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Velocity Reversal and the Arrows of Time

John G. Cramer[1]

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A gedanken *experiment is proposed for distinguishing between two models accounting for the macroscopic arrow of time. The experiment involves the velocity revesal of components of an isolated system, and the two models give contrasting predictions as to its behavior.*

1. INTRODUCTION

The purpose of this paper is to point out a dichotomy, a binary distinction that can be made among models dealing with the problem of the arrow of time. Here by "arrow of time" we refer to the intrinsic and evident macroscopic asymmetry between the past and the future. The "arrow of time problem" concerns the origins of the macroscopic asymmetry and the general absence of a similar microscopic asymmetry. As will be evident later in the paper, we propose a *gedanken* experiment involving velocity reversal of all components of an isolated system and ask, in the context of a particular model, if the time arrow is also reversed by this operation.

Let us begin with a brief review of several distinguishable time arrows. At the macroscopic level it is self-evident that the past and the future are not the same. We remember the past but not the future. We can send electromagnetic signals to the future but not to the past. Isolated systems have low entropy in the past but gain entropy and become more disordered in the future. The universe was smaller and hotter in the past but will be larger and cooler in the future. The K_L^0 meson exhibits weak decay modes having matrix elements and transition probabilities which are larger for the decay process than for the equivalent time-reversed process.

[1] Department of Physics, FM-15, University of Washington, Seattle, Washington 98195.

The *subjective* arrow of time is the arrow most directly perceived by our consciousness. We remember the past but cannot change it; we have no direct knowledge of the future but view it, in part, as changeable by our actions and decisions. In the past, we were born and progressed through childhood to become adults. In the future, we will grow old and die. From the subjective point of view the past and future are so different that it is difficult to comprehend their near indistinguishability at the microscopic level.

The *elecromagnetic* arrow of time is the arrow most difficult to perceive directly. An observer watching a movie showing an electromagnetic process would be unable to say whether the film was running backwards or forwards through the projector, because emission in the forward direction looks like absorption in the reverse direction. In quantum electrodynamics we can distinguish normal "retarded" electromagnetic waves and photons as having positive energy eigenvalues and a time dependence characterized by $\exp(-i\omega t)$, while exotic "advanced" electromagnetic waves and photons would have negative energy eigenvalues and a time dependence characterized by $\exp(+i\omega t)$. The equations of electrodynamics treat these two species of radiation equivalently and quite even-handedly. But empirically, it is clear that an electromagnetic time asymmetry exists. Atoms can spontaneously emit retarded photons and lose energy; they cannot spontaneously emit advanced photons and *gain* energy. If we pass an alternating current through an antenna we can produce retarded waves that travel into the future but not advanced waves that travel into the past. We can construct delay lines from which a signal emerges some time after it enters, but not "advance" lines from which a signal emerges *before* it enters.

The *thermodynamic* arrow of time is an arrow that is quite apparent after one has digested the concept of entropy, a measure of the disorder of the system. The second law of thermodynamics states that the entropy of an isolated system must always remain constant or increase with time. This natural law has an unusual status, in that it is not only confirmed by observation and experiment, but it has also been "proved" by Boltzmann in his famous "H-theorem." We will have more to say about the H theorem later. In any case, when we observe the manifest irreversibility of an egg being scrambled, a log burning, a automobile fender being crumpled, it is the thermodynamic arrow that is in operation.

The *cosmological* arrow of time is an arrow that, from one point of view, is not at all apparent. It is based on the hard-won realization that the universe is expanding with time, that the universe was smaller in the past and will be larger in the future, that space itself is stretching with time. This is an observation that slowly emerged from decades of careful work by Hubble and other astronomers who studied the systematics of Doppler shifts of light from distant galaxies. But from another point of view, the cosmological time arrow is also "obvious." If the universe were not expanding, but rather had been static or contracting over a time period spanning many billions of years, then the night sky, as first pointed out by Obler, would now have the average temperature of the surface of a star. Life as we know it would be impossible. The cosmological time arrow creates the condition of thermodynamic disequilibrium that makes life possible and in a sense is a precondition for all of our observations.

The *kaon* arrow of time is the time arrow that was discovered most recently and that remains the most mysterious. It arises from the discovery by Fitch and Cronin in 1964 that the K_L^0 meson can decay into two pi mesons, a violation of parity in a system which is its own charge-conjugate and is therefore a violation of CP invariance. Since CPT invariance is a property of essential all formalisms describing fundamental particles, the implications of this CP violation as an implicit violation of time reversal invariance in a microscopic system was immediately realized. Subsequently, it was inferred from measurements of the K_L^0 system that the weak charge exchange reaction $K_L^0 + e^+ \to \pi^+ + \bar{\nu}_e$ will have a distinctly different reduced cross section from that of the inverse reaction $\pi^+ + \bar{\nu}_e \to K_L^0 + e^+$. The K_L^0 system also shows a preference for matter over antimatter in that the probability for the weak decay process $K_L^0 \to \pi^+ + e^- + \bar{\nu}_e$ is larger than the probability for the charge-symmetric weak decay process $K_L^0 \to \pi^- + e^+ + \nu_e$. Zel'dovich has suggested[7] that there is a connection between the manifest matter-antimatter asymmetry of the universe and the cosmological arrow of time, in that the former "cancels" the latter, thereby preserving the overall macroscopic CPT symmetry of the universe. The action of CP non-invariant processes similar to the K_L^0 decay acting in the early Big Bang may have provided the agent for Zel'dovich's speculation.

One of the most profound unresolved problems of contemporary physics is to establish the connections and relationships between these several seemingly unrelated arrows of time. We would like to know which arrows are the causes and which are the consequences. This is an unresolved problem not because none have suggested answers but because there is no consensus and all such answers at present have the status of speculations. There are at least two families of models for the interconnections between the time arrows.

Figure 1 shows two block diagrams distinguishing these model families. Figure 1a illustrates what we shall call Model A, which might be called the present orthodox model. Authors that have advocated all or part of this scenario include Wheeler and Feynman,[1,2] Davies,[3] Layzer,[4] and more recently Hawking.[5] In model A the expansion of the universe (which may be connected in the early phases of the Big Bang through the kaon

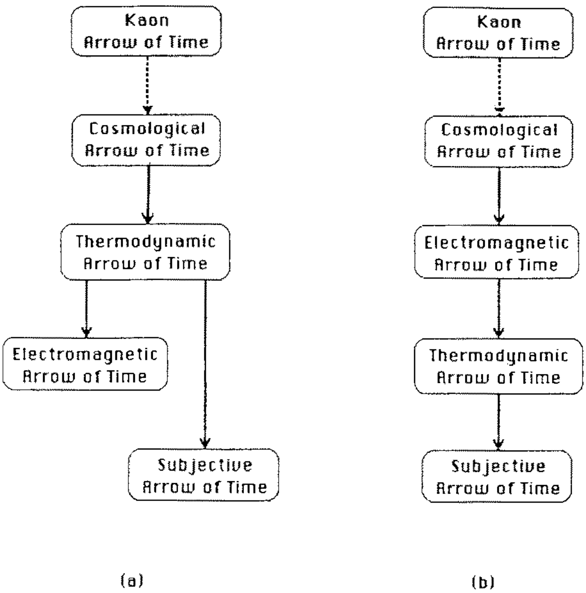

Fig. 1. Block diagram of the relationships of the various arrows of time as postulated by model *A* (Fig. 1a) and by model *B* (Fig. 1b).

arrow) has produced a condition of thermodynamic non-equilibrium. The macroscopic system, acting through the second law of thermodynamics, becomes progressively more disordered. The subjective arrow of time and the electromagnetic arrow of time are consequences of thermodynamic irreversibility.

Figure 1b illustrates Model *B*, an alternative scenario that was proposed in my 1983 paper on the arrow of time.[6] Here the Big Bang acts as a reflection boundary condition at time $T=0$, suppressing all advanced radiation travelling in the negative time direction. This suppression produces the electromagnetic arrow of time as an immediate and direct consequence of the Big Bang. The only allowed electromagnetic interactions are then through retarded potentials. The thermodynamic arrow then becomes a consequence of the electromagnetic arrow. Boltzmann's H-theorem can be interpreted[6] as demonstrating that entropy must increase with time under the cumulative influence of time-delayed interactions through purely retarded potentials. Thus the electromagnetic arrow becomes the cause of the thermodynamic arrow rather than its consequence. The thermodynamic arrow is in turn the cause of the subjective arrow of time.

The central difference between these two models centers around the connection between the electromagnetic and thermodynamic arrows. This in turn goes back to the interpretation of Boltzmann's H-theorem. Advocates of model *A* argue that while the basic interactions involved in the establishment of thermodynamic equilibrium are electromagnetic in nature, the particle velocities are so slow as to be completely non-relativistic, the interaction distances are small, and the intrinsic time delays arising from the retarded character of electromagnetic interactions must be completely irrelevant. Thus the thermodynamic arrow must be the more fundamental, and the electromagnetic arrow must be a consequence of it. And Boltzmann's H-theorem is often cited as demonstrating the independence of the thermodynamic arrow from the electromagnetic.

As an advocate of models *B*, I would argue rather differently. The time delay arising from the retarded interactions is indeed a tiny one, which must be cumulative to produce any observable effects and cannot be expected to show up in any measurable way in the first few (or indeed in the first few trillion) interactions. But Boltzmann's H-theorem provides a clue to the role of the retardation. One of the H-theorem's apparently reasonable assumptions is that the motions of colliding members of a system of particles are uncorrelated before a collision. This assumption smuggles into the problem an implicit time asymmetry which makes entropy constant or increasing with time. If one had, in the spirit of extending the H-theorem, assumed that the motions of colliding particles were uncorrelated after the collision, then it is demonstrated with equal rigor that the entropy was constant or decreasing with time. The retarded character of electromagnetic interactions insures that there will in normal systems be no such pre-correlations due to precursor interactions before the actual collision, and the retardation produces the post-correlations after the collision. Thus Boltzmann's H-theorem implicitly depends upon electromagnetic retardation for its derivation of the second law. In effect the second law of thermodynamics has been shown to be a consequence of the electromagnetic arrow of time.

The purpose of the present paper is to propose an experiment, at the level of a *gedanken* experiment, which distinguishes between model *A* and model *B* by giving a different result depending on which model is used. The experiment is a very simple one, at least in conception. A system under observation is isolated in the thermodynamic sense, and at a particular instant the velocities of all particles in the system are reversed. The question then is, does time run backwards for the system, in the sense that its recent history is reenacted in reverse order, or does it not? Model *A* would answer this question *yes* while Model *B* would answer *no*.

The reason for this difference should be apparent from this discussion. In the context of model *A* the system of particles is now prepared in just the state that will exactly reverse their motions. In the terms of the H-theorem their motions are now correlated *before* each collision in just the same way that they were correlated after the collision during their pre-reversal history. After velocity reversal the entropy of the system must decrease, or at least refrain from increasing, indefinitely as time progresses. Gas molecules escaping from a pressure bottle into a larger volume should now return to the bottle and recompress themselves.

In the context of model B the entropy of the system is not expected to decrease indefinitely. Velocity reversal produces a condition in which particle motions are correlated *before* each collision as they were after previous collision, but such pre-correlations will ultimately be destroyed because the intrinsic retardation of the intractions has not been reversed with the velocities. The system has not been truly time reversed because the arrow of electromagnetic time remains pointing in the same direction. In practice, one would expect an initial tendency, as predicted by the generalized H-theorem, for a decrease in the entropy of the system after the velocity reversal, but this effect should rapidly die away as the cumulative effects of many retarded interactions wash out the pre-correlation.

Thus we are able to distinguish between the model A and model B accounts of the arrow of time problem in their predictions of the outcome of the proposed *gedanken* experiment. It is always of value to identify and consider such dichotomies when considering rival models which can not yet be confronted with experimental tests. It is the next best thing to actual testing.

How feasible is the velocity reversal *gedanken* experiment? Interestingly enough, there are two techniques which are very much in the direction of the experiment proposed. The first is the well known "spin echo" technique. In such an experiment the nuclei of a paramagnetic salt are initially aligned in a magnetic field and then allow to precess in an external magnetic field. In systems with many spin projections or with varying local fields, the nuclear dipoles will precess at different rates and the alignment will soon be destroyed. Then the external field is reversed. This causes all of the individual nuclear dipoles to suddenly reverse their precessions. They then "undo" the precessions and the system is restored to a state of alignment or partial alignment. One can study how the degree of restored alignment depends on the length of time after precession began when the field reversal was executed. This procedure, of course, does not reverse all velocities. It only reverses those associated with spin precession, and so the dissipation of alignment with time has more to do with thermal perturbations than with the actions of retarded interactions. Nevertheless, it represents a parallel to the proposed *gedanken* experiment which is worth considering.

Laser physicists have provided us with another technique for performing the operation of velocity reversal on a system of light photons. The apparatus for performing this is called the four-wave conjugate mirror. To understand what this device does, let us first consider what an ordinary mirror does. Basically, a mirror reflects light by reversing the component of the light's electric field which is perpendicular to the mirror surface. This makes the light change direction, moving away from the mirror but usually also away from the direction from which it came.

The four-wave conjugate mirror is quite different from an ordinary mirror in that it reflects all three velocity components of the light waves. If the waves start with the functional form $\exp(+i\mathbf{k}\cdot\mathbf{r})\exp(-i\omega t)$ then after the four-wave reflection the wave would have the form $\exp(-i\mathbf{k}\cdot\mathbf{r})\exp(-i\omega t)$. This operation constitutes perfect space reversal but not time reversal which would also convert the $\exp(-i\omega t)$ factor to $\exp(+i\omega t)$. This kind of reflection is accomplished by mixing the incoming light wave with two oppositely directed plane waves of light generated by lasers within the apparatus. These three waves interact with a transparent medium through which they pass to produce a fourth wave which is the spatial reverse of the initial wave. In effect the incoming light wave and one of the plane waves combine to inscribe a temporary hologram on the medium, and the other plane wave (the space reverse of its counterpart) then interacts with this hologram to produce the space-reverse of the incident wave.

Since the fourth wave is the reverse of the incoming wave it will go back along precisely the same path taken by the incoming wave. If the original wave was spreading out from a source point, the new wave will converge back to that source point. If the original wave was distorted and diffused by irregularities and dust particles in the intervening air, the new wave will travel back through the same irregularities and *undo* the distortions to produce a wave just like the one which originally emerged from the source. The photons comprising the fourth wave are just velocity flipped counterparts of the photon particles which entered the apparatus. Thus at least for photons we have just the kind of velocity reversal apparatus contemplated in the *gedanken* experiment.

Another way of addressing the problem posed here is to perform a computer experiment rather than a real one. The time evolution of a system of particles could be computed, and at a selected time their velocities could be reversed. A comparison of time-symmetric contact interactions with proper retarded electromagnetic interactions could test the assertions of the two models described. However, this test may not be possible even with presently available supercomputers. Recent studies of evolving multiparticle systems have shown that even when time-symmetric contact interactions are used, the system cannot be properly reversed by velocity reversal because of the "noise" introduced by the cumulative effects of small roundoff errors in the calculations. Until a calculational precision is achieved in which such roundoff effects become negligible compared to the effects of retarded interactions, the test described previously is not feasible. However, the very fact that roundoff noise removes the reversibility of the calculations may in itself be taken as evidence that the cumulative effects of retarded interactions will have a similar effect, thus favoring the predictions of model *B*.

It should be noted in closing that the entropy decrease expected from the velocity reversal operation discussed here does not represent a violation of the second law, any more than does the temperature drop in the interior of a refrigerator. A system being operated on by external apparatus is not an isolated system, in the thermodynamic sense, and the second law applies only to isolates systems. To assess the actions of the second law one would have to include the effects of the velocity reversal operation on the apparatus which produces the velocity reversal. In the opinion of the author, the entropy of the overall system will certainly increase with time in accordance with the second law.

REFERENCES

1. J. A. Wheeler and R. P. Feynman, *Rev. Mod. Phys.* **17**, 157 (1945).
2. J. A. Wheeler and R. P. Feynman, *Rev. Mod. Phys.* **21**, 425 (1949).
3. P. C. W. Davies, *The Physics of Time Asymmetry* (University of California Press, Berkeley, 1974).
4. D. Layzer, *Vistas of Astronomy, Vol. XIII* (Pergamon Press, New York, 1972).
5. S. W. Hawking, *Phys. Rev.* **D32**, 2489 (1985).
6. J. G. Cramer, *Found. Phys.* **13**, 887 (1983).
7. Ya. B. Zel'dovich and I. D. Novikov, as quoted in G. Steigman, *Annual Rev. Astron. Astrophys.* **14**, 339 (1976).