What can a better coupling between space and time concepts bring to thermodynamics?

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Abstract

The present text is our communication to JETC conference in Budapest (Joint European Thermodynamics conference, May 21-25, 2017). It discusses some issues referring to the relations between space, time and thermodynamics. Thermodynamics has a close relationship with time, if only for the discussion of irreversibility. But the concept of time remains mysterious and misunderstood for many, including in physics. In our view, it is absurd to consider the question of time alone: time is an abstract concept not to be separated from the world by giving it a substantial value. To understand time is to understand how one abstracts it from the movements of material entities (including photons) in space. To tell it short, time and space are of the same substance, i.e. movement: they are constructed by comparing different movements, and an arbitrary (left to free will) choice is made to define the boundary between them, depending on scale. Some consequences of this approach bear on the conceptual understanding of thermodynamics in general. The following statements, reconsidered in the new picture, are examined briefly: - 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; - the constant association of the temporal variations and the spatial gradients ("space arrows"), 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. The link between thermodynamics and quantum mechanics is also discussed.

Key words: thermodynamics; time; space; movement; relation-based thinking; equilibrium; non-equilibrium; entropy; scales; time arrow; space arrow; duality; flux; entropy flux; Lorentz invariance; quantum mechanics.

1. Introduction

I wish to discuss here some issues referring to the relations between space, time and thermodynamics. Time is deeply associated to thermodynamics, but, as is well known, it is a difficult subject. As many of you I suppose, I have been thinking about time for several years. In my case, I reached the conclusion that time is another way to think of space, and movement.

These are the main steps of my talk. I will present first my understanding of time. Then I will present some qualitative consequences that one may derive in thermodynamics. In a third part, I will show some more quantitative consequences, as ways of research.

My talk will remain mostly qualitative, maybe some of you will think too philosophical. I do like equations, I do like mathematics, but I think that, if we want to (maybe) improve thermodynamics, we must also go back to its basic concepts. The foundations of thermodynamics cannot be disconnected from a hopefully better, if not easier, understanding of space and time.

2. Space = time, some images for a new paradigm

So let me present my vision of time. In my understanding, time does not exist. It does not exist alone, as an independent substance of the world. It is abstracted from the world, from which it cannot, ultimately, be separated. Specifically for me, time is abstracted from the movement in space of material entities in the large. However, when we abstract time, we construct an object which has pragmatic effects that can be studied and discussed.

The understanding of time is the understanding of the abstraction of time. To tell it short, time and space is the same. To avoid too many words, I make use of what French philosopher Bergson called the philosophical intuition, I call it the comprehensive, or relation-based thinking, often made of images (the equations may play this role), that comes in composition, not in opposition, with the discursive, disjunctive, substance-based thinking, mostly made of words. For issues that concern us, we especially need both. Let us then have, as Bergson also commented in this context, an artistic approach, trying to grasp at once, as a whole, the objects of thought. Another way to tell my story would be to discuss some points in relativity theory, but it would take more time.

How to speak of space and time? Let us start by noting that neither space nor time exist by themselves, but they are based on the phenomena of the world. Let us look at this landscape[1], as other people have done before us. Space: some benchmarks borne by the mountains, as geographical markers that are planted there, as a set of points connected by the GPS network. Time as the sun going across the sky, or as the clouds, or as this cart: their movement allows us to classify, to sequence the events: when the cart was here, I did this, when it was there, I did that. Or, another landscape, another vision of time and space: a mountain allows to build space; ocean waves allow to build time: their progress serves me as a clock.

In what we have done, we feel that we can look at space with no need to look at time. But this is not the case, and this is the heart of my discourse: time and space are not only related to the world, but also relative to, or in relationship with each other. For a proof, a change of scale is necessary. Let us think through tens, hundreds of millions of years. The stone wave[2] is then strictly identical to the ocean wave that we saw a short time ago: it moves like it and can serve us to measure time. Which served us to define space now serves us to define time. We can think of other stone waves, like that of the Sainte Victoire, dear to Cézanne, in the South of France.

But, conversely, if we live at the scale of nanoseconds, the sand in the hourglass does not move for the duration of our entire life; the ratio of the nanosecond to the second is the same as that of the second to the century. The grains of sand may serve us as a distance gauge. Which was used to set time is now used to set space. Over short time scales, the relief of the river water and its swirls is similar to the landscape we contemplated a while ago, we can pinpoint its irregularities to locate us.

You will say it is a beautiful allegory, but at some point we will be able to stop and say: here is space, here is time. Well, no, in this infinite transhumance that transforms time into space and space into time, we cannot stop; we are inside the world and we cannot bring rulers and

[1] Some pictures were shown during the talk ; from the present text, one will guess what they looked like. This part of the talk has already been given in French (see e.g. Guy, 2017a and b).
[2] On the first picture, there was a cliff showing a stone wave, i.e. a geological fold, or bending of the rocks.

clocks from outside the world to measure it. We can only compare the phenomena to the other phenomena and, from this comparison, build space and time.

So if we stop, it is not that we would have found a pure time, a pure space, with words defined in advance, as waiting to be used; but this is because we are tired. We stop at a scale relevant to the phenomena that we want, or that we can, study, and make a provisional sharing, between what does not move too much, we build space on it, and what is defined by comparison, and that moves more, and we call it time; but we are not sure of the ultimate meaning of the very words we use to talk about them.

Of course, all this would need longer developments. Here are some first general consequences. - Time and space are of the same substance; they are separated thanks to the multiplicity of relationships and the sharing of them in two classes defined in opposition to each other. - We use a relation-based thinking that needs to be stabilized by a decision left to the free will: that of a judgment by which we choose, within the same thought, a declared constant immobility (the spatial frame) in composition with a declared, also constant, mobility (the standard movement, whether human or offered by the physical world on which our knowledge builds and loops: the postulates of relativity theory are there). - There are hidden conceptual loops in this process (in fact we need movement to define movement). - A speed is defined by comparing two movements, one of which is selected as a standard. There are no longer rulers nor clocks but only a standard movement. So we do not talk about the speed of light because it is what defines both the standards of space and time; or we can say that this speed is unity or merely say that light is the standard of movement. - Initially, times are plural, as are spaces, supported by the multiplicity of local movements. All is not solved, the mystery of time is moved, but we have new keys to reread many issues, from humanities and social sciences to physics.

3. **Qualitative consequences**

Let us now go back to thermodynamics and list some qualitative consequences that one may derive in this domain. I will just list the consequences with a minimum of comments (each would deserve a debate!). Fundamentally, the boundary between space and time is subject to arbitrariness.

1) A first consequence refers to the definition of thermodynamic equilibrium and the separation between equilibrium and non-equilibrium. One of the ways to talk about equilibrium is to say that it is a quality of what does not evolve over time. Without going into the detail of the question (which also calls for mathematical properties induced by the minimization of potentials), we understand that the parting between equilibrium and non-equilibrium is not an intrinsic or substantial property to investigate, but that it can be situated differently in different contexts.

2) The concept of scale follows: a lower scale is defined by that where we ignore the movements of possible sub-particles together with their own evolution.

3) The concept of entropy also logically follows. Indeed, when we refuse to see some movements and we freeze them on a smaller scale, we may ask: in what state can we freeze, what arrangement to confer to what we freeze? The reasonable answer is to say: we freeze the systems, whose variations we do not want to see, in their most probable state. A function thus arises, entropy, that allows this procedure.

4) The possibility of assigning an entropy to an individual particle is acceptable provided that the particle is considered as the collection of putative sub-particles on a lower scale, the most likely configuration of which would be taken to define the properties at the higher scale.

5) The concepts of the interior and the exterior of a system, and of its boundary, are also consequences of the division of space and time and of the scale duality: we speak of the interior when the system is no longer monolithic and is regarded as the sum of moving particles at a lower scale.

6) The notions of heat and of internal energy, which are characteristic of thermodynamics, also derive naturally from these considerations: the energy balance of mechanics is closed by considering the energies associated with the movement of particles at the lower scale.

7) The division between heat and work is not intrinsic but is also a matter of scale.

8) One cannot ultimately separate chemical kinetics from transport (diffusion) processes, it is depending on the choice of scale.

9) The division between space and time does not only define a duality of scales. On the contrary, it can define a hierarchy of scales by reconsidering as much as we want, in one direction or another, the subdivision of systems into smaller mobile entities, or their aggregation into larger entities, and freezing the pieces that are being gathered (Figure 1).

We then understand that the concepts of microscopic and macroscopic levels have no meaning by themselves, but that one can define a whole hierarchy of levels. Each transition from level n-1 to level n thus requires defining a series of functions such as entropy, internal energy, amount of heat, and so on.

10) We can say that thermodynamics is the generic discipline that makes it possible to carry out such transitions, whatever the levels n - 1 and n. We can also state / construct different variables and functions at the different levels, and we must then define different thermodynamics according to the levels that we connect (Figure 2).

11) We also see in this context that entropy may have a temporary role in the transition from one level to another. Once we have defined the most probable organization of the lower level by means of the entropy at this level, we have at the same time defined laws and parameters at the higher level that express this choice. Then we no longer need entropy. One can give as an example the obtaining of the molecular diffusion law with the use of a diffusion coefficient. The positive sign of this coefficient is the remainder of the use of an entropy function; this function has made it possible to choose, among the myriads of movements on the lower scale, the most likely ones, i.e. those which correspond to a positive diffusion coefficient:

$$P(S) = \int D(\frac{\partial c}{\partial x})^2 \geq 0 \Rightarrow \mathrm{D} \geq 0$$

12) These remarks have a bearing on the way we write the entropy balance itself. Two writings may indeed coexist at the two scale levels that we are connecting. At the lower level where we have frozen what is even lower, there is no production term. At the higher level, as long as we have not stabilized this level, a production term appears.

$$\frac{\partial S_n}{\partial t} + \frac{\partial F(S_n)}{\partial x} = P(S_n)$$

$$\frac{\partial S_{n-1}}{\partial t} + \frac{\partial F(S_{n-1})}{\partial x} = 0$$

Where we note S_n the entropy which makes the transition from level n-1 to level n. It is thus possible to choose whether or not we write a production term according to the level at which we are located and according to what we have decided to freeze on a smaller scale. We also see that, from a general standpoint, we define a pair (entropy, entropy flux) at the so-called lower level.

13) If entropy is understood as giving us a probability of states, entropy flux may be understood as giving us a probability of trajectories (an author such as Ken A. Dill, 2008, reached the same conclusion). The Galton board gives an illustration of this idea, assuming for the generality that one can stack the balls at a given level and that one can also evacuate them down.

14) The writing $dS = d_iS + d_eS$ may be discussed in the same context. It is better to use the entropy balance with partial derivatives and with flux and source terms, rather than to suggest that the writing refers to different ways of differentiating one and the same function S.

15) The so-called time problem, i.e. the connection between reversible mechanics and irreversible thermodynamics is also related. The limit between irreversibility and reversibility is decided and is in relation to scale. To the pragmatic understanding of the irreversibility already discussed by many authors (perturbations make the system go towards more probable states) is connected a more fundamental understanding related to the indeterminacy of the space-time boundary and the indeterminacy of the positions of the particles.

16) The understanding of the temporal irreversibility must never be separated from spatial gradients: one can speak of the space arrows, always associated with the time arrow. The various thermodynamic irreversibilities always correspond to spatial gradients of various kinds. Entropy is a function that characterizes the homogeneity of a system. This approach

makes it possible to reconcile the two formulations of the second principle, the macroscopic phenomenological formulation (Carnot, Clausius) involving Q / T sums, and the statistical formulation (Boltzman, Gibbs) involving numbers of microscopic configurations.

17) Other questions, still of a rather qualitative nature, can be discussed in this context, such as the conceptual loop between the microscopic and the macroscopic levels. Thermodynamics is not merely the theory that makes us go up from the microscopic to the macroscopic, but the one that connects these two levels, and there are links in both directions. We need to know average quantities at the macroscopic level so as to discuss their values on individual particles at the microscopic level. This micro-macro recursiveness is also a way of seeing the time-space recursion where each is defined in opposition / composition with each other. The situation is similar to the wave-particle duality in quantum mechanics, analyzed in terms of complementarity by the philosophers of science.

4. **More quantitative consequences**

Each of the preceding points would entail more quantitative consequences, but let us now have a look at some more straightforward quantitative consequences, that one may also consider as directions of research (new equations, or new ways to consider the equations).

1) We shall especially mention the necessity of writing the laws of physics by handling physical quantities in pairs of functions (f, g) such as the pair (E, B) in electromagnetism, or all the pairs such as (E, p), (c, J), and so on, found in mechanics and thermodynamics. In the context of a relational thinking, we do not know the quantities by themselves, we know only of the variations of the paired quantities with respect to the space and time variables respectively, within which I call zeroth degree laws of the type

$$\frac{\partial f_i}{\partial t_j} = \frac{\partial g_j}{\partial x_i}$$

Where f and g are both two 3-D vectors, so as those pertaining to position r (x_i) and time t (t_i). Be careful, time is not three dimensional; time as a scalar is defined from the position of a moving marker defined by its three coordinates (think of the position of the sun in the sky or that of a photon in an atomic/optic clock); we can write for instance:

$$t = \sqrt{t_1^2 + t_2^2 + t_3^2}$$

The preceding laws are Lorentz invariant, which facilitates the co-working with the theory of relativity.

We may just mention that this writing provides a quantitative way of expressing some conceptual loops, for example that bearing on energy, important to thermodynamics: we don't know what is energy, we only know a link between an energy variation and a momentum variation, as it may already be stated from special relativity theory (cf. also Newton's second law of motion).

2) In this context, we are again encouraged to define entropy, not by a single quantity, but, as we already saw before, by a pair of functions (entropy, entropy flux), (S, F), as mathematicians do in hyperbolic problems. S and F functions are linked together within a zeroth degree law with no entropy production. The Lorenz transformation acting upon this duality will get new functions (S', F') in the moving frame, coming from the (S, F) functions in the rest frame, in a similar writing as that for other physical fields that come in pairs: (E, B), E, p), (r, t) etc.

One may wonder: why always associate an entropy flux to an entropy function? The answer again refers to the separation between space and time, that is to say in that case to the opening or the closing of the system, which is not known perfectly. A "small" entropy flux is associated with our ignorance of the closure of the system (in the similar fashion, we can associate a magnetic field with an electric field, even for a stationary electric charge the immobility of which is not known perfectly). In this context, we can write indeterminacy relations linking the indeterminacy on the previous conjugate variables, such as time and space, entropy and entropy flux etc. These are another expression of the laws of degree zero. They can be written as:

$$\frac{\delta S}{S}\frac{\delta F}{F} \cong \dots \frac{\delta E}{E}\frac{\delta B}{B} \cong \dots \frac{\delta x}{x}\frac{\delta t}{t} \cong \frac{v^4}{4c^4}$$

Where v represents a "small" unknown velocity affecting a moving reference frame with respect to a rest frame, a way of simulating the indeterminacy we have on the boundary between time and space.

3) In this context, the space-time pair (r, t) must be considered on the same footing as the other pairs of the (f, g) type associated with the various physical phenomena. Any pair can be chosen to define space and time. Generalized exchanges between pairs can then be envisaged and this opens up numerous avenues, such as that of the conceptual linking of general relativity and quantum mechanics that have a priori different ways to handle space and time.

4) The ergodic principle may be discussed in this context, where one is led to declare the equality of the probability densities (or the average values) with respect to both time and space of some physical quantity:

$$f_X = f_T$$

5) This brings us to the side of the probability stuff and quantum mechanics. We can write similar formulations for thermodynamics and for quantum mechanics such as the followings:

$$\frac{\partial S}{\partial t} + \frac{\partial F}{\partial x} = 0$$

$$\frac{\partial \psi}{\partial t} + \frac{\partial \varphi}{\partial x} = 0$$

where the first equation relates the entropy function and the entropy flux, and the second relates functions referring to a probability density of presence (ψ) on one side and to a probability density of a flux (φ) on the other side, and that can be compared with the Dirac equation. Both S and ψ have a probability meaning. When trying to link thermodynamics with quantum mechanics, we can then ask: should we pile up the two probability approaches, or try to identify them? In my guess, this is the second answer to investigate: just as the second law makes us skip improbable states, quantum jumps may be understood as skipping improbable states, as we can see from an hyperbolic problem type formulation of quantum mechanics, where quantization is ruled by the second law itself (in so doing we relate a microscopic level n-1 to a macroscopic level n).

5. Conclusion

As a matter of fact, I have no conclusion. Everywhere do we find the working of time and its link with space and movement. This is a huge task developing these ideas in different domains, from fundamental physics to humanities and social sciences. I am beginning this task in collaboration with other researchers, from various fields. The younger generation may or may not continue this work, we will see.

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The following list includes works that have been used to prepare the talk, together with some references given in the text.

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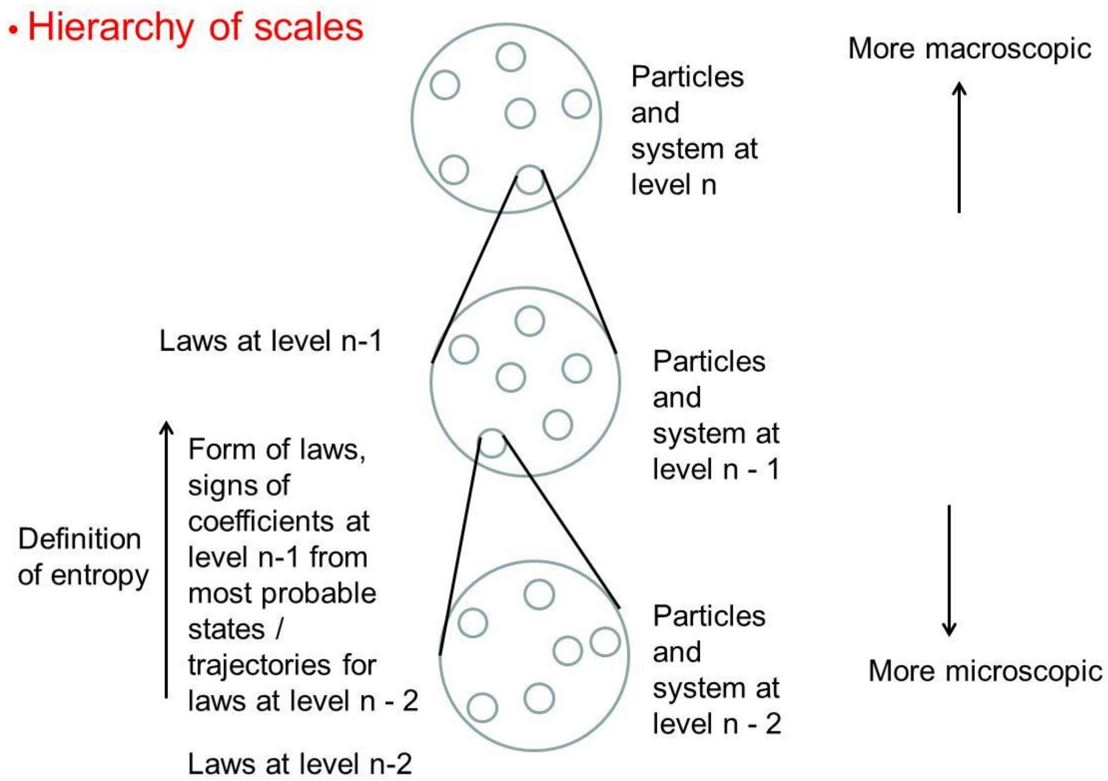

Figure 1

Corresponds to qualitative consequence number 9 (see text).

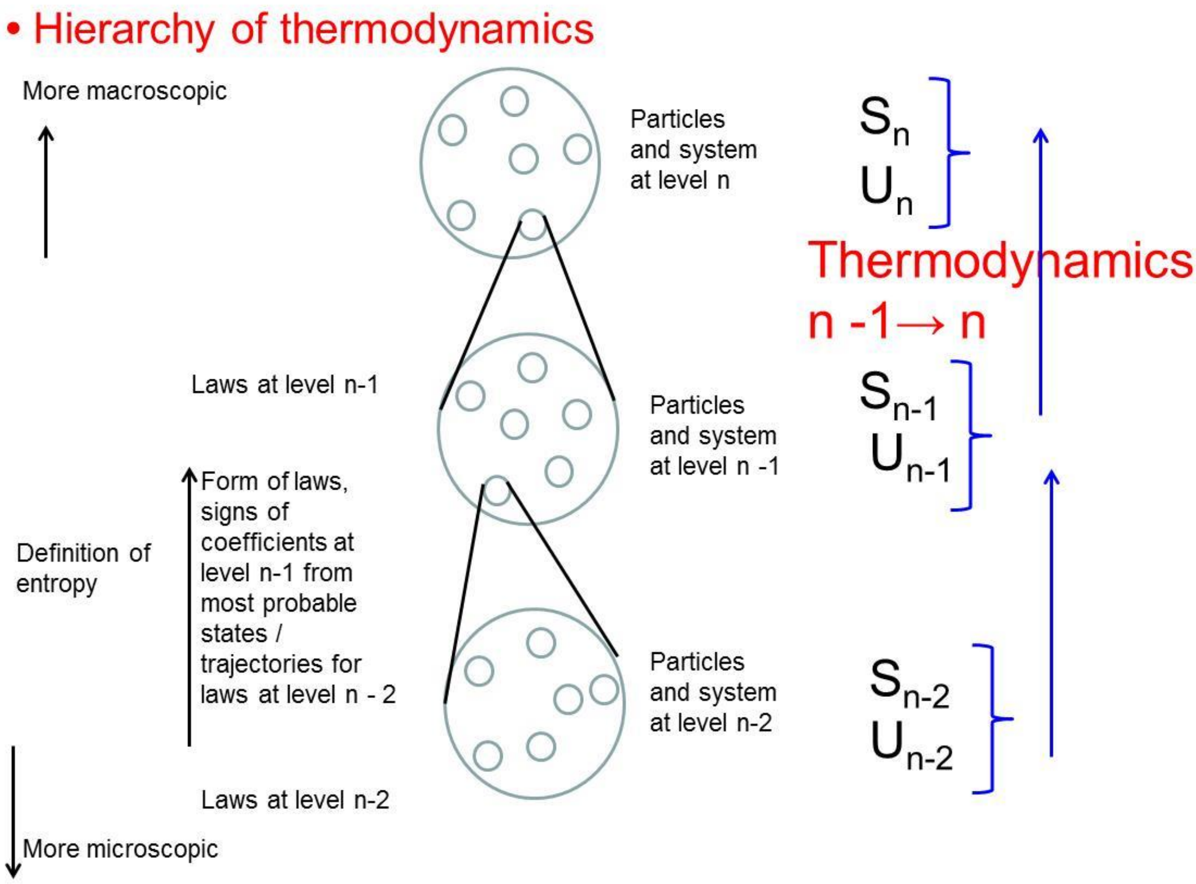

Figure 2

Corresponds to qualitative consequence number 10 (see text).