On the cross-fertilization of the foundations of thermodynamics, quantum mechanics and relativity theory

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ON THE CROSS-FERTILIZATION OF THE FOUNDATIONS OF THERMODYNAMICS, QUANTUM MECHANICS AND RELATIVITY THEORY

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ABSTRACT

Thermodynamics proposes very general principles; the question then arises as to its links with the other major fields of physics that are the theory of relativity and quantum mechanics. Is it upstream? Can it be derived from them? Our conviction is that the concepts of physics, including space and time, are a way of naming comparisons between phenomena, within a relational approach. Each field of physics results from a particular *perspective* on reality, and does not reflect the particular *functioning*, on its own, of a limited segment of that reality. The question then is *not* to try to link supposedly achieved mathematical corpuses corresponding to each of these fields, but, by returning to the study of "raw" phenomena, to find, within the different fields, the qualities still hidden and already perceived in the others. In this spirit, we will discuss several concepts (each one is brought rather by one field) such as: time, space, movement, locality / non-locality, conservation / evolution, reversibility / irreversibility, scale, quantization (discretization), probability, opening / closing of systems, qualification of physical quantities by quadrivectors, Lorentz invariance, etc. We will show the cross contributions between thermodynamics, quantum mechanics and relativity theory, leading to a shift in concepts, and suggesting new avenues of research at the crossroads of the three fields. On this occasion, we will take a look at other ways of understanding thermodynamics by other authors (Bejan, Ben-Naim, Mariano, Muschik).

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1. INTRODUCTION

My goal here is not to consolidate the foundations of thermodynamics. As a physicist, my first wish is to develop the knowledge of the phenomena offered by nature. Thermodynamics, but also major theories such as quantum mechanics or the theory of relativity, each bring some insights. But these theories are constantly being reworked and their relationships evolve. None of them is a complete whole, none an isolated system. Also, it does not seem useful to me to look at thermodynamics for itself. It must be considered in all its relations with the rest. This allows us to better understand the different ways that authors have to grasp it.

In a first part (Section 2), I will present how I see the construction of knowledge in a very general way. Then, I will discuss (Section 3) the historical foundations of thermodynamics. Then (Section 4), I will present the remarks I make to myself about thermodynamics in terms of my understanding of space and time, as sketched in Section 2, and the possible ways of evolution. I will then present (Section 5) a few lines on the crossed relations between thermodynamics, relativity theory and quantum mechanics, another way to understand and anticipate the progress of these disciplines. Finally (Section 6) I will evoke the works of some authors who have a different vision of thermodynamics and I will comment on their contribution, to be seen in a wider thermodynamics.

2. THE BUILDING OF KNOWLEDGE

The knowledge we build is relational in nature, that of an observer who cannot extract himself from the world to look at it from the outside; inside the world, he can only compare phenomena with each other. This game of comparisons is based on an objective knowledge without words, that roots the concepts in the body. From there, words, concepts, laws, equations, are fashioned, which can differ according to the points of view from which one looks at reality. So are the concepts: space, time, movement, locality, synchronicity, conservation / evolution, energy, reversibility / irreversibility, continuity / discontinuity (quantification), opening / closing, etc. Space and time do not exist in themselves, these are the names of the comparison of phenomena. In this idea, I am led to give to "movement" (elementary way of speaking about phenomena) a first place, before space and time [11]. These are defined in opposition the one to the other, by comparisons of movements (to space the stopped, or invisible, movements, to time the continued, or visible, movements). Movement shown, lived, precedes space and time of the words. But the relational point of view is unstable and leads to endless regressions: when have we exhausted the terms to be compared to each other? Which standard should we choose for our measurements? To be sure of its constancy, do we need another standard? In this situation, we are led to stop the quest in a provisional way and to attribute, by decree, constant characteristics to a specially chosen phenomenon. This is the paradoxical status of the standards: they receive what looks like a substantial content within our relational approach (cf. the c = cte of the theory of relativity). The affirmation of the existence of a piece of space, that is to say of a constancy, of a conservation, is inseparable from the affirmation of a constant motion, that is to say of a standard evolution (which will allow to evaluate by comparison the other evolutions). Conservation and evolution are the other name of the relation, here we are at the foundations of thermodynamics.

3. HISTORICAL FOUNDATIONS OF THERMODYNAMICS

Historically, thermodynamics was interested in phenomena on the macroscopic scale of vapor reservoirs. Then, with the discovery of material corpuscles, it took on the task of linking the laws written at the microscopic scale (in terms of positions, velocities, masses, using Newton's laws) and those written at the macroscopic scale such as Fourier's laws, Fick's laws, etc. (with new variables, temperature, pressure, concentrations). Very generally, I understand thermodynamics as the science of transition between several scales, i.e. the linking of various levels of description of reality.

The way to make this transition is to freeze the microscopic behavior in its most probable state and to take the quantities of this level thus averaged to evaluate what happens at the macroscopic scale. The notion of entropy appears naturally; it characterizes and measures the deviation from the most probable state, i.e. from homogeneity (we will speak of a uniform distribution in terms of probabilities), at the lower scale.

The evolution of the system, under the effect of perturbations that may come from the outside, makes it move towards its most probable state; in other words, not only do we envisage a function realizing a maximum of probability (the entropy S) but we declare that the system left to itself will effectively move towards the corresponding state (via the "entropy production", which will itself be able to satisfy a principle of economy). The writing of the conservation of energy linking the different levels makes the internal energy appear, another fundamental quantity of thermodynamics.

The second principle has a statistical value and can be violated for more or less long periods and sizes of systems. When we go from Newton's laws (microscopic scale) to Fick's law (diffusion of matter on a macroscopic scale), we can forget about the paths which, on a microscopic scale, could be made by going up the gradients; they are improbable (with a low probability) compared to those made in the direction of the gradients. The second principle allows us to make this choice, but, once acquired, it can be forgotten; it remains hidden in the writing of Fick's law and the positivity of the diffusion coefficient D which intervenes there.

4. CONSEQUENCES AND WAYS OF RESEARCH

Some consequences of the relational space / time picture (Section 2) bear on the conceptual understanding of thermodynamics in general. The following statements, reconsidered in the new picture, will be examined briefly [10]: - there is no ultimate parting between equilibrium and non-equilibrium, heat and work, kinetics and (diffusion) transport, this is a matter of scale; - the concept of entropy, the attribution of an entropy to an individual particle, the interior and the exterior of a system and its boundary, the definition of the quantities proper to thermodynamics such as internal energy, heat etc., all derive from the understanding of the necessary link between the different scale levels at which to examine the system; -entropy may be defined whatever there is equilibrium or not; - the constant association of the temporal variations and the spatial gradients ("space arrows" [9]), of a fundamental nature, opens up to the conceptual unification of the two expressions of the second law, i.e. the phenomenological and the statistical ones. In total, it is possible to envisage a hierarchy of thermodynamics, moving from one scale level to another. We can define thermodynamics generically, or on the contrary define several, according to the variables and physical quantities defined.

By getting more into the equations, avenues for research are derived from our point of view. The quantities must go in pairs of the type (f, g) like the pair (electric field, magnetic field) in electromagnetism, the pair (energy, momentum) in mechanics, the pair (concentration, flux) in thermodynamics etc., and verify laws expressing correlated variations with respect to time and space variables (within a relation-based thinking; these variations are the only thing we can know, not the single quantities themselves). For entropy S, we are invited to propose a pair (S, F), not S alone, which can be interpreted as a couple (entropy, entropy flux) or (probability of state, probability of trajectory). The previous equations are Lorentz invariant, which allows a better connection with relativity theory.

5. CROSS VIEWS ON THERMODYNAMICS, QUANTUM MECHANICS AND RELATIVITY

Relations between thermodynamics and relativity. The reflection on the trilogy space / time / movement leads us to see in the theory of relativity the archetype of a relational and non-local theory (time is built from the position of a distant moving point, a photon; a position also links the considered point to a distant origin); the theory promotes the use of pairs of quantities in quadrivectors (opening to the writing of Lorentz invariance; see also [13]), it underlines the hidden conventions in the choice of a standard. All these aspects irrigate thermodynamics and suggest directions of evolution: thus we have spoken of the definition of the pair (S, F) or (entropy, entropy flow). But, reciprocally, thermodynamics is already present in the theory of relativity, seeing an entropy in the coordinate axes that this theory manipulates. A ruler, allowing to measure lengths, is constructed by marking regular graduations delimiting segments of supposedly equal sizes. The space (and time) standards are derived from the movement standard, supported by the assumption of constancy of the "speed" of light. The increments i of the ruler correspond to pieces of space traveled during equal times to the speed of the standard motion. Giving them the same weight is another way of talking about the constancy of the speed of light. We can consider the size of the different increments i of the spatial axis as values X(i) of a discrete random variable X of probabilities p_i; to say that they all have the same value is to proclaim the uniformity of the variable. Another way is to require the maximum of the associated entropy $\Sigma p_i \ln p_i$.

Relations between thermodynamics and quantum mechanics. Quantum mechanics concludes that there are no closed systems: there is always an influence of an environment. "One of the basic ideas is that there is no thermodynamic system without an environment and that both subsystems have to be treated quantum mechanically. Even for a thermally closed system the existence of an environment and the interaction with it is indispensable" [8]. This is a new incentive to write the pair (S, F) within conservation laws including fluxes, even for closed systems; the precision of the closure is limited by the indeterminacy of the space and time variables, based on the phenomena. Conversely, one can understand thermodynamics and the second law as having a hidden role in the management of quantization/discretization phenomena, provided that one can understand the representation of these phenomena in space. Probabilities can be defined by the spreading in space of the values of the physical quantities, with respect to the whole spatial amplitude occupied by the other values; a (quantum) jump is understood as the improbability of intermediate values. Writing the equations in the sense of distributions requires adding entropy conditions to keep a physical meaning to the solutions. The spreading of the wave packet in the Schrödinger equation is for some authors the mark of an irreversible behavior.

Relativity theory and quantum mechanics. Relativity encourages quantum mechanics to treat physical quantities in pairs such as (ψ, φ), which can be interpreted as (wave function, wave function flux), each of the quantities having a three-dimensional vector value: these characteristics are fulfilled in the case of the Lorentz invariant Dirac equation. The non-locality of relativity must be extended to that of quantum mechanics: one can see in the uncertainty relations a link between the two theories, each one arriving at it by its own way.

6. OTHER WAYS TO PRESENT AND UNDERSTAND THERMODYAMICS

Many authors have asked questions about the foundations of thermodynamics. We are especially interested here in four of them: Adrian Bejan, Arieh Ben-Naim, Paolo Maria Mariano, and Wolfgand Muschik. The questions raised are numerous and important, and I do not pretend to understand them in detail, nor, more generally, to know all the areas of thermodynamics and physics to which they are related. These questions include the link between the second law and the understanding of time's arrow (Ben-Naim [4, 5]), whether one can define entropy for a non-equilibrium system (Muschik [12], see also [6]), the link between mechanics, statistical physics and thermodynamics (Mariano [7]), the place of finite-time thermodynamics and its own principles in relation to the whole of thermodynamics (Bejan, in particular with respect to the "constructal" theory and the optimization of fluxes [2, 3], see also [1]), the place of information theory (Ben-Naim). None of these approaches questions the existence of time, which is admitted from the beginning. Without at all denying the efficiency of such an option and the good functioning of the equations, which has a meaning by itself, I will ask whether we can see these different questions in another perspective by discussing the existence of time; by seeing its strong coupling with the question of space and movement; in the background, there is the fragility of all knowledge and the necessity of always posing arbitrary conventions, i.e. subject to free will, in order to stop endless regressions. Conversely, we will be able to ask how the approaches of the quoted authors bring nuances on the functioning of the concepts of space, time and movement in the foundations of thermodynamics and which directions of research we can propose.

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