Information and thermodynamic arrows of time

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Abstract

The article examines the thermodynamic arrow of time and the information arrow of time. The thermodynamic arrow of time is related to the second law of thermodynamics, and the information arrow of time shows that it is only possible to record information from the past, but not from the future. It has been concluded that on certain occasions the thermodynamic arrow of time and the information arrow of time may have different directions. According to the interpretation of Stueckelberg-Feynman-Sudarshan-Recami, the antiparticles are particles moving backwards in time. Classical thermodynamics can be extended to describe the physical properties of antimatter in two mutually exclusive ways: CP-invariant or CPT-invariant thermodynamics. From this point of view, the article shows the existing possibilities for the directions of the thermodynamic arrow of time and the information arrow of time. Thermodynamic systems have been examined that are composed of only matter or of only antimatter and observed (investigated) by hypothetical observers made of matter or antimatter. The information and entropy properties of the computational processes performed by a computer made of antimatter have been discussed.

***Keywords*:** Arrows of time; Entropy; Information; Antimatter; Opposite direction of time

The direction of time is determined by a multitude of arrows–thermodynamic, psychological/perceptual, cosmological, radiative, causal, quantum, weak force arrow of time, etc. The thermodynamic arrow of time shows the direction of the increase in entropy - typically, this is the direction from the past towards the future. It is based on the second law of thermodynamics. The thermodynamic arrow of time is related to the circumstance that the Universe started with very low entropy (The Big Bang). If the entropy increases from past to future, we will say that the thermodynamic arrow points forwards in time. If the entropy decreases from past to future, we will say that the thermodynamic arrow points backwards in time.

The psychological arrow of time is about our remembering the past that has already happened, and not remembering the future which lies ahead. The psychological arrow of time is more difficult to be examined because the microphysical basis of human thinking is still not quite clear. For that reason, we will substitute the question "Why do we remember the past and do not remember the future?" with the question "Why is the information copied only in one direction in time?". The advantage of a question posed in such a way is that it has a physical nature and is not related to fields such as psychology or philosophy [1]. Further in this article we will use the term information arrow of time instead of psychological arrow of time. The information arrow of time shows that it is only possible to record information from the past, but not from the future.

It is thought that there is a relation between the information arrow of time and the thermodynamic arrow of time. The arguments are as follows: There is an essential understanding of the arrows of time when the question is about computers – the undertaking and completing of a calculation and its recording afterwards is a primary computational succession whose entropic properties are well known (elaborated by [2], [3] and others) and conform to the second law of thermodynamics very well. If human thinking can be likened to a computational process, a thermodynamic explanation of the information arrow of time could be applied. The direction of time in which a *computer memorizes the past* is the same as the one in which entropy increases. Entropy increases with time because we measure the time in the direction in which entropy increases [4]. But these lines of reasoning do not prove that the information and thermodynamic arrows of time are related and always have the same direction. Most often the asymmetry between past and future is explained with the second law of thermodynamics, but the problem does not seem to be settled entirely [5].

But if the information arrow of time is not related to the thermodynamic arrow of time, then how can it be explained? An observer remembers past events because to him those events have already happened, but does not remember future events simply because according to him those events have not taken place yet (they are probably expected to happen in the future). The information arrow of time is related to the circumstance that a past event could influence a present event, but a future event cannot influence a present event. (Present events exert influence on future events, but the reverse is impossible). What is more, an observer could get information about a given past event only if this event belongs to the causal region of the observer. For this reason, it is possible to record information from the past, but it is not possible to record information from the future. Therefore, the information arrow of time is related to the principle of causality. According to this principle, every present event taking place in a given physical system can exert influence on the future state of this system, but cannot affect its behavior in the past. This means that the cause always precedes the effect, but not vice versa.

An observer can only get information from his past (which has already taken place), but not from his future (because it has not taken place yet). Consequently, for an observer who observes (examines) his own history the information arrow of time always points forwards in time in the direction from the past to the future.

There are cases in which the information arrow of time is opposite to the thermodynamic arrow of time. For example, in a system in which information moves from past to future, but entropy decreases from past to future, the thermodynamic arrow and the information arrow will have opposite directions. The possibility that this will happen follows from the statistical nature of the second law of thermodynamics. It is absolutely possible for a system to pass from a state of high entropy to a state of low entropy, although such events are rare and unlikely. Statistical fluctuations of this kind can be observed much more often in systems with a small number of particles. According to Poincaré recurrence theorem, if given long enough time, a dynamical system with finite energy and confined to a finite region of space will return arbitrarily close to its initial condition. This theorem leads to an unexpected consequence: For example, let us look at a container with a partition that divides it into two compartments, one of which is full of gas, and the other one is empty. If the partition is removed, after a while, there is a non-zero probability that all the molecules of the gas will gather in the part of the container where they were initially. The system will go from a state of high entropy to a state of low entropy. In this case the entropy of the system will decrease in the direction from past to future, but an observer will remember the past, and not the future. (The explanation of this "paradox" lies in the time this takes to happen. With systems with a great number of particles the time required may be longer than the age of the Universe, but systems with a small number of particles may take a much shorter time. And since in our daily lives we come across phenomena in which an extremely great number of particles participate, there is no way we can observe a violation of the second law of the thermodynamics). Therefore, the information arrow of time does not always coincide with the thermodynamic arrow of time. There are four possibilities:

Table 1

		Thermodynamic arrow	
	Direction:	**From past to future** (→)	**From future to past** (←)
Information arrow	**From past to future (→)**	(1) Entropy increases from past to future, information runs from past to future	(2) Entropy increases from future to past, information runs from past to future
	From future to past (←)	(3) Entropy increases from past to future, information runs from future to past	(4) Entropy increases from future to past, information runs from future to past

Case (1) is customary and well known to us from our daily life. For example, we have often observed the causal relationship between the falling of a glass and its breaking into lots of pieces. This process is related to the increase in entropy. But we have never observed the opposite process so far - lots of small glass pieces assembling into a whole glass, which is connected with a considerable decrease in entropy. Case (2) is not very likely to happen, but, as we noted above, it is also possible. If in case (1) we swap the words „past" and „future", we will get case (4). By analogy, if in case (2) we swap the words „past" and „future", we will have case (3). Cases (3) and (4) are completely symmetric to cases (2) and (1) respectively, and this gives us reason to think that they might also be realized in the physical reality. It could be assumed that these possibilities are realized as far as antimatter is concerned.

In the relativistic quantum mechanics, to every particle an antiparticle is attached. The so called "Switching principle" (or "reinterpretation principle") is formulated by Stueckelberg-Feynman-Sudarshan-Recami [6-18]. According to it "positive energy objects traveling backwards in time do not exist; and any negative energy particle travelling backwards in time can and must be described as its antiparticle, endowed with positive energy and motion forward in time (but going the opposite way in space)" [19]. Thus, the antiparticle, moving forwards in time and possessing positive energy in fact can be regarded as a particle, moving backwards in time and possessing negative energy [20].

Let us give a definition of normal, positive direction of time, and opposite, negative direction of time. We assume as normal and positive the direction of time in which we ourselves and the familiar material objects that surround us move. Let us examine two hypothetical observers O_m and O_a who are moving in opposite directions of time. Let us suppose that the time flowing for the observer O_m has a normal, positive direction whereas the time flowing for the observer O_a has an opposite, negative direction. Let an event E_0 happen at the time moment t_0 of the time flowing for the observer O_m. We assume that according to the time flowing for the observer O_a the event E_0 happened at the time moment $\overline{t_0}$. Let us suppose that at the time moment t_1 of the time flowing for the observer O_m another event E_1 took place. We assume that there is a causal relationship between the events E_0 and E_1. Let $\overline{t_1}$ be the time moment of the time flowing for the observer O_a, at which the event E_1 was realized. Let us assume that $t_0 \neq t_1$ and $\overline{t_0} \neq \overline{t_1}$, and also that t_0 is a past time moment as compared to the time moment t_1 (i.e. according to the time flowing for the observer O_m the event E_0 is the reason for the event E_1). We will have: $t_1 > t_0$. We will say that the time flowing for the observer O_a has an opposite, negative direction if the time moment $\overline{t_0}$ proves to be future, pending, compared to the time moment $\overline{t_1}$, that is, $\overline{t_1} < \overline{t_0}$. Therefore, according to the time flowing for the observer O_m, the event E_0 precedes the event E_1, and according to the time flowing for the observer O_a the event E_1 precedes the event E_0. We see that past and future change their "roles" when a succession of the same events is recorded by two observers, with the time for one of the observers flowing in a direction opposite to the direction of the time flowing for the other observer.

In accordance with the above reasoning the time flowing on the particles (matter) has a normal, positive direction, and the time flowing on the antiparticles (antimatter) has an opposite, negative direction. Hypothetical observers made of antimatter, are called antiobservers, while the term observers refers only to us -observers made of matter. Properties of matter measured by us (the observers) and properties of antimatter measured by antiobservers are referred to as intrinsic.

Conventional thermodynamics, which is formulated for our world populated by radiation and matter, can be extended to describe physical properties of antimatter in two mutually exclusive ways: CP-invariant or CPT-invariant [21]. CPT-invariant thermodynamics is based on the following principles [21, 22]:

• **Reversible equivalence**. There is no distinction between matter and antimatter with respect to the first law of thermodynamics.

• **Inverted irreversibility**. Thermodynamically isolated antimatter can increase its entropy only backward in time (unlike any isolated matter, whose entropy increases forward in time).

• **Observational symmetry**. Antimatter and its interactions with matter are seen (i.e. observed, experimented with or measured) by antiobservers in exactly the same way as matter and its interactions with antimatter are seen by observers.

In CPT-invariant thermodynamics, the thermodynamic quantities temperature $\overline{T_a}$, entropy $\overline{S_a}$ and internal energy $\overline{U_a}$ which characterize the intrinsic properties of antimatter, are apparent as

$$T_a = -\overline{T_a}\,, S_a = -\overline{S_a}\ ,\ U_a = \overline{U_a}$$

from our perspective [22]. The overbar symbol indicates that the quantities are evaluated from the perspective of an antiobserver, whose time $\bar{t} = -t$ goes in the opposite direction as compared to our time *t*.

In the case of CP-invariant thermodynamics, the second principle is to be replaced by entropy increase forward in time for both matter and antimatter [21]. While CPT invariance is commonly known as a theorem in quantum field theory, its application to macroscopic processes and/or to the whole of the Universe is a hypothesis, not a theorem [21]. For example, Penrose [23] believes that CPT invariance would not hold if applied to the whole of the Universe - this view corresponds to the CP-invariant version of thermodynamics.

Let us take a look at two thermodynamic systems K_m and K_a which do not interact with each other. The system K_m is composed only of matter and the observer O_m (also made of matter) is in it. The system K_a is composed only of antimatter and the antiobserver O_a (made of antimatter) is in it. We will examine the following four possibilities:

• **The observer O_m observes (investigates) the processes in the system K_m:**

According to the observer O_m, the entropy in the system K_m increases in the direction from past to future (in accordance with the second law of thermodynamics). Besides, information moves in the usual direction from past to future. According to the observer O_m, in the system K_m the directions of the thermodynamic and information arrows coincide and both arrows point forwards in time (in the direction from past to future). This situation corresponds to case (1).

• The antiobserver O_a observes (investigates) the processes in the system K_m:

The observer O_m remembers his past but does not remember his future. But the past for the observer O_m is in reality the future for the antiobserver O_a and vice versa – the future for the observer O_m is the past for the antiobserver O_a. Therefore, according to the antiobserver O_a the observer O_m in fact remembers the future, but does not remember the past. According to the antiobserver O_a, the entropy in the system K_m increases in the direction from future to past. Therefore, for the antiobserver O_a the information and thermodynamic arrows of time in the system K_m have the same direction – from future to past. In fact, the situation described above corresponds to case (4).

• The antiobserver O_a observes (investigates) the processes in the system K_a:

In accordance with the reasoning above, if the antiobserver O_a observes (investigates) his own history, the information arrow always points in the direction from past to future. Therefore, the antiobserver O_a will remember his past and will not remember his future. If CPT-invariant thermodynamics is valid, according to the antiobserver O_a, the entropy in the system K_a increases in the direction from past to future. This situation corresponds to case (1) (the information and thermodynamic arrows have the same direction – forwards in time). If CP-invariant thermodynamics is valid, according to the antiobserver O_a, the entropy in the system K_a increases in the direction from future to past, which corresponds to case (2).

• The observer O_m observes (investigates) the processes in the system K_a:

As O_m and O_a move in opposite directions in time, according to the observer O_m the information arrow of time in the system K_a has the direction from future to past. If CPT-invariant thermodynamics is valid, according to the observer O_m, the entropy in the system K_a increases in the direction from future to past. This situation corresponds to case (4). If CP-invariant thermodynamics is valid, according to the observer O_m, the entropy in the system K_a increases in the direction from past to future, which corresponds to case (3).

According to the results obtained, if CPT-invariant thermodynamics is valid, the directions of the information and thermodynamic arrows always coincide (cases (1) and (4)). If CP-invariant thermodynamics is valid, it might be possible for the information and thermodynamic arrows to have opposite directions (cases (2) and (3)).

In conventional thermodynamics, the likeness of the future states is evaluated for a selected time moment in the future, given fixed conditions specified in the present [22]. The initial conditions for the thermodynamic system K_m will be fixed in the past according to the time, flowing for the observer O_m (and similarly, in the future according to the antiobserver O_a). In an analogous way, the initial conditions for the thermodynamic system K_a will be fixed in the past according to the time flowing for the antiobserver O_a (and similarly, in the future according to the observer O_m). If the antiobserver O_a traces a computational process done by a computer which is made of matter, then in reality he will obtain information of a future event. (The future for the antiobserver O_a is the past for the observer O_m.) In an analogous way, if the observer O_m traces a computational process done by a computer made of antimatter, then he will obtain information of a future event.

We will call the hypothetical computer made of antimatter an anticomputer. Let us suppose that the anticomputer is assigned a computational task at a time moment $\overline{t_1}$ of the time flowing for the antiobserver O_a. For an interval of time $\Delta t>0$ (determined according to the antiobserver O_a) the anticomputer does certain calculations, with the results of the calculations being recorded in its memory at the time moment $\overline{t_2} = \overline{t_1} + \Delta t > \overline{t_1}$ of the time flowing for the antiobserver O_a. According to the observer O_m, the anticomputer is assigned the computational task at the time moment t_1, and the results of the calculations are recorded in its memory at the time moment t_2, which is a past time moment compared to the time moment t_1, i.e. $t_2 < t_1$.

The entropic properties of the computational process and the recording made by the anticomputer depend on the validity of either CPT-invariant thermodynamics or CP-invariant thermodynamics. If CPT-invariant thermodynamics is valid, then according to the antiobserver O_a, entropy increases in the process of doing the calculations and making a recording. If CP-invariant thermodynamics is valid, then according to the antiobserver O_a, entropy decreases in the process of doing the calculations and making a recording.

A conclusion can be drawn from the above reasoning that the information arrow of time is not related to the thermodynamic arrow of time. These two arrows do not always point forwards in time and on certain occasions can have opposite directions. The thermodynamic, entropic and informational properties of the matter and antimatter may be radically different. In the future, these assertions will probably be experimentally tested. This could happen when a greater number and more considerable quantities of antimatter are produced and investigated in experiments with high-energy accelerators.

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