Metaphysical Problems of Physics
Lecture 3
Maxwell's *Matter and Motion* III: Energy

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1 *Précis* of Themes

> What is remarkable… is not the reign of law, but the reign of *simple* laws. If the transfer of energy were subject to laws as complicated as those governing the transfer of English land, we should never succeed in discovering them…
>
> Bertrand Russell
> *The Analysis of Matter*

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1. energy as a physical quantity, all the different forms it comes in, in different types of systems, in different theories, all the different properties those different forms have, as basis/touchstone for examination of different views on quantity

2. exemplar of logical analysis of a (seemingly univocal) particular feature of the physical world, founded on and starting from the best scientific theories we have (and their development), showing what is required (the Kantian side) for such a class of theoretical entities to find such different representations and yet have something enough in common for us to want to say (the Newtonian side) that they all get at the same physical quantity, property, category, predicate, . . . , and what the physical world reveals to us about itself based on the patterns, regularities, generalizaions, we have been able to latch onto—one of the most fundamental tasks of philosophy of science and philosophy of physics, one of its aboriginal purposes

3. decisive illustration of the vacuity of the realism-antirealism debate: neither can do justice simultaneously to, on the one hand, the different forms of representation with different properties designating "the same physical quantity", and, on the other, the central role the quantity plays in fundamental physics (Hamiltonian in quantum field theory, stress-energy tensor in general relativity, energy in thermodynamics)—over and above the fundamental differences in "mathematical form" (vectorial, scalar, spinorial, *etc.*), there are differences in the role each plays in the respective theory (conserved or not, generator of dynamical evolution, conjugate to time, regulator of spacetime curvature, measure of irreversibility of processess); and yet there are profound similarities (measure of capacity to do work); and the concept, in its respective idiosyncratic form, plays a central role in each framework, in its respective idiosyncratic way—and yet it is central

2 Types and Forms of Energy, Conservation

2.1 Types and Forms

Maxwell

1. "WORK is the act of producing a change of configuration in a system in opposition to a force which resists that change." (§72)

2. energy is "capacity of doing work" (§72)

3. so far as we know, it is conserved (§§73–74)

4. it comes in two types: potential and kinetic; these can be defined in complete abstraction from the kind of system in which they are manifested

5. it can take many forms (impulsive, percussive, elastic, viscöelastic, thermal, oscillatory, electromagnetic, chemical, gravitational, . . .); the definitions of these depend on the kind of system they accrue to (§97)

6. it is the only quantity known to accrue to *all* kinds of systems across all fields of physics (§§73, 112)

Contemporary Physics

1. There are (at least) two different fundamental characterizations (types) of energy in contemporary physics: the generator of time-translations; and the capacity to do work. Since work depends only on spatial translation, the latter makes not even an implicit reference to time.

2. "generator of time-translations": in Hamiltonian mechanics, the most remarkable state of affairs obtains—a single scalar quantity, the Hamiltonian, representing the total energy of a system, determines the entirety of that system's dynamical evolution; it "generates time-translation";[1] one cannot define work done by or on the system

3. "capacity to do work": fundamentally the same as in Maxwell's definition, but now definable only in Lagrangian mechanics, not in Hamiltonian mechanics, where, once again, the entirety of the dynamical evolution is determined by a single scalar quantity (the Lagrangian), but now that scalar has no direct physical significance, in the sense that it cannot be measured, seems to represent no physical quantity accruing to the system, but it does allow one to define work done by and on the system, but energy has no direct role in "generating the time-translations" of the system[2]

4. there is a third, heat, that does not really fit into this classificatory scheme:

   a. it is not the generator of time-translations, if for no other reason than that in classical thermodynamics there is no dynamical evolution

   b. it is not the capacity to do work (though it is related to it), because (modulo some technical conditions) one cannot transform all the heat of a body into work (that is a general statement of the Second Law of thermodynamics)—there is always "residual heat" that cannot be transformed into work, that has no capacity to do work

   c. and yet it is intimately related to work, as, in classical thermodynamics, *transfers* of heat are most usefull defined as that part of energy exchange in systems that does not take the form of work

1. This is the modern conception of Maxwell's claim (§73):

> When once apprehended it [the principle of the conservation of energy] furnishes to the physical inquirer a principle on which he may hang every known law relating to physical actions, and by which he may be put in the way to discover the relations of such actions in new branches of science.

The same, *mutatis mutandis*, holds for Lagrangian mechanics, discussed immediately below. This is clarified in §86:

> A complete knowledge of the mode in which the energy of a material system varies when the configuration and motion of the system are made to vary is mathematically equivalent to a knowledge of all the dynamical properties of the system.

2. See Curiel (2014) for a thorough discussion of the differences between Lagrangian and Hamiltonian mechanics.

5. kinetic vs. potential does not seem physically substantive distinction in this sense: there seem to be no interactions that couple only to (depend only on) potential or only to kinetic energy, and not to total energy

Conservation

1. Without too much historical inaccuracy, one can say that energy conservation was elevated to the status of a general law in the 1840s by Helmholtz, Joule and Julius Mayer, and first enunciated with complete generality by Clausius and Rankine around 1850. Before that, discussion of energetic quantities and their total conservation was indeed restricted to particular mechanical contexts, and it was not an idea that received much sustained attention or was thought to have much deep physical significance.

2. Maxwell (1877, §73): conservation of energy cannot be "deduced" from phenomena (as some force laws can, as sketched in Maxwell 1876, and discussed in great detail in Curiel 2020); as a "science-producing" doctrine, however, it is enormously fruitful,[3] and the more successful applications of it we make, the more credibility it has

3. Maxwell (1877, §107):

   > All that we know about matter relates to the series of phenomena in which energy is transferred from one portion of matter to another, till in some part of the series our bodies are affected, and we become conscious of a sensation. . . . ¶ Energy, on the other hand, we know only as that which in all natural phenomena is continually passing from one portion of matter to another.

   follow with passages from §§108–110, *ff.*

4. Feynman (1965, pp. 68–9):

   > Of all the conservation laws, that dealing with energy is the most difficult and abstract, and yet the most useful. . . . ¶ The conservation of energy is a little more difficult [than, *e.g.*, conservation of charge], because this time we have a number which is not changed in time, but this number does not represent any particular thing.

   Then Feynman gives the lovely metaphor of the mother trying to find blocks hidden by the children; the difference is that, with energy, one never sees any "blocks" (p. 70):

3. Maxwell (1875):

> [W]e must bear in mind that the scientific or science-producing value of the efforts made to answer these old standing questions is not to be measured by the prospect they afford us of ultimately obtaining a solution, but by their effect in stimulating men to a thorough investigation of nature. To propose a scientific question presupposes scientific knowledge, and the questions which exercise men's minds in the present state of science may very likely be such that a little more knowledge would shew us that no answer is possible. The scientific value of the question, How do bodies act on one another at a distance? is to be found in the stimulus it has given to investigations into the properties of the intervening medium.

> What we have discovered about energy is that we have a scheme with a sequence of rules. From each different set of rules we can calculate a number for each different kind of energy. When we add up all the numbers together, from all the different forms of energy, it always gives the same total. But as far as we know there are no real units, no little ball-bearings. It is abstract, purely mathematical, that there is a number such that whenever you calculate it it does not change. I cannot interpret it any better than that.

3 Mathematical Classification of Quantities

1. Maxwell (1869, p. 260):

> The division of the energy into vector factors affords results always capable of satisfactory interpretation. Of the two factors, one is conceived as a tendency towards a certain change, and the other as that change itself.
>
> Thus the elementary definition of Work regards it as the product of a force into the distance through which its point of application moves, resolved in the direction of the force. . . .
>
> Thus, instead of dividing kinetic energy into the factors "mass" and "square of velocity," the latter of which has no meaning, we may divide it into "momentum" and "velocity"...

4 Invitation to a Short Essay

I invite you to write me a short discussion (no more than 2 pages, *i.e.*, no more than 1000 words) on any issue discussed in any of this week's three readings. You can raise further questions, propose answers or interpretations, or whatever seems of most interest to you. If you get it to me by the start of next lecture (24. May), then I will return it to you with my comments the following week.

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