Landauer Principle: Re-Formulation of the Second Thermodynamics Law or a Step to Great Unification?

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Abstract: The Landauer principle supplies the estimation of the minimal mass of a particle which is capable to record/erase information within a thermal bath at the temperature of *T*. Particles lighter than $\widetilde{m}_0 = \frac{k_B T ln2}{c^2}$ will not transform the information to the surrounding bodies and are well expected to be undetectable. The relation of the Landauer principle to the problem of "dark matter" is discussed. The maximal informational content of a particle at rest, estimated as $I_{max} = \frac{m_0 c^2}{k_B T k n2}$ is introduced. The Landauer principle also allows the estimation of minimal energy of the field which is capable to record/erase 1 bit of information in the surrounding at the temperature of *T*. The relativistic aspects of the Landauer principle and its relation to the relativistic transformation of temperature are addressed.

Keywords: Landauer principle, entropy; information; relativity, particle, field.

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1. Introduction

Informational theory is usually supplied in a form that is independent of any physical embodiment. In contrast, Rolf Landauer in his papers argued that information is physical and it has an energy equivalent [1-3]. It may be stored in physical systems such as books and memory chips and it is transmitted by physical devices exploiting electrical or optical signals [1-3]. Therefore, he concluded, it must obey the laws of physics, and first and foremost the laws of thermodynamics. The Landauer principle [1-3] establishing the energy equivalent of information remains in the focus of investigations in the last decade [4-10]. In spite of the fact that non-equilibrium and quantum extensions of the Landauer principle were reported, the exact meaning and formulation of the principle remain obscure and both of them have been exerted to the stormy discussion [5-7, 11-12]. The Landauer principle in its general meaning established the relation between thermodynamic and logical reversibility, and consists of two statements [7, 11, 12]: 1) any logically irreversible process must result in an entropy increase in the non-information bearing degrees of freedom of the information-processing system or its environment; 2) any logically reversible process can be implemented thermodynamically reversibly. In its strict, tight and simplest meaning the Landauer principle states that the erasure of one bit of information requires a minimum energy cost equal to $k_B T$ ln2, where *T* is the temperature of a thermal reservoir used in the process and *k* is Boltzmann's constant [1-4, 8, 13]. Later Landauer applied the principle to the *transmission* of information and re-shaped it as follows: an amount of energy equal to $k_B T$ln 2 (where $k_B T$ is the thermal noise per unit bandwidth) is needed to transmit a bit of information, and more if quantized channels are used with photon energies $h\nu > kT$ [3]. The extension of the Landauer principle for the situation when multiple physical quantities (and not only energy) conserve has been reported [13-14]. An angular momentum (spin) cost necessary for recording/erasure of information was reported [13-14]. The generalization of the Landauer principle for indeterministic operations was addressed [15].

On the other hand, the Landauer principle was intensively criticized by J. D. Norton who argued that since it is not independent of the Second Law of thermodynamics, it is either unnecessary or insufficient as an exorcism of Maxwell's Demon [5-6, 16-18]. J. Bub, in turn, suggested the asymmetry of recording and erasing of information and stated that there is in principle no entropy cost to the acquisition of information, but the destruction of information does involve an irreducible entropy cost [19]. The Landauer principle was defended in a series of recent papers [11-12], however the discussion is far from to be exhausted. In our present paper we demonstrate the informational re-formulation of thermodynamics [20-25] may be useful as a step for the "great unification" of physics, enabling new glance on the fundamental physical problems.

2. Results and discussion

2.1. The Landauer principle and the minimal mass of the particle enabling recording/erasing information within the surrounding medium

Consider particle with energy E in contact (not necessarily in thermal equilibrium) with the thermal bath T. The energy of the particle may be used for recording/erasing information within the thermal bath. According to the Landauer principle and relativity the maximal information I_{max} which may be recorded by the particle with the bath equals:

$$I_{max} = \frac{E}{k_B T ln2} = \frac{mc^2}{k_B T ln2} \quad , \qquad (1)$$

where k_B is the Boltzmann constant and m is the relativistic mass of the particle. The value I_{max} may be seen as the maximal informational content of a relativistic particle. If the potential energy of the particle is negligible, and $\frac{v}{c} \ll c$, takes place, where v is the velocity of the particle, Eq. 1 is re-shaped as follows:

$$I_{max} = \frac{m_0 c^2}{k_B T kn2} \qquad (2)$$

The value I_{max} supplied by Eq. 2 may be interpreted as the maximal informational content of a particle *at rest*. The particle may exchange information with the medium, if *at least one bit* of information will be transferred from the particle to the medium (thermal bath), thus inequality $I_{max} \geq 1$ should hold. This inequality yields:

$$m_0 \geq \frac{k_B T ln2}{c^2} \qquad (3)$$

The particle with a rest mass smaller than $\tilde{m}_0 = \frac{k_B T ln2}{c^2}$ will not transform information to the medium at the temperature of T. Assuming $T = 2.73K$ (which is the temperature of the cosmic microwave background [26]), we obtain the estimation $\tilde{m}_0 \cong \frac{1.6\times10^{-4} eV}{c^2} \cong 2.0 \times 10^{-40} kg$. It should be emphasized that all of known for today elementary particles (including neutrino $m_{neutrino} < 0.120 \frac{eV}{c^2}$) are heavier than $\tilde{m}_0 =$

$2.0 \times 10^{-40} kg$. Particles lighter than $\tilde{m}_0 = 2.0 \times 10^{-40} kg$ will not transform the information to the Universe and are well expected to be undetectable.

2. 2. The Landauer principle and the great unification of physics.

The Landauer principle supplies a new glance of the problem of great unification of physics. Indeed, Eq.1 may be easily extended to fields. Consider a field (for example an electromagnetic field) in a thermal contact (not necessarily in thermal equilibrium, as it takes place in a black body radiation problem) with surrounding *T*. The energy of the field may be used for recording/erasing information in the surrounding. The maximal information to be recorded (the informational content of the field) according to the Landauer principle will be given by:

$$I_{max} = \frac{E_f}{k_B T ln2} , \qquad (4)$$

where E_f is the energy of the field. Consider, that the physical nature of the field does not matter. If the information and the temperature are taken as a basic physical quantities, Eq. 4 will be universal for all kinds of physical fields. The field is capable to record/erase the information if inequality $E_f > k_B T ln2$ takes place. The Landauer principle changes the status of temperature, usually seen as the derivative of basic physical quantities, such as energy and entropy. Contrastingly, the Landauer principle tells us that the it is just the temperature which determines the possibility to erase/record the information, seen as a basic physical value.

2.3. The Landauer principle and the relativistic transformation of temperature.

The relativistic transformation of temperatures remain a subtle and open theme, in which different expressions for this transformation were suggested [27-31]. Planck and Einstein suggested that the transformation of temperatures is governed by: $T = T_0 \sqrt{1 - \frac{u^2}{c^2}}$ [27]. In contrast, Ott suggested for the same transformation $T = \frac{T_0}{\sqrt{1-\frac{u^2}{c^2}}}$ [28]. It was mentioned that the relativistic transformation of temperature works, when energy is transformed under the constant momentum, whereas, the transformation suggested by Ott is valid when the velocity of a particle is constant [27, 28]. Consider, that in relativity the momentum and velocity of a particle are not proportional one to another. Thus, it was suggested that an unambiguous relativistic transformation of temperatures is impossible [27, 29, 31]. It was also suggested that temperature is the relativistic invariant [30].

It is reasonable to suggest that the maximal number of bits which may be recorded by a particle in the thermal bath is a relativistic invariant (as well as the entropy is the relativistic invariant [27]). Thus, the Landauer principle and Eq. 1 support the idea that is transformed according to the transformation suggested by Ott, namely $= \frac{T_0}{\sqrt{1-\frac{u^2}{c^2}}}$.

2.4. The Landauer principle and the dark matter problem.

The Landauer principle enables a fresh glance on the "dark matter" problem [32]. We still do not know to explain how stars orbit in galaxies and how galaxies orbit in clusters. A wide array of candidates for particle dark matter was suggested, including neutralinos and sterile neutrinos [33-34]. However, numerous experiments have failed to find evidence for dark matter particles, and it was suggested that gravity theory should be modified [35]. Eq.3 enables revisiting of the "dark matter" problem. Indeed, if the dark matter is built from for particles for which $m < \tilde{m}_0 \cong \frac{k_B T ln2}{c^2} \cong 2.0 \times 10^{-40} kg$ takes place, they could not be registered due the fact, that they do not transform information to the surrounding media and experimental devices.

2.5. The Landauer principle and the informational content of the Universe.

The computational capacity of the Universe was recently estimated and broadly discussed [36, 37]. We involve Eq. 2 for the estimation of the upper bound of the computational capacity of the Universe ΔI_{tot}:

$$\Delta I_{tot} \cong \frac{m_{tot} c^2}{k_B T}, \qquad (5)$$

where $m_{tot} \cong 1.5 \times 10^{53} kg$ is the mass of the observable Universe [38]. Substituting $m_{tot} \cong 1.5 \times 10^{53} kg$ and $T = 2.73K$ we obtain: $\Delta I_{tot} \cong 3 \times 10^{92}$ bits, in the satisfactory vicinity to the estimation reported by Seth Lloyd [37], based on quite different considerations (when gravitational degrees of freedom are taken into account, the estimation reported in Ref. 37, is much larger, i.e. $\Delta I_{tot} \cong 10^{120}$ bits).

Conclusions

The physical roots, justification and precise meaning of the Landauer principle [1-3] remain obscure and were exposed to the turbulent discussion recently [5-14]. We demonstrate that the Landauer principle supplies the estimation of the minimal mass of the particle allowing recording/erasing information within the surrounding medium at temperature T. Particles lighter than $\tilde{m}_0 = \frac{k_B T ln2}{c^2} \cong 2.0 \times 10^{-40} kg$ will not transform the information to the surrounding bodies and are well expected to be undetectable (assuming $T = 2.73K$ which is the temperature of the cosmic microwave background). All of known for today elementary particles are heavier than $\tilde{m}_0$. This approach is easily extended to fields. Perhaps, the Landauer principle helps to explain the problem of the undetectable "dark matter", if we assume that the "dark matter" is built from particles with $m < \tilde{m}_0 \cong \frac{k_B T ln2}{c^2}$. The Landauer principle enables estimation of the total informational content of the Universe. The relativistic aspects of the Landauer principle and its relation to the highly debatable relativistic transformation of temperature are discussed.

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