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On the Concept of Energy: Eclecticism and Rationality

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Abstract In the theory of heat of the first half of the nineteenth century, heat was a substance. Mayer and Joule contradicted this thesis but developed different concepts of heat. Heat was a force for Mayer and a motion for Joule. Both Mayer and Joule determined the mechanical equivalent of heat. This result was, however, justified in accordance with those concepts of heat. Mayer's characterisation of force reappears in the very common textbook definition 'energy cannot be created or destroyed but only transformed' and his theory led to a phenomenological approach to energy. Joule and Thomson's concept of heat led to a mechanistic approach to energy and to the common definition 'energy is the capacity of doing work'. One and the same term 'energy' subsumed these two approaches. The problematic concept of energy, energy as a substance, appears then as a result of an eclectic development of the concept. Another approach, which appeared in the 1860s, is directly based on the mechanical equivalent of heat and can be characterized by the use of 'principle of equivalence' instead of 'principle of energy conservation'. Unlike the others, this approach, which has been lost, poses no problems with the concept of energy. The problems with the energy concept as to the kind of phenomena dealt with in the present paper can, however, be overcome, as we shall see, in distinguishing between that which comes from experiments and that which is an interpretation of the experimental results within a conceptual framework.

1 Introduction

The very common notion of energy in contemporary textbooks states: *energy can neither be created nor destroyed but only transformed*.[1] If energy cannot be destroyed, it must be a real existing thing, since it does not make any sense to say that we are unable to destroy

[1] See, for instance, Chalmers (1963, p. 43), Bueche (1972, p. 95), Hudson and Nelson (1982, p. 95), Hänsel and Neumann (1993, p. 222), Cutnell and Johnson (1997, p. 177), Dransfeld, Kienle and Kalvius (2001, p. 109), Young and Freedman (2004, p. 264).

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what does not exist. If energy can be transformed, then, in reality, it must appear in different forms. Thus, based on that notion of energy, one is easily led to the idea that energy is a real thing, a kind of substance. This concept of energy is often used, as when it is said, energy can flow, it can be carried, be lost, stored or added to a system. These are substance metaphors, adds Lancor (2012, p. 17). This characterisation of the sentences as metaphors tells us that those expressions are not precise enough, which hinders their use in a logical way.[2]

If energy can be transformed and heat is the end product of such a transformation, it is understandable that heat is considered a form of energy.[3] The definition of heat as a form of energy, has, however, been criticized (Cotignola et al. 2002, p. 285; Doménech et al. 2007, p. 54). In some textbooks, it is pointed out that heat is not a form of energy (Hertel 2007, p. 135) and it is defined as energy transferred (Keller et al. 1993, p. 423; Breithaupt 1999, p. 376). Different points of view concerning the concepts of heat and energy can become confusing for a student or even for a teacher.[4]

Another common definition of energy in textbooks is: *energy is the capacity of doing work*.[5] The subject of the previous sentence is energy. Therefore, energy has this ability. If this is the case, then energy must be something real. So real, that it is able to act, namely to do work. This reading also agrees with that common idea of energy seen above. This definition of energy as the capacity of doing work has also been criticized.[6]

In contradiction with the concepts of energy presented above and common in textbooks on physics, chemistry and biology, some physicists have defended that energy is not a substance (Feynman 1966, 4–1; Hudson and Nelson 1982, p. 95). Some physicists do even assert that we do not know what energy is (Feynman 1966, 4–1; Bergmann and Schaefer 1998, p. 616; Dransfeld, Kienle and Kalvius 2001, p. 109).[7] Bergmann and Schaefer further added that a physicist is in the same situation as a layman regarding the question of what energy is. Indeed, concerning this question, the development of physics has not been helpful.[8] Whereas everyone would agree that the development of science since the end of the nineteenth has been brilliant, the concept of energy as a substance had already been a problem for Planck (1921 [1887]). Hertz (1899 [1894]) criticized it and Poincaré (1897) not only corroborated this but also added other criticisms. In fact, the energy concept problem has existed for decades.

Where do the problematic concepts of energy (1) as a substance, (2) as the capacity of doing work and (3) transfer of energy come from? These are the questions to be addressed

[2] The need of supporting students' logical and critical thinking has been pointed out by several authors (Bailin 2002; Kalman 2002, 2011; Doménech et al. 2007; Matthews 2009; Galili 2009; Malamitsa, Kasoutas and Kokkotas 2009).

[3] Atkins (1986, p. 233), Hänsel and Neumann (1993, p. 222), Böge and Eichler (2002, p. 83), Nolting (2002, p. 148).

[4] See, for instance, Sexl (1981), Duit (1981, 1987), Hicks (1983), Bauman (1992), Chrisholm (1992), Arons (1999), Galili and Lehavi (2006), Doménech et al. (2007), Rizaki and Kokkotas (2009), Papadouris and Constantinou (2011).

[5] See, for instance, Breithaupt (1999, p. 157), Tipler (2000, p. 129), Serway and Beichner (2000, p. 183).

[6] See, for example, Lehrman (1973), Sexl (1981, p. 287), Duit (1981, p. 293), Hicks (1983), Kemp (1984, p. 234), Doménech et al. (2007, p. 49).

[7] If we do not know what energy is, then it is not to be expected that students will grasp it. Empirical research has shown their difficulties with the concept (Watts 1983, Duit 1986, Nicholls and Ogborn 1993, Trumper 1990, 1991, Cotignola et al. 2002, Barbosa and Borges 2006, de Berg 2008, Svedholm and Lindeman 2012, among others).

[8] According to Bunge (2000), the general concept of energy belongs in metaphysics (Bunge 2000, p. 461).

in the present paper. In order to identify the origin of the problem, the history of the concept of energy, in the extent to which it is useful for this goal, will be considered.

2 On the Discovery of Energy

The history of science teaches us that energy was discovered in the 1840s. Mayer, Joule, Colding and Helmholtz have generally been considered the discoverers.[9] On the basis of their texts, it can be verified that they agree with the thesis '*heat is not a substance*' and with an equation of the form

$$\alpha\, mechanical\, units = \beta\, thermal\, units.$$

They disagree concerning the nature of heat and the justification of the equation, as we shall see. The different justifications of this equation constitute the basis for those common definitions of energy (introduction), as we also shall see. These justifications, in turn, are related with the science of that time. Hence, we will consider firstly the scientific background concerning the concept of heat and living force (*vis viva*).

2.1 From the Historical Background: *Vis Viva* and Heat

The *vis viva* issue matters for several reasons. Mayer subsumed Leibniz's conservation of *vis viva* into his theory. Helmholtz's theory is based on two ultimate forces, the living force being one of them. In his famous paper on the paddle-wheel experiment, Joule (1850) presents two sentences as a motto: one of them stems from Leibniz and concerns the living force.

The topic 'heat' is significant because Mayer, Joule, Colding and Helmholtz took position regarding the concept of heat in the science of that time. What they claimed about heat was in contradiction with that concept. Hence, they needed to develop a theory to explain heat phenomena, which they also did.

2.1.1 On Vis Viva

In 1686, Leibniz published a paper with the title "Brief Demonstration of a Notable Error of Descartes and Others Concerning a Natural Law, According to which God is Said Always to Conserve the Same Quantity of Motion; A Law Which They Also Misuse in Mechanics". According to Descartes' general law of motion, the quantity of motion in the universe is conserved (Descartes 1973 [1644], II, Sect. 36). This law has, as a consequence, that in the rules of impact—impact is the fundamental phenomenon in the Cartesian universe—the quantity of motion before and after impact is the same (Descartes 1973, II, §§ 46–52). This quantity is given by the product of mass and velocity.[10] Leibniz (1686)

[9] Planck (1921 [1887]), Mach (1896), Helm (1898), Haas (1909), Kuhn (1959), Theobald (1966), Breger (1982), Schirra (1989), Smith (1998), Guedj (2000), Coelho (2006), Coopersmith (2010). On Mayer: Weyrauch (1890), Riehl (1900), Hell (1914), Timerding (1925), Lindsay (1973), Mittasch (1940), Heimann (1976), Caneva (1993); On Joule: Fox (1969), Forrester (1975), Cardwell (1989); on Colding: Dahl (1963); on Helmholtz: Elkana (1974), Heimann (1974), Bevilacqua (1983, 1993), Ordónez (1996).

[10] Indeed, 'mass' was not the term used by Descartes and 'velocity' is not a vector in his theory of motion.

claimed that this magnitude is not conserved but rather what he called 'quantity of force' (Leibniz 1971, pp. 117–118). This thesis is justified in the following way.

If a body with the mass of 1 unit falls at the height of 4 units, its force will be enough to elevate a body of 4 units of mass to the height of one unit (Fig. 1). Leibniz's claim can formally be given as

$$m_A \cdot h_A = m_B \cdot h_B \tag{1}$$

In the next step, Leibniz expresses height h by means of the velocity of the body. To do this, he uses Galileo's proposition (Leibniz 1971, p. 118), according to which the durations of time and the distances covered in falling are to each other as the natural numbers are to the odd ones (Galilei 1965, Vol. X, p. 115; Vol. VIII, p. 210).

Duration of time	Distance covered
1	1
2	3
3	5
4	7

Body A in Lebniz's example covers 4 units of space. Therefore, it spent 2 units of time, since in the first it covered 1 and the in second, 3. If 4 units are covered in 2 units of time, its velocity is equal to 2 (units are set aside here). The velocity of the other body is 1, for the same reason. The quantity of motion of each body is therefore 2 and 4. It follows then that the Cartesian conservation law does not hold in this case. To maintain the initial equality, $m_A h_A = m_B h_B$, Leibniz claims that it is the magnitude

$$m \cdot v^2$$

that is conserved. In the present case,

$$1 \cdot 2^2(\text{body A}) = 4 \cdot 1^2(\text{body B}) \tag{2}$$

Thus, he justified his thesis as: the quantity of motion is not conserved in the universe but the quantity of force is. He called this magnitude 'living force' (*vis viva*) later on (Iltis 1971, p. 25).

In 1842, Mayer addressed the *vis viva* conservation and mentioned "Leibniz" and "Descartes". He was therefore referring to what we have just seen. Mayer claimed that he subsumed Leibniz's conservation principle in his theory (Mayer 1842, p. 236). Let us see what he did.

According to Mayer, weight and height together make up the cause of falling.[11] What results from this is the motion which is expressed by the body's *vis viva* (mv^2) (1842, pp. 235–236). As he admits that cause equals effect, he writes[12]

[11] This contradicted the science of that time, according to which 'weight' alone was the cause of falling. Mayer argues however that weight is not enough for falling because without height there is no fall. Thus, he justified that *weight* · *height* is 'fall force' (Mayer 1842, p. 236).

[12] Mayer did not distinguish between weight and mass.

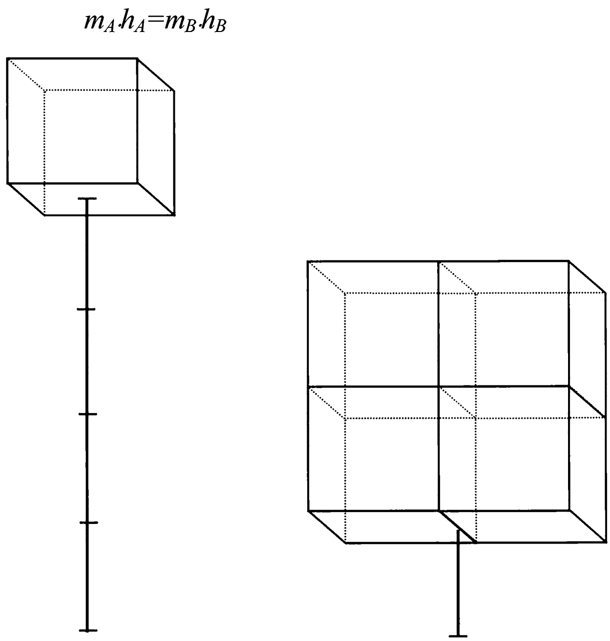

Fig. 1 The force of body A ($m = 1$, $h = 4$) equals the force of B ($m = 4$, $h = 1$)

$$mh = mv^2. \tag{3}$$

This shows that Mayer needed a justification to put these two magnitudes in an equation. This justification was drawn from the classical proposition “cause equals effect”.[13] Taking ‘cause = effect’ as a principle, the fall force (mh) becomes equal to the motion (mv^2).

Helmholtz (1882 [1847]) came up with the idea that there are two ultimate forces in nature: moving force and the motion resulting from it. To make them equivalent to each other, he made recourse to the proposition ‘it is impossible to get a durable force out of nothing’. Taking this as a principle, he drew the consequence that, in the case of a falling body, moving force is equivalent to the resulting motion. Since the first is given by *weight·height* and the second by the body’s *vis viva* (½ mv^2),[14] it follows

$$mgh = \tfrac{1}{2} mv^2. \tag{4}$$

It might seem strange to us that both Mayer and Helmholtz needed a justification to equate the two magnitudes: “*weight·height*” and “*mass·velocity squared*” (details are secondary here). Mayer used for that the classical proposition ‘cause equals effect’, as a principle, and Helmholtz, the proposition ‘it is impossible to obtain a force out of nothing’, also as a principle. Indeed, Leibniz’s conservation concerns two bodies, whereas Mayer’s and Helmholtz’s concern only one body. Therefore, even though the *vis viva* is similar to

[13] Mayer quoted this proposition in Latin, “*causa aequat effectum*” (Mayer 1842, p. 233).

[14] Helmholtz proposed to take ½ mv^2 as *vis viva*, instead of mv^2, which he did throughout his paper.

kinetic energy, some work was carried out on it, by Mayer and Helmholtz, to make it part of the energy conservation principle.

2.1.2 On Heat

In the first half of the nineteenth century, textbooks were often divided into two parts, where the first one deals with matter which has weight and corresponds to mechanics, and the second, with electricity, magnetism, light and heat (see also Muncke 1830, p. 765). This second part had the term 'imponderables' in the title, like 'on the fundamental imponderable substances of bodies' (Suckow 1813) or 'on imponderable powers' (Muncke 1829). In a paper published in *Gehler's Physical Dictionary* (Gehler 1825–1845), Muncke (1830) pointed out that heat might *either* be an imponderable substance *or* a force *or* perhaps neither. Mayer knew this distinction, to which he took a position in his first paper (Mayer 1842, p. 234) and anew, in his 1845 book. Here he wrote: "Let us express the great truth: there is no immaterial material" (1845, p. 36). This "great truth" may seem strange to us but it is really significant for the following reason. Mayer characterises matter by weight and impenetrability. Thus, what is weightless cannot be matter. Weightlessness is a property of force, according to Mayer (1842, p. 234). Therefore, when he asserts that heat is a force, he is taking it from the side of matter onto the side of force. That proposition, "the great truth", tells us therefore that heat, which is weightless, cannot be matter.[15] If it is not matter, then, according to that disjunction—either matter or force—, *heat must be a force*.

In the 1843 paper, Joule mentioned a Rumford experiment, as one that corroborates his thesis, *heat is motion* (Joule 1884, p. 157). In 1798, Rumford carried out series of friction experiments. In one of them, he filled a box with water into which he immersed a cannon barrel and a borer. Measuring the water temperature from time to time, he verified that it increased until reaching boiling point (Rumford 1798, pp. 91–92). He concluded then that heat is motion (p. 99). A similar thesis was defended by Davy (1839 [1799], pp. 13–14). He rubbed two pieces of ice together and verified that the ice melted. As these pieces had been isolated, the heat could not have come from outside. Therefore, it was produced by friction. He also verified that, in general, bodies expand through friction. He concluded then that the bodies' particles move away from each other. This motion or vibration was produced by friction. "Therefore, we may reasonably conclude that this motion or vibration is heat" (Davy 1839 [1799], p. 14).

Despite these experiments, the common thesis on the nature of heat during the first half of the nineteenth century was '*heat is a substance*'. Some authors posed the question of what heat is when they discussed their experimental results. This was, for instance, the case of Haldat, (1807, p. 214), Berthollet (1809, p. 447), in cooperation with Pictet and Biot, and Colladon and Sturm (1828, p. 161). All concluded that heat was a substance. Davy (1839), in turn, considered his experiments mentioned above as a production from his "infant chemical speculations" (1839 [1799], p. 3). William Thomson (1848), who had met Joule in 1847 and was acquainted with his experiments, proposed an absolute thermometric scale based on Carnot's theory, according to which heat is a substance (Carnot 1824, pp. 10–11, 28). In the following year, he published "An Account of Carnot's Theory", in which the same principle is defended: the quantity of heat does not change (Thomson 1849, p. 544). In this paper, he further pointed out that there was no experimental proof that heat could be converted into motion (p. 545).

[15] Rumford (1799) had experimentally shown that heat has no effect on the weight of bodies (Rumford 1799, p. 194).

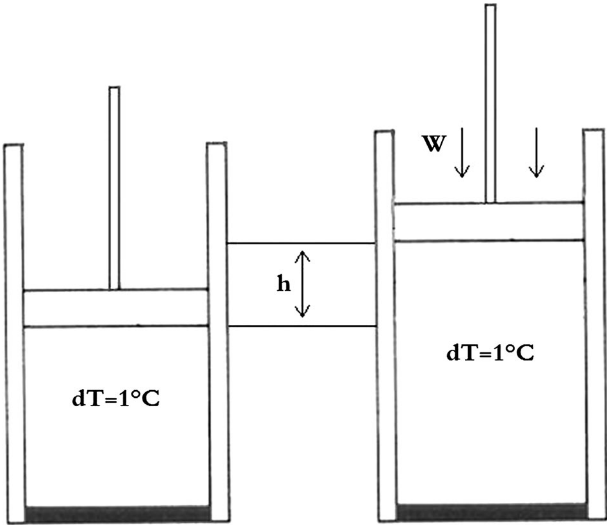

Fig. 2 Illustration of the experimental set up on which Mayer based his calculations. In both recipients, the temperature of the air increases by 1 °C. In the first case, the volume is constant, in the second, the pressure is constant. (The height *h* is not as large as represented)

All this represented an obstacle to Joule's point of view. If heat is a substance, it cannot be created by motion, since being a *substance* was associated with *constancy in quantity*. This makes it understandable that Joule's first attempt was to show experimentally that heat can be generated by motion. Once he had proved this (this was his view), he went further to determine the mechanical equivalent of heat. In the 1850 paper in *Philosophical Transactions*, Joule 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" (Joule 1850, p. 61). Rumford is quoted because he said, heat is motion. Davy's experiment of rubbing two pieces of ice together is also referred to (Joule 1850, pp. 61–62).

In short, Mayer and Joule agree with the thesis 'heat is not a substance'. However, whereas for Mayer, heat is a force, and not motion, Joule claimed that heat is motion. As we shall see, Colding took heat as a force, without knowledge of Mayer's paper. Helmholtz, who knew Joule's papers, defended that heat is motion.

2.2 Mayer

Figure 2 illustrates the experimental set up, on which Mayer's calculation of the mechanical equivalent of heat is based.

In both recipients (Fig. 2), the temperature of the same quantity of atmospheric air is increased by 1 °C. In one case, the volume is constant, in the other, the pressure is constant. The heat needed to increase the temperature at constant pressure is greater than that at constant volume. In the first case, however, there is some motion and in the second, there is none. Mayer takes the difference between these quantities of heat as equal to the motion observed (Mayer 1842, p. 240, 1845, pp. 14–15). Formally written

$$C_p - C_v = W \cdot h \qquad (5)$$

where C_p and C_v stand for specific heats, at constant pressure and volume, W for the weight of the column of air on the recipient and h, for the height covered due to the dilation of the gas. According to the values known at that time, Mayer calculated the mechanical equivalent of heat (Mayer 1842, p. 240, 1845, pp. 14–15). Let us concentrate on each element of Eq. (5).

On the left hand side, we have *heat* and on the right-hand side, *motion* (this way of expression is used here for the sake of simplicity). How did Mayer justify this equation with heat and motion from an *ontological* point of view, i.e., before he justifies it within his own theory? Mayer had proved previously that a cause-effect relationship between heat and motion exists (Mayer 1842, p. 237–239). This proof consists of experiments or phenomena in which motion is performed and only heat appears or vice versa, heat is supplied and only some motion comes out. The experiment considered above (Fig. 2) exemplifies this. The heat $(C_p - C_v)$ is the cause of the resulting motion $(W{\cdot}h)$. Making recourse to the classical saying 'cause = effect', Mayer justifies the equality of these magnitudes, therefore, Eq. (5).

Let us consider the *theoretical* point of view. Within Mayer's theory, there are five kinds of force. Heat and motion are two of them (Mayer 1845, p. 33). Thus, from the theoretical point of view, Eq. (5) is read as

$$force{-}heat = force{-}motion.$$

The sign '=' is now justified by the indestructibility of force. This property of force means that its quantity is kept constant. Hence, the quantity of force at the beginning (quantity of heat) must be equal to the quantity that exists at the end of the process (quantity of motion). The fact that heat differs from motion and the equation takes both together is justified by another property: force is transformable. Thus, the force 'heat' is transformed into the force 'motion'.

2.3 Joule

In 1843, Joule determined the mechanical equivalent of heat by means of a magneto-electric machine. The core of this machine consists of an electromagnet that rotates in the proximity of a much larger electromagnet. This rotation produces an electric current, which, in turn, produces heat. This heat was measured by Joule. The rotation of the electromagnet is performed through falling bodies. Thus, Joule was also able to measure the mechanical power used in the rotation (1884 [1843], p. 149). He then connected the mechanical and thermal magnitudes as follows:

$$\left(W_{mag-ele} - W_{mech}\right) \cdot h = C \tag{6}$$

where $W_{mag\text{-}ele}$ represents the weights used to move the magneto-electric machine, W_{mech} the weights needed to produce the same motion when the machine works only mechanically, h, the distance covered by these weights and C, the heat developed (1884 [1843], p. 151).

From the *ontological* point of view, this equation is justified by experiments. Joule had proved that the magneto-electric machine allows the increase (or decrease) of the quantity of heat. Therefore, heat could not be a substance. According to the disjunction 'either substance or motion' (Sect. 2.1.2), heat must then be motion. If heat is motion, it makes sense to calculate the mechanical equivalent of a thermal unit, for which Eq. (6) was used. In sum, Joule took heat from the side of substance onto the side of motion due to experiments (1884 [1843], Part I).

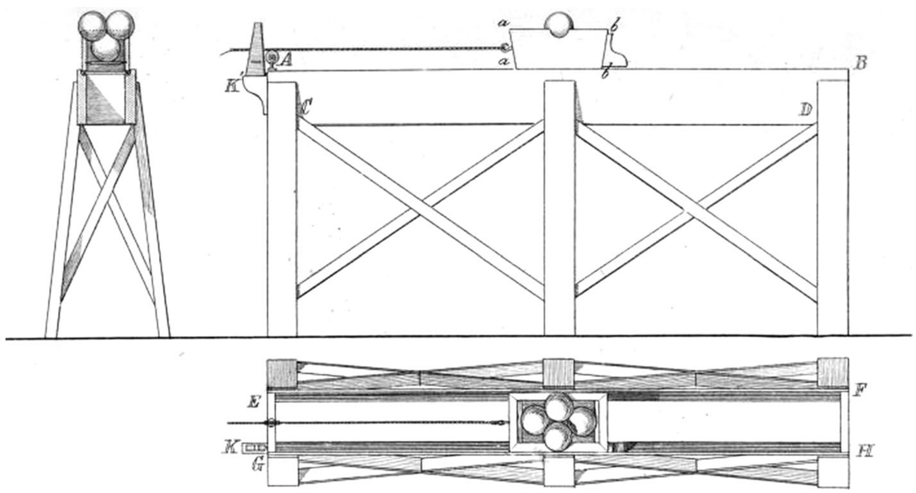

Fig. 3 From Colding's paper (1856)

From the *theoretical* point of view, within Joule's theory, Eq. (6) is read as[16]

$$\textit{motion-falling bodies} = \textit{motion-heat}.$$

The thesis 'heat is motion' renders homogeneous what is diverse by observation, motion and heat. Joule explained then that motion gives heat by conversion, i.e., visible motion is converted into another kind of motion, heat. He presumed that heat was a state of vibration (Joule 1884 [1843], p. 123).

2.4 Colding

In 1843, Colding carried out friction experiments with solids. Figure 3 gives us an image of his apparatus from the front, from the side and from the top.

The apparatus is made up of two parallel bars, made of tin, of about two meters long. On these, a small sledge slides. The sledge carries balls, whereby its weight varies. The distance covered by the sliding is the same in all experiments and the course is run twice. According to the author, the speed of the sledge is more or less the same in all experiments. The dilation of the bars and of the runners on the base of the sledge indicates the heat produced (1972, p. 3).

Colding carried out 10 series of experiments. In each of the series, the moving force to pull the sledge and the heat produced are measured (1972, p. 6–11). In the third series, 56 measurements were made and the average values of force and of the heat developed were calculated. The final result was of 11 pounds for force and 0.72° for heat. Taking the ratio between all values measured and those of the third series, Colding obtains the following sequence of results[17]:

[16] Equations of this form support the calculation of the mechanical equivalent of heat (see Joule 1884 [1843, 1845], 1850).

[17] Beyond these results, there are three more that the author does not consider capable of being valuable (Colding 1972, p. 12).

Moving force	1	1.24	1.68	1.74	1.77	1.79	2.75
Developed heat	1	1.20	1.66	1.80	1.76	1.83	2.77

Colding concludes that the amount of heat developed in all cases is proportional to the loss of moving force. (He did not calculate the mechanical equivalent of heat.)

From the *ontological* point of view, Colding's research is based on the idea that forces of nature are imperishable. This idea was taken as a law of nature and formalised as follows. Assuming that a given moving force $\boldsymbol{q}$ has a totally lost effect, the new action, in which the force is manifested, is also equal to $\boldsymbol{q}$. Colding adds that the moving force produces, in general, an amount of heat. Therefore,

$$moving\,force = heat\,produced.$$

According to that point of view, we have a force of nature on each side of this equation. The phenomenological diversity of the sides of the equation, heat and motion, is justified by transformation: motion is transformed into heat (Colding 1972, pp. 1–2).

2.5 Helmholtz

In 1847, Helmholtz published the book *On the Conservation of Force*. Force is conserved because there are only two ultimate forces in nature and if one increases, the other decreases in the same proportion. These forces are the 'living force' and 'force of tension', which are justified in a *philosophical* way.

The task of the theoretical part of science consists of the search for the ultimate causes of phenomena, according to Helmholtz (1882 [1847], p. 13). In science, he continues, objects of the external world are considered according to a double abstraction: matter and force. Matter, as such, does not have any effect on our senses; the effects that external objects have on us are forces. Thus, it is based on force that we infer the existence of matter (1882, p. 14). According to this meaning of force, immutable forces are those that reach the sensory organs in an invariable way through time, which, in turn, reflect what is permanent in matter. Thus, Helmholtz takes 'immutable forces' as a synonym of 'indestructible qualities of matter'. These qualities are the chemical elements (1882, p. 15).

If we think of the world, Helmholtz continues, as constituted by these chemical elements, any change in it can only come from motion. Hence, the task of science should be to trace phenomena back to motions of matter, where the moving forces can only depend on spatial relationships (1882, p. 15). The next step concerns the determination of this dependency. The intensity of force depends on the distance between any two bodies and its direction is the direction of the line that connects these bodies. Thus, Helmholtz reaches the final determination of the task of the theoretical part of science: the tracing back of phenomena to immutable forces of attraction or repulsion (1882, p. 16).

Once this task is established, Helmholtz makes recourse to an assumption that, according to him, Carnot and Clapeyron had used successfully: it is impossible to obtain a durable force out of nothing. This proposition was transformed into a principle. It was assumed by Helmholtz that a moving force and its resulting motion are *equivalent* (1882, p. 17). The mathematical expression for this is based on the law of conservation of living force. This equation states

$$\frac{1}{2}mv^2 = mgh. \tag{4}$$

From the *theoretical* point of view (Helmholtz 1882, p. 18), this equation is read

$$living\,force = force\ of\ tension.$$

This relationship is then generalized for every central force and the principle of the conservation of force formulated 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.

In the case of phenomena involving heat and motion, Helmholtz establishes a connection between loss of mechanical force and heat appeared. This is justified by Joule's experiments (1843 and 1845). He criticized the lack of precision of these experiments but accepted the equivalence between heat and motion (1882, p. 33). In order to explain how heat can generate work, he states that if we accept that heat is matter, the production of work would have origin in the expansion of the substance. He shows then 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. Hence, Helmholtz defends that heat is a kind of motion. In his theory, an amount of heat is understood as the sum of the living forces of the atoms and the forces of tension between them. The heat connected with living forces would correspond to the so called 'free heat' and the heat connected with forces of tension, to the so called 'latent heat'. From the motion of atoms, an idea is given but it is presented as a mere hypothesis (1882, p. 35). According to Helmholtz, it is enough that the phenomena of heat can be thought of in terms of motion (1882, p. 36).[18]

3 Two Approaches Under the Same Concept

Mayer's approach may be called phenomenological, since it is based on observables. Beyond the experiment presented above, others can be used to illustrate his kind of approach. He agitated water in a glass tube vehemently and the temperature increased (Mayer 1842, p. 238). He explains this on the basis of what is observed: motion is performed and the water temperature increased, therefore, motion causes heat. The electrophorus, which illustrates the relationship electricity-motion, is dealt with in the same way (Mayer 1845, pp. 23–24, Coelho 2009, 964–965). Even physiological or biological phenomena are dealt with in the same way. For example, since soldiers at the barracks need less food than agricultural workers in the field and prisoners need still less food than soldiers, Mayer concludes that the need for food depends on the efforts made (Mayer 1845, p. 52). What we eat and the air we breathe are used, he says, to maintain our body temperature and for our movements. In all these explanations, Mayer uses what is observable. This contrasts with Joule's approach.

Joule claimed that heat is motion but this motion is not observable. This kind of approach may be called mechanistic. It was developed by Helmholtz. The idea that force of tension correspond to latent heat and living force to sensible heat is a mechanical conjecture. The same holds, for example, to his treatment of electric circuits (Helmholtz 1882, pp. 57–58, 61–62). Based on the mechanistic concept of heat, Thomson developed a concept that will be used for both the phenomenological and the mechanistic approach.

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

In 1851, Thomson adhered to the dynamical theory of heat (1851a). According to this theory, heat is not substance but rather motion. As heat is a kind of motion and can produce motion, he searched for a way of calculating the capacity of a body of doing work. The quantity of mechanical activity that a body is able to produce was called *mechanical energy* (Thomson 1851b, p. 475). This 'mechanical energy' has nothing to do with 'form of energy'. Mayer, however, was associated with this theory of energy in the following way. Thomson (1851a) presents Davy as the founder of the dynamical theory of heat due to his experiment of melting two pieces of ice by rubbing them together (Thomson 1851a, p. 261). He further claimed that Mayer's and Joule's friction experiments would be enough to prove Davy's point of view. Indeed, a dynamical theory of heat is conforming to Joule's point of view but not to Mayer's, who had pointed out that he did not defend that heat is motion (Mayer 1842, p. 239, 1851, pp. 42–43). A few years later, the phenomenological approach was firmly connected with 'energy' by Rankine.

In 1855, Rankine published the paper "Outlines of the Science of Energetics". The first part of the paper concerns philosophy of science (Rankine 1855, p. 381–385). Here he distinguishes two methods of framing a physical theory: the abstractive and the hypothetical (which are linkable with the two approaches mentioned above). According to the abstractive method, a class of objects or phenomena is defined by properties perceived by the senses. This method is illustrated by the science of mechanics, which was seen as the only example of a complete physical theory. According to the hypothetical method, a class of objects or phenomena is defined according to a conjectural conception of their nature. The mechanical theory of heat illustrates this method. The science of energetics developed by Rankine uses the abstractive method (Rankine 1855, p. 386). Later on, both approaches were used conjointly.

Maxwell's *Theory of Heat* is an example of a textbook in which both approaches, the phenomenological and the mechanistic, appear. He says, for instance, that heat does not seem to be a substance but rather a form of energy (Maxwell 1873, p. 93). This is directly connectable with Mayer, as well as what follows, "the energy takes the forms of heat, magnetisation, electrification, &c." (Maxwell 1873, p. 92). Kinetic and potential energy are also presented as the forms of energy, which is related with the mechanical origin of the concept of energy. Still in accordance with this view, Maxwell states: "the energy of a body may be defined as the capacity which it has of doing work" (Maxwell 1873, p. 90).

This last definition of energy was criticized by Lodge (1879). He argues that the capacity of a body of doing work depends on other bodies. To avoid this dependency, he proposed to measure energy by means of the work done by one body *on* another body (Lodge 1879, p. 279). This led to the idea that energy exists in bodies and is transferred from one to another. In the cases, in which the bodies involved in the transference of energy are not connected with each other, Lodge makes recourse to the ether, through which energy could move (Lodge 1885, p. 484). In the 1893 paper, he defends anew that energy is a real existing thing moving through space (Lodge 1893, pp. 304–305).

The science of energetics received a new impulse from the German "*Energetiker*". In the 1895 meeting in Lübeck (Germany), Ostwald and Helm defended energetics enthusiastically (Hiebert 1971). There was some criticism of this, which reappeared in papers the following year.[19] Nevertheless, energetics developed. In 1908, Ostwald published the book *Energy* (*Energie*), in which Mayer's 1842 paper is reproduced. Mayer's systematization of force in 5 forms, from the 1845 book, is presented in its original type. Despite this great interest in Mayer's theory, there are significant differences between both Mayer and

[19] Boltzmann (1896a, b), Planck (1896), see also Ostwald (1896) and Helm (1896).

Ostwald. Whereas for Mayer force and matter are opposed (Sect. 2.1.2), Ostwald's energy subsumes matter (Ostwald 1912, p. 60). For example, the traditional distinction between matter and spirit is overcome by energy, since, according to Ostwald, energy is able to account for phenomena that had been ascribed either to matter or to spirit (Ostwald 1912, p. 144). To play the role of matter, energy must be something real. Indeed, Ostwald, who became Chemistry Nobel Laureate in 1909, claimed that energy is what is really real (Ostwald 1912, p. 5). Let us move on now to the questions posed in the introduction.

4 Answer to the Questions

The **first** of the questions posed in the introduction is where the very common definition of energy—*energy cannot be created or destroyed but only transformed*—comes from. This way of presenting energy has its origin in Mayer's characterisation of force, who said force is indestructible and transformable. If we substitute force by energy, then energy is 'indestructible' and 'transformable'. This appears in the current definition 'energy cannot be destroyed' and 'energy can only be transformed'.

The third property of Mayer's force 'imponderability', unlike the others, has disappeared. This property clearly distinguished force from matter, since matter has weight. Hence, Mayer's force could not be a substance. Ostwald's energy concept changed this completely (Sect. 3). Such an alteration influences the meaning of the other properties of Mayer's force.

The property of indestructibility was ascribed to force by Mayer only to express that the quantity of force is kept constant (Sect. 2.2). Transformability is the property ascribed to force to justify the phenomenological diversity of, for instance, heat and motion but it has no ontological meaning, as Mayer highlighted several times (for example, Mayer 1845, p. 10, 1851, p. 43). All this differs from the energy concept conveyed by the very common definition of energy. In other words, the original meaning of indestructibility and transformability do not support the meaning of these terms in the current definition of energy. The original 'force' was in no way a substance. The most common presentation of energy in textbooks leads us to think of energy as something real.

The **second** question to address here concerns the common definition of energy in textbooks *energy is the capacity of doing work*. This definition has its origin in Thomson's mechanistic theory of heat. From this, emerged the definition "energy is the capacity of a body of doing work". Between this and that common definition of energy, there is a significant difference because in one, a body is the subject of the sentence whereas in the other, energy is. In this latter case, energy must be something real, since non-real things cannot do any work. Thus, the mechanical activity (energy) of a body has become a substance. Thomson, who introduced this concept, could not accept this hypostatising of energy (Smith 1998, p. 298).

The **third** question asked in the introduction concerns 'transference of energy'. This idea has its origin in the definition of energy proposed by Lodge. Instead of defining energy by the capacity of doing work, he proposed to define it by the work actually done on a body. As the quantity of energy is constant, the quantity that appears in a body must stem from other bodies. This idea is adequately expressed by 'transference of energy'. This idea of transference acquired a strong ontological meaning due to Poynting's paper (1884) on the transfer of energy in the electromagnetic field. Mathematical tools used by Poynting were interpreted by Lodge (1885) as they had a physical meaning. He claimed then that trajectories of energy in space can be followed (Lodge 1885, pp. 482–483). The ideas of 'energy in a body' and 'energy in motion' reappeared, for instance, in Westphal's distinction between 'work stored' and 'work' (Westphal 1970, p. 38–39, see also Çengel and Boles 2002, p. 127).

The concepts of kinetic and potential energy agree, in a different ways, with the mechanistic approach and the phenomenological. These concepts have their origin in Thomson's distinction between static and dynamical energy (Thomson 1852, p. 139). Rankine (1853) replaced Thomson's double (static-dynamical) by 'potential-actual'. This last double subsumes a relationship between both terms potential and actual energy (Rankine 1853, p. 106). It accounts, for example, for the relationship between Helmholtz's force of tension and living force. The substitution of 'actual' by 'kinetic' was only terminological (Thomson 1884, vol. II, p. 34). Kinetic and potential energy are also connectable with the phenomenological approach. Mayer's forces of falling and motion, for instance, correspond to potential and kinetic energy respectively. (The details of this correspondence are out of place here.)

5 Conclusion

The thesis 'the quantity of heat is constant' held in the theory of heat of the first half of the nineteenth century (Sect. 2.1.2). Mayer's and Joule's theses concerning the mechanical equivalent of heat (Eqs. 5, 6) require that the quantity of heat is not constant. According to these, heat varies with the mechanical effect. There were, therefore, two opposite theses in the 1840s:

1. The quantity of heat is conserved
2. The quantity of heat varies with the mechanical effect.

The question of whether the first, the second or neither of these theses holds can be answered by laboratorial means (conditions are out of place here).

The theoretical expression of thesis 1 was 'heat is a substance'. Scientists said this because the meaning of being a substance was that its quantity does not vary and they believed that the quantity of heat is constant. The theoretical expressions of thesis 2 were: 'heat is a force' (Mayer) and 'heat is motion' (Joule). These are two ways of taking heat from the side of substance, as we have seen (Sects. 2.2, 2.3). All these sentences

1.1 heat is a substance
2.1 heat is a force
2.2 heat is motion

taken by themselves are no longer laboratorial issues.

We can, therefore, distinguish between testable propositions—theses 1 and 2—and theoretical expressions of them in a certain conceptual framework—propositions 1.1, 2.1, 2.2. According to this distinction, Mayer's force belongs to this second level, the level of expression. This 'force' was replaced by 'energy'. The terms 'indestructibility' and 'transformability', which characterize force, reappear in the characterisation of energy. Playing the role of Mayer's force, energy, consequently, belongs to this second level.[20] Thus, 'energy can neither be created nor destroyed but only transformed' is not a statement

[20] It is true that the meaning of energy has changed and energy has become a substance, which Mayer's force was not, but this alteration was not a consequence of a discovery of a substance with those properties. If it were, energy would belong to the primary level.

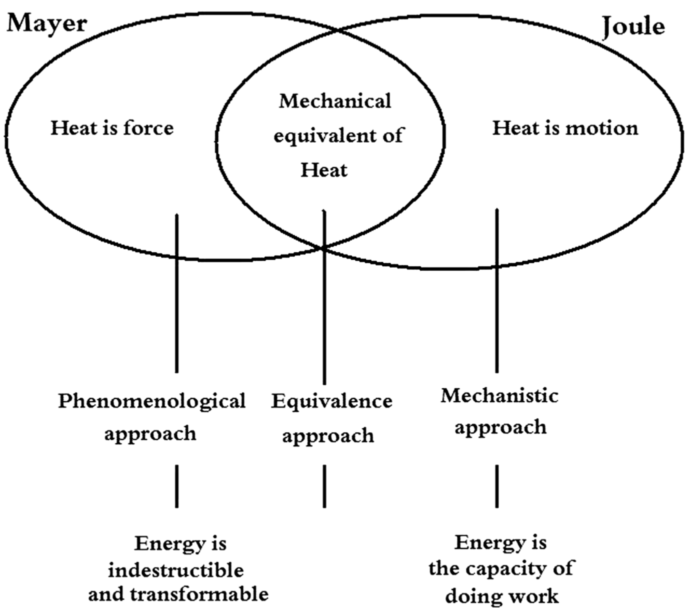

Fig. 4 Schema of the three approaches

of primary level (theses 1 and 2). Therefore, it cannot be a laboratorial issue by itself. This explains why Bergmann and Schaefer (1998) said that a physicist is in the same situation as a layman concerning the question of what energy is (Sect. 1). Indeed, this is not a question for a physicist as such. On the contrary, the question of whether *1 cal = 4.185 J* is an experimental issue. This is a question of primary level. In fact, the mechanical equivalent of heat is the statement of primary level which corresponds to the proposition of secondary level 'energy is conserved and transformed'.

What has just been said about Mayer's force could be said *mutatis mutandis* about the thesis 'heat is motion'. Joule did not try to show the motion he called heat. He did try to show by experiments that the quantity of heat can be increased or decreased, since this was sufficient to contradict thesis 1.

Beyond the phenomenological and the mechanistic approach, there was another one that focused on the mechanical equivalent of heat. Between the 1860s and the beginning of the twentieth century, some physicists understood energy in terms of equivalence. Instead of principle of conservation of energy, they used 'principle of equivalence' to refer to the experimental relationship between heat and motion. This was the case of Verdet (1868–1872, p. 38 *et seq.*), Poincaré (1892, p. 53 *et seq.*), Müller and Pouillet (1926, p. 109), Preston (1919, p. 667), among others (see also Mayer 1851, p. 41–43, Caneva 1993, p. 260). Although Einstein's relationship between mass and energy deserves special attention due to the amount of literature, it can be shown, even though briefly, that the original texts fit well with the equivalence concept. In his 1905 paper, "Does the inertia of a body depend upon its energy content?", Einstein defended that a variation of mass is proportional to a variation of energy. He further argued that this relationship could be verified experimentally by means of the radiation of salts of radium (Einstein 1989, p. 314). The weight of this substance at the beginning of radiation and at the end should be different. In 1907, Einstein expressed that same relationship in terms of "the equivalence of mass and energy" (1989, p. 425). He explained, 1909, "Mass and energy appear as so equivalent magnitudes as heat and mechanical effect" (1989, p. 572).

In fact, the mechanical equivalent of heat is the statement of primary level referred to by all three approaches (see Fig. 4). This can also be shown by the role of *conditio sine qua non* it plays: if the mechanical equivalent of heat had not held, there would be no principle of equivalence, no energy conservation and Joule would not have had support for his thesis. The advantage of the equivalence approach over the others is that this uses a simple way of expressing the primary level statement. The disadvantage of the others is that energy has been hypostatised. Its "thingness" has been misleading. Taken as a real thing, energy has become a primary level issue. This has led to the question of what energy really *is*. This question, in turn, has led to answers such as "we have no knowledge of what energy is" (Feynman 1966, 4–1), "we do not know what energy really is" (Bergmann and Schaefer 1998, p. 135), etc. We know now that this is not a well-posed question, i.e., it is rather an expression of the difficulty people feel with the concept of energy, which, in turn, is a consequence of an eclectic development of this concept.[21]

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[21] If the question is not well-posed, then there is no reason for keeping it. Hertz presented a similar solution for a similar question. Concerning the question of what force is, he wrote: "the answer which we want is not really an answer to this question. It is not by finding out more and fresh relations and connections that it can be answered; but by removing the contradictions existing between those already known, and thus perhaps by reducing their number. When these painful contradictions are removed, the question as to the nature of force will not have been answered; but our minds, no longer vexed, will cease to ask illegitimate questions" (Hertz 1899, p. 8).

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