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Considerations on non equilibrium thermodynamics of interactions

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HIGHLIGHTS

- Nature can be considered the first engineer.
- Nature designs open systems.
- Open systems are interacting systems.
- Interactions can be achieved by flows.

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ABSTRACT

Nature can be considered the "first" engineer! For scientists and engineers, dynamics and evolution of complex systems are not easy to predict. A fundamental approach to study complex system is thermodynamics. But, the result is the origin of too many schools of thermodynamics with a consequent difficulty in communication between thermodynamicists and other scientists and, also, among themselves. The solution is to obtain a unified approach based on the fundamentals of physics. Here we suggest a possible unification of the schools of thermodynamics starting from two fundamental concepts of physics, interaction and flows.

1. Introduction

Nature, from a physical, biological, chemical and mathematical point of view, is a complex system, while from an engineering point of view, it is the "first" engineer! But, for scientists and engineers, dynamics and evolution of complex systems are not easy to predict. A fundamental approach to study complex system is thermodynamics. Indeed, this science is brief, simple, unambiguous, and continuously improving, able to provide global (engineering thermodynamics), local (statistical thermodynamics), linear (classical thermodynamics) and complex (non-equilibrium thermodynamics) approaches to natural systems. But, the result of too many schools of thermodynamics is the difficulty in communication between thermodynamicists and other scientists and, also, among themselves. The solution is to obtain a unified approach based on the fundamentals of physics.

Here we suggest the proof of the possible unification of the too many schools of thermodynamics starting from two fundamental concepts of physics, interaction and flows. The result is the analytical formulation of the non equilibrium thermodynamics of interactions, named constructal, which can play the role of a "rallying point" of all the schools of thermodynamics. This result could be very important not only for physics and engineering, but also for other sciences as biology, medicine, etc. because it highlights the fundamental role of flows suggesting two different ways to evaluate the results, depending on the knowledge of the phenomenon considered.

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2. The non equilibrium thermodynamics of interactions

All the thermodynamic schools agree that for an "adiabatic closed system with zero-work transfer" (usually named "isolated" system), its entropy increases during changes inside the system [1].

Now, we consider a natural system. It can change heat and mass with its environment. So, it is an open system which interacts with its environment [2]; it can be a simple or complex system too. We consider the environment as a thermostat [3,4]. Consequently, the system, together with its environment, is an adiabatic closed system. So, the total entropy increases, as a consequence of the second law [2–4]. Now, the entropy can be written as [5,6]:

$$\mathrm{d}S = \mathrm{d}_i S + \mathrm{d}_e S \tag{1}$$

where $\mathrm{d}S$ is the total entropy elementary variation, $\mathrm{d}_e S$ is the entropy variation for interaction between the open system considered and its environment and $\mathrm{d}_i S$ is the entropy variation due to irreversibility, such that:

$$\frac{\mathrm{d}_i S}{\mathrm{d}t} \geq 0. \tag{2}$$

Moreover, the stationary state of the open system corresponds to the equilibrium state of the adiabatic closed system.

Now, we can write the relation (1) as [7]:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \int_V \left[-\nabla \cdot \left(\frac{\mathbf{Q}}{T} \right) + \dot{s}_g \right] \mathrm{d}V \tag{3}$$

where $\mathbf{Q}$ is the heat flow, T is the temperature, V is the volume, t is the time and $\dot{s}_g$ is the density of the entropy generation rate [8].

Considering the system together with its environment, we are analyzing an adiabatic closed system, so the entropy variation for the volume considered is maximum at the equilibrium [3,4]:

$$\mathrm{d}S = 0 \Rightarrow \left[-\nabla \cdot \left(\frac{\mathbf{Q}}{T} \right) + \dot{s}_g \right] = 0 \tag{4}$$

and

$$\nabla \cdot \left(\frac{\mathbf{Q}}{T} \right) = \dot{s}_g. \tag{5}$$

This last relation allows us to state that the flows between the open system and its environment cause the entropy generation rate density, so the interaction between system and environment is responsible of irreversibility: without interaction no irreversibility occurs.

Now, considering that the entropy generation rate density can be written as [7]:

$$\dot{s}_g = \sum_k \mathbf{J}_k \cdot \mathbf{X}_k \tag{6}$$

where $\mathbf{J}_k$ is the flow of the kth quantity involved in the process considered and $\mathbf{X}_k$ is the related thermodynamic force [7]. In relation to the mathematical form (6) we must highlight the Curie principle [9] for which fluxes and forces of different tensor properties are never coupled, so that we can consider the different components to be always independent of one another [7].

Now, considering that:

$$\nabla \cdot \left(\frac{\mathbf{Q}}{T} \right) = \mathbf{Q} \cdot \nabla \left(\frac{1}{T} \right) + \frac{1}{T} \nabla \cdot \mathbf{Q} = \sum_k \mathbf{J}_k \cdot \mathbf{X}_k \tag{7}$$

the relation (5) becomes:

$$\frac{1}{T} \nabla \cdot \mathbf{Q} = \sum_k \mathbf{J}_k \cdot \mathbf{X}_k - \mathbf{Q} \cdot \nabla \left(\frac{1}{T} \right) \tag{8}$$

in agreement with Le Chatelier's principle [10], for which any change in concentration, temperature, volume, or pressure generates a readjustment of the system in opposition to the effects of the applied changes in order to establish a new equilibrium, or stationary state. It follows that the fundamental imperative of Nature is to consume free energy in least time. This quest will yield the ubiquitous scale-free patterns [11]. Any readjustment of the state of the system can be obtained only by generating fluxes of free energy which entail any process where the system evolves from one state to another. The free energy "fuels" evolutionary processes so that the basic building blocks of Nature, the quanta of energy, are either absorbed from the surroundings to the system in the form bound energy or emitted from the system to its surroundings as freely propagating photons.