] The energy of an isolated system remains constant, according to physics. The same quantity of energy must therefore be there. It is, however, not possible, says Planck, to localise the energy in the system.[75] Energy, as a substance, is then considered by him as a concept which one day should be overcome.[76]

[70] "In this case very near the wire, and within it, the lines of magnetic force are circles round the axis of the wire. The lines of electric force are along the wire [...] energy is therefore flowing in perpendicularly through the surface, that is, along the radius towards the axis" (p. 350).

[71] "In that paper he introduces the idea of continuity in the existence of energy [...] whenever energy is transferred from one place to another at a distance, it is not to be regarded as destroyed at one place and recreated at another, but it is to be regarded as transferred, just as so much matter would have to be transferred; and accordingly we may seek for it in the intervening space, and may study the paths by which it travels" (p. 482).

[72] "The energy may be watched at every instant. Its existence is continuous; it possesses identity" (p. 483).

[73] "In the older and more hazy view of conservation of energy the idea of 'potential energy' has always been felt to be a difficulty [...] it was not easy or possible always to form a clear and consistent mental image of what was physically meant by it [...] The usual ideas and language current about potential energy are proper to notions of action at a distance" (p. 484).

[74] "diese Auffassung ist für die unmittelbare Anschauung überaus bequem durch ihre Analogie mit dem Verhalten der Materie, die auch in verschiedene Formen überführbar, aber nach ihrer Quantität (Masse) unveränderlich ist. Ebenso wie die Gesamtmasse eines Körpers sich als die Summe der Massen der einzelnen in demselben enthaltenen chemischen Substanzen darstellt, so setzt sich die Energie eines Systems zusammen aus der Summation der einzelnen Energiearten" (p. 116).

[75] "die Unbestimmtheit liegt dann im *Begriff* der Energie, man kennt den Platz nicht, den man ihr anweisen soll, und hat auch kein Mittel, ihn zu finden" (p. 117).

[76] "Gewiß ist zuzugeben, daß diese (sozusagen materielle) Auffassung der Energie als eines Vorrats von Wirkungen, dessen Menge durch den augenblicklichen Zustand des materiellen Systems bestimmt ist, möglicherweise später einmal ihre Dienste getan haben und einer anderen, allgemeineren und höheren, Vorstellung Platz machen wird: gegenwärtig ist es jedenfalls Sache der physikalischen Forschung, diese Auffassung als die anschaulichste und fruchtbarste überall bis ins einzelne durchzubilden und ihre Konsequenzen an der Hand der Erfahrung zu prüfen" (p. 118).

In 1894, Hertz criticised the concept of energy as a substance.[77] He pointed out that what we say about potential energy does not comply with our concept of substance. The quantity of a substance depends upon the substance itself and not on the existence of other substances, whereas the potential energy of a body is dependent on other bodies.[78] The quantity of a substance, further argues Hertz, is a positive quantity, whereas potential energy of a system can be negative.[79] When the amount of a substance is expressed analytically, an additive constant has the same importance as the rest. In the expression of the potential energy of a system, an additive constant never has any meaning.[80] In sum, according to Hertz, it is not logically permissible to understand energy as a substance, since energy has properties which contradict the concept of substance itself.

In a book published in 1908, Ostwald, who became Nobel Laureate for Chemistry in the following year, claimed that energy is what is really real.[81] Energy could subsume matter and the properties of matter, like heat. The traditional distinction between matter and spirit should be overcome thanks to the concept of energy.[82] Furthermore, energy is also used by him in the context of sociology, ethics and culture (Ostwald 1912).

5 Some Educational Implications

The distinction between dealing with phenomena and interpretation of them has shown that Robert Mayer did not find anything like a substance but rather a methodology. Using observable or measurable elements the German physician established *equivalences* between different domains, such as those which concern heat, motion, position or electricity. The theory for this, carried out by him, is based on the indestructibility and transformability of force. Admitting that these properties were derived from phenomena, one can be led to the idea that force is something concrete. This point is important due the characterization of energy.

[77] "Mehrere ausgezeichnete Physiker versuchen heutzutage, der Energie so sehr die Eigenschaften der Substanz zu leihen, daß sie annehmen, jede kleinste Menge derselben sei zu jeder Zeit an einen bestimmten Ort des Raumes geknüpft und bewahre bei allem Wechsel desselben und bei aller Verwandlung der Energie in neue Formen dennoch ihre Identität" (pp. 25–26).

[78] "[...] kann der Inhalt eines physikalischen Systems an einer Substanz nur abhängen von dem Zustande des Systems selbst; der Inhalt gegebener Materie an potentieller Energie aber hängt ab von dem Vorhandensein entfernter Massen, welche vielleicht niemals Einfluß auf das System hatten" (p. 26).

[79] "Die Menge einer Substanz ist eine notwendig positive Größe; die in einem System enthaltene potentielle Energie scheuen wir uns nicht, als negativ anzunehmen" (p. 26).

[80] "Bedeutet ein analytischer Ausdruck die Menge einer Substanz, so hat eine additive Konstante in dem Ausdruck dieselbe Wichtigkeit wie der Rest; in dem Ausdruck für die potentielle Energie eines Systems hat die additive Konstante niemals eine Bedeutung" (p. 26).

[81] "Die Energie ist daher in allen realen oder konkreten Dingen als wesentlicher Bestandteil enthalten, der niemals fehlt, und insofern können wir sagen, *daß in der Energie sich das eigentlich Reale verkörpert*. Und zwar ist die Energie das Wirkliche in zweierlei Sinn. Sie ist das Wirkliche insofern, als sie das *Wirkende* ist; wo irgend etwas geschieht, kann man auch den Grund dieses Geschehens durch Kennzeichnung der beteiligten Energien angeben. Und zweitens ist sie das Wirkliche insofern, als sie den *Inhalt* des Geschehens anzugeben gestattet" (p. 5).

[82] "Es besteht [...] gar nicht mehr die Aufgabe, zu ermitteln, wie Geist und Materie in Wechselwirkung treten können, sondern es entsteht die Frage, *wie sich der Begriff der Energie, der viel weiter als der der Materie ist, zu dem Begriff des Geistes stellt*" (p. 144).

The principle of conservation of energy or the concept of energy are often presented in the form: energy can neither be created nor destroyed but only transformed.[83] If energy cannot be produced and if there is some, it cannot be annihilated, then it must be a real existing thing. If energy can only 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.

Let us now suppose that we use the other part of Mayer's contribution: his methodology for dealing with phenomena. We are then aware that we are applying a methodology to a process, to a phenomenon, where there is a cause-effect relationship, as Mayer said. Let us consider, therefore, the measured quantity concerning the "initial" part of the process equivalent to the "final" one. As we know, then, that an equivalence is established by us between those quantities, we do not need the 'indestructibility' of an entity to express that the quantity does not change. This is now a mere consequence of our dealing with the measured quantities. As we establish an equivalence between different domains, as is the case in general, we do not need to suppose the 'transformability' of the same entity. We know in advance that we are dealing with different measurement processes and units. Thus, using the concept of equivalence learned from Mayer's treatment of the phenomena and from Joule's as well, we can understand the conservation of energy as a consequence of our dealing with the phenomena and dispense with the unknown entity whose properties justify our own methodology. Equivalence was already a key word in teaching thermodynamic issues.

Textbooks published towards the end of the nineteenth century or the beginning of the following century used the expression "principle of equivalence" concerning the heat-motion relationship. This is the case of Verdet's *Thermodynamics* (1868), in which most of the experiments concerning the discovery of energy are considered in detail. In Poincaré's *Thermodynamics* (1892), there is also a chapter with the title "The Principle of Equivalence". According to Preston's *Theory of Heat* (1919), the first law of thermodynamics is called principle of equivalence.[84] In the chapter "Principle of Equivalence" of Müller and Pouillet's *Physics*, 11th edition, 1926, one reads that the first law is to be formulated in the form: heat and mechanical work are equivalents.[85] When the principle of energy is spoken of, the authors pointed out that with the thesis, energy is indestructible, the principle is not an experimental law anymore but a postulate.[86] Understanding the principle of conservation of energy as a principle of equivalence and the equivalence factor as a value, which is determined experimentally, the difficulty with the concept of energy does not seem to

[83] See, for instance, Chalmers (1963, p. 43), Bueche (1972, p. 95), Hänsel and Neumann (1993, p. 222), Cutnell and Johnson (1997, p. 177), Young and Freedman (2004, p. 264).

[84] "The modern science of thermodynamics is based on two fundamental principles, both of which relate to the conversion of heat into work. The first of these is the principle of equivalence established by Joule, and is represented algebraically by the equation W = JH. This principle, which is known as the *first law of thermodynamics*, asserts than when work is spent in producing heat, the quantity of work spent is directly proportional to the quantity of heat generated […] This conception is derived from the dynamical theory, according to which heat is regarded as a form of energy" (p. 667).

[85] "Die am engsten an die unmittelbare Erfahrung sich anschließende Formulierung des ersten Hauptsatzes, die von jeder Hypothese, etwa über die Natur der Wärme frei ist, besagt daher einfach: Wärme und mechanische Arbeit sind äquivalent" (p. 109).

[86] "*Energie (beliebiger Form) kann weder erzeugt, noch vernichtet werden*. Die einfachste Gestalt nimmt das Energieprinzip wohl in der Form an: *Die Summe aller einem abgeschlossenen System innewohnenden Energieformen bleibt bei sämtlichen Umwandlungen desselben konstant*. Bei noch etwas schärferer Fassung nimmt der vorangehende Gedankengang folgende Gestalt an: Energie wird als unzerstörbar angesehen. Das Energieprinzip ist somit zunächst kein empirisches Gesetz, sondern ein *Postulat*, das sich allerdings mit den Erfahrungstatsachen (Äquivalenzgesetz) durchaus im Einklang befindet" (p. 126).

have existed in teaching thermodynamics. The concept of energy as a methodology can also be useful nowadays.

Duit (1987) Prideaux (1995), Arons (1999) corroborate Feynman's concept: energy is not a concrete thing and energy conservation is a mathematical principle. The idea that energy is not a real existing thing is conform with Mayer's and Joule's dealing with phenomena. The mathematical character of the conservation principle highlighted by Feynman complies with the establishment of equivalences between certain quantities. Duit (1987, p. 145) pointed out that Feynman's concept is too abstract for teaching at basic level. Concerning this topic, Mayer's dealing with the phenomena could have some advantage. Marques (2007, pp. 90–101) was successful in introducing the concept of energy through the "reconstruction" of Mayer's experiment—vehement agitation of water—carried out by the pupils in the classroom.

Duit (1987) pointed out some inconveniences of the concept of energy as something quasi material, defended by some physicists. According to Beynon (1990), there is so much confusion with energy "because it is not treated as an abstract physical quantity but something *real*, just like a piece of cheese" (p. 315). Empirical educational research shows alternative ideas, such as 'Energy is fuel' or 'Energy is stored within objects' (Nicholls and Ogborn 1993, p. 73; Prideaux 1995, p. 278). Doménech et al. (2007) deconstruct ideas which could lead to an interpretation of energy as something possessed by the objects themselves (pp. 51–53). All criticised topics concern the supposition that energy is a real thing. If energy is understood as a method for dealing with phenomena, difficulties which arise from the concept of energy as a substance can be overcome.

Cotignola et al. (2002, p. 285), Doménech et al. (2007, p. 54) criticised the definition of heat as a form of energy, presented in some textbooks. If energy is not a substance, it can neither be something which changes its form. Thus, the idea of heat as a form of energy would be out of place.

The universal validity of energy, highlighted by Doménech et al. (2007, p. 48), poses a very difficult question within the traditional context: to find out a definition of energy, which could subsume all cases in which the concept is used. Furthermore, we cannot rule out the possibility of new forms of energy, which could make the problem still more difficult. The universal validity of energy can however now be interpreted as an expression for the great applicability of Mayer's methodology. This means that the establishment of certain equivalences can be carried out concerning a wide variety of phenomena or is useful in different scientific domains.

The generality of the conservation principle justifies Bunge's thesis: it belongs in philosophy rather than in physics (2000, p. 460). Since the principle of energy conservation is a methodology which is applied to phenomena, it is not derived from them. This point of view becomes still clearer, if we consider the foundation of Mayer's approach: 'cause equals effect' or 'nothing comes from nothing'. In fact, he justifies the equation between heat and motion, for instance, through the classical statement "cause equals effect" and presents another or more profound justification in 1845: nothing comes from nothing and nothing becomes nothing.[87] These classical statements, which are quoted in Latin, clearly do not come from physics.

[87] "Es entsteht keine Wirkung ohne Ursache; keine Ursache vergeht ohne entsprechende Wirkung ***Ex nihilo nil fit. Nil fit ad nihilum***" (p. 5).

The concept of energy in the 1850s includes Mayer's point of view as well as Joule's thesis, heat is motion. Thus, 'conservation' and 'transformation' appeared connected with energy but also 'capacity of doing work'. Since the concept of energy was worked out in a mechanical context, the criticism that the definition of energy as capacity of doing work is too restricted, is understandable (Lehrman 1973; Sexl 1981, p. 287; Duit 1981, p. 293; Hicks 1983; Kemp 1984, p. 234; Doménech et al. 2007, p. 49).

Thomson's systematisation of stores of energy has a meaning within the same context. When he says that the potential energy of a stone is converted into actual or dynamic energy, 1854, he means that the energy available for man in form of motion is increasing but the potential energy is decreasing.[88] This differs from Lodge's interpretation: the potential energy existing in space is transferred to the falling stone. Thomson could not agree with this meaning for the concept introduced by him: he suspected that the people who claimed that energy is a real existing thing do not know what it really is[89] In fact, energy had become a real thing. This semantic development caused some difficulties.

It is difficult for a student to articulate 'transformation of energy', energy being something real, with his observation of a falling stone. This is not a question of understanding but of experimental data, which are not enough to support that idea. In fact, a technical registration of a falling body yields no more information than the places and times of it. The concept of energy based on Mayer's and Joule's dealing with the phenomena enables us to overcome that difficulty. This can be useful in supporting students' reflections, of which the significance has been pointed out (Doménech et al. 2007, p. 46, 60).

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[88] "A stone at a height [...] has potential energy. If the stone be let fall, its potential energy is converted into actual energy during its descent, exists entirely as the actual energy of its own motion at the instant before it strikes, and is transformed into heat at the moment of coming to rest on the ground" (p. 34).

[89] "Young persons who have grown up in scientific work within the last fifteen or twenty years seem to have forgotten that energy is not an absolute existence. Even the Germans laugh at the 'Energetikers'. I do not know if even Ostwald knows that energy is a capacity for doing work" (Letter to Joseph Larmor, 1906, quoted by Smith 1998, p. 289).

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