

BLACK-HOLE UNCERTAINTY ENTAILS AN INTRINSIC TIME ARROW

A Note on the Hawking-Penrose Controversy

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Abstract

Any theory that states that the basic laws of physics are time-symmetric must be strictly deterministic. Only determinism enables time reversal of entropy increase. A contradiction therefore arises between two statements of Hawking. A simulation of a system under time reversal shows how an intrinsic time arrow re-emerges, destroying the time reversal, when even slight failure of determinism occurs.

PACS: 01.55.+b; 03.65.Bz; 04.70.Dy; 05.70.-a

Keywords: Time's arrow; Black holes, Indeterminism, Information loss

The Second Law of Thermodynamics has been dismissed by the majority of authors as observer-dependent. As proved by Hawking [1], has the Universe's entropy increase been reversed, this reversal would be impossible to observe. This is because the time orientation of all biological processes (as we show elsewhere in detail [2, 3]) relies solely on entropy's increase. Consequently, our memory and our distinction between "past" and "future" are similarly oriented. Has the Universe's entropy increase been reversed, memory and perception would run backwards too. It therefore cannot be ruled out that we actually live in a universe whose entropy is decreasing.

One might try to dismiss this possibility by arguing that such unique initial conditions that lead to entropy decrease are highly improbable. Unfortunately, probabilistic arguments become circular when applied to the entire Universe [4]. We assign different probabilities to past and future states, yet *the very notions of "past" and "future" are, by convention, based on the entropy gradient*. When observing a system's evolution, one assigns the temporal designations "earlier" and "later" according to the universal entropy gradient prevailing outside the system. No such external reference arrow exists for the Universe itself. Probability theory cannot, therefore, rule out that the Universe's entropy increase, as well as all the related perceptual processes, run backwards. Rather, within the four-dimensional Minkowskian spacetime, entropy can be equally described as increasing or decreasing, depending on one's arbitrary choice of time direction [5].

What, then, is the cause of entropy's "increase"? Hawking [6] and Penrose [7] have long been taking opposing views on this issue, their debate being recently published as a book [8]. Penrose believes that the long-desired theory of quantum gravity will eventually reveal an intrinsic time-asymmetry that would account for the macroscopic entropy increase. Hawking, in contrast, argues that entropy increase only reflects some unique initial conditions in the universe's evolution ([8], p. 8). Causation itself, he stresses, is perfectly time-symmetric:

So if state A evolved into state B, one could say that A caused B. But one could equally well look at it in the other direction of time, and say that B caused A. So causality does not define a direction of time ([9], p. 346).

On one point, however, both adversaries agree. For reasons revealed long ago by Hawking [10, 11], black holes must eventually evaporate in the form of purely thermal radiation. Now, both Penrose and Hawking agree that all the information about the objects that have fallen into the black hole is destroyed when the black hole evaporates. Unlike the ordinary loss of information due to mixing or noise (which can, in principle, be retrieved), information loss by black hole evaporation is absolute. In Hawking's words: "quantum gravity introduces a new level of unpredictability into physics over and above the uncertainty usually associated with

quantum theory” ([8], p. 60).

We would like to show that Hawking’s two assertions are mutually incompatible. If information is destroyed, by whatever process, then time’s arrow is inherent to causality itself. This conclusion would then rule out the awkward possibility that entropy increase, with the concomitant psychological time arrow, run backwards.

It should be stressed that we do not attempt to prove Hawking’s information-loss hypothesis but only point out its surprising consequences. Our conclusion, however, rigorously applies to any other theory that makes a similar assumption, be it the GRW model of spontaneous collapse [12], Penrose’s [7] hypothesis concerning the role of gravity in quantum measurement, or any other assertion that information is really destroyed. The gist of our argument is this: *i)*Information loss indicates indeterminism. *ii)*Indeterminism in itself is as time-symmetric as determinism. *iii)*However, in a world in which entropy is increasing, indeterminism indicates that causality is asymmetric: Low entropy events determine high entropy events - but not *vice versa*.

1 Indeterminism Entails a Universal Time-Arrow

There is a well-known yet crucial difference between the normal, entropy increasing evolution, and the time-reversed, order increasing one. *The latter, not the former, requires infinitely precise pre-arrangements of all the system’s elementary particles.* For a normal process, no special care is needed to arrange its particles so as to increase entropy. Boltzmann’s definition of entropy, $S = k \ln W$, indicates that there are numerous microscopic arrangements that make disordered states but only few arrangements that make ordered ones. Hence, nearly every initial arrangement will eventually give rise to entropy increase. Consequently, a change in the initial arrangements can hardly affect entropy increase (Fig. 2a). Not so with the time-reversed system: The slightest change in the position or momentum of a single particle will create a disturbance in the system’s evolution that - given sufficiently many interactions between the particles - will further increase as the system evolves. Consequently, entropy will increase in the time-reversed system too (Fig. 2b). As Yakir Aharonov vividly puts it, take out one worm from a dead person’s grave, and the time-reversed evolution will fail to bring him or her back to life.

This restriction is almost trivial, but its far-reaching consequences have not been explored. Had physics been able to prove that determinism does not always hold - that some processes are governed by fundamentally probabilistic laws - it would follow that entropy *always* increases, regardless of the system’s initial conditions. An intrinsic time-arrow would then emerge in *any* system, independent of the initial conditions. Rather, the emergent time arrow would be

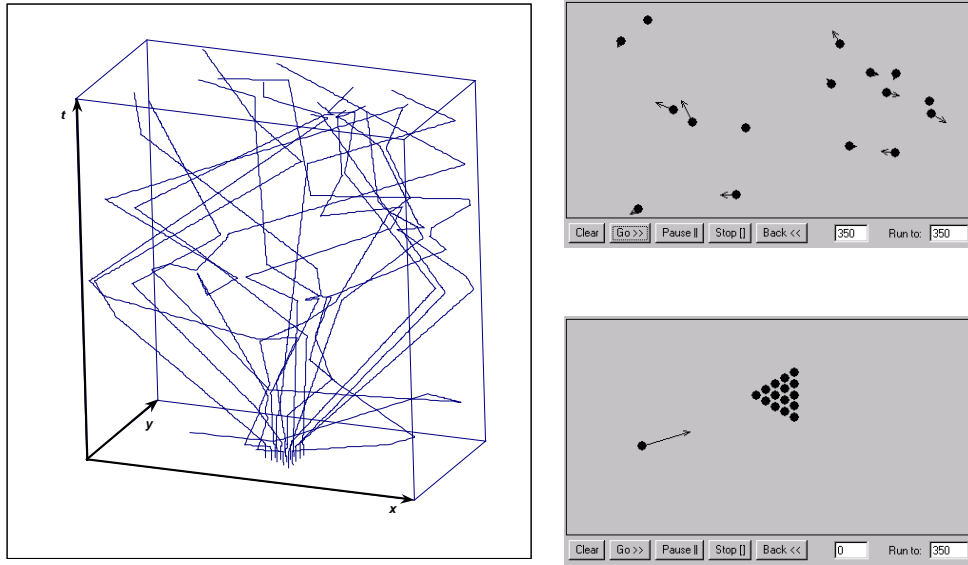


Figure 1a: A computer simulation of an entropy increasing process, with the initial and final states (right) and the entire process using a spacetime diagram (left). One billiard ball hits a group of ordered balls at rest, dispersing them all over the table. After repeated collisions between the balls, the energy and momentum of the first ball is nearly equally divided between the balls.

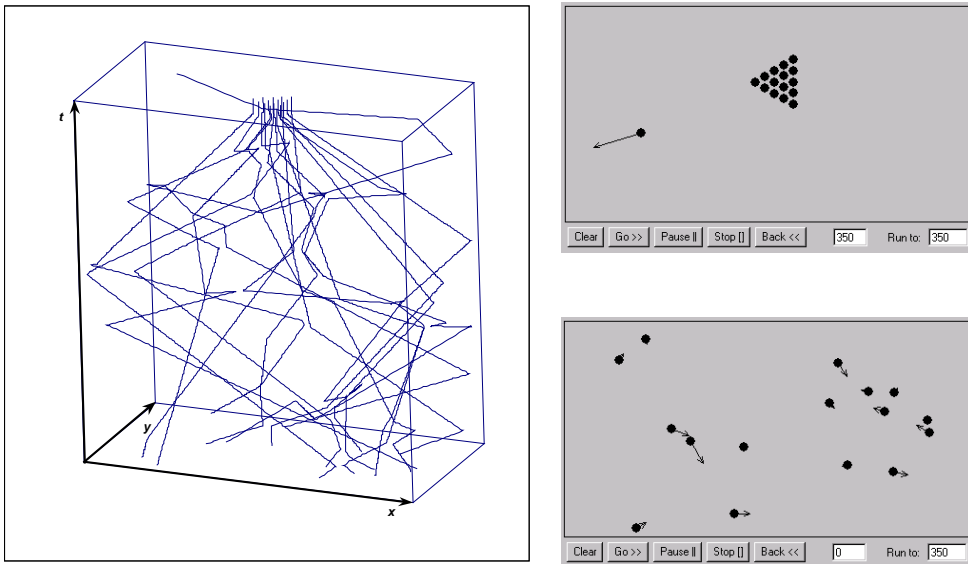


Figure 1b: The time-reversed process. All the momenta of the balls are reversed at $t=350$. Eventually, the initial ordered group is re-formed, as at $t=0$, ejecting back the first ball.

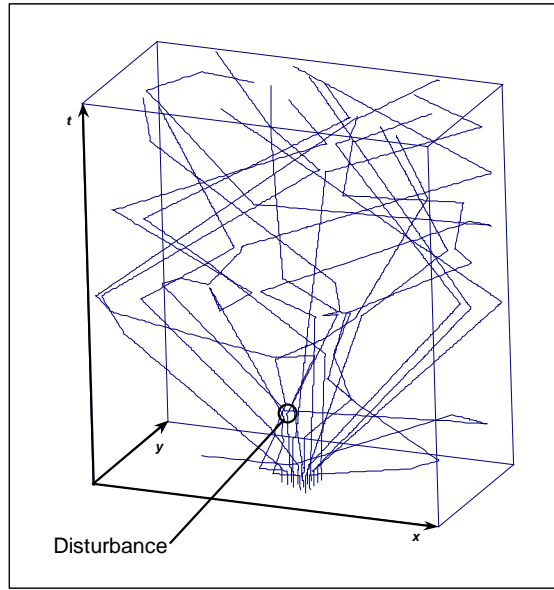


Figure 2a: The same simulation as in 1a, with a slight disturbance in the trajectory of one ball (marked by the small circle). Entropy increase seems to be indistinguishable from that of 1a.

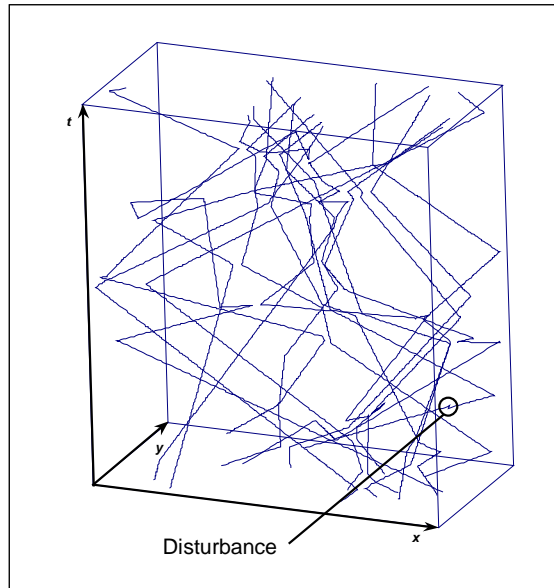


Figure 2b: The same computer simulation as in 1b, with a similar disturbance. Here, the return to the ordered initial state fails.

congruent with that of the entire universe, of which closed systems are supposed to be shielded.

2 Quantum Mechanics does Not Disprove Determinism

At first sight, quantum mechanics seems to have disproved determinism long ago, thereby giving an intrinsic time arrow. A closer consideration, however, shows that QM has never ruled out the possibility that determinism still exists at some unobservable level [13, 14].

To see this, let us examine an alleged demonstration quantum mechanical indeterminism often used by Penrose [7, 15]. A half-silvered mirror splits the wave function of a single photon such that one half hits a detector and the other half goes to the wall. In 50% of the cases, the detector will click. Suppose now that we time-reverse this process. The photon's wave function will be split again by the beam splitter when going back, thereby giving 50% probability for not returning to the lamp but rather going to the opposite wall. This, for Penrose, indicated time-asymmetry at the quantum level.

Recently, however, Penrose [8] conceded that this asymmetry may merely be reflecting the asymmetry of the boundary conditions. In the normal time-evolution, half of the wave function initially goes to the wall. Now this half wave function is a real physical phenomenon: Reflected back by a mirror, this half can be used to create interference effects (The Elitzur-Vaidman bomb-testing experiment [16], to which Penrose [15] gives a vivid exposition, proves how real this "empty" half is.). Therefore, for a real time reversal to take place, the wall's absorption of the half wave-function (i.e., its interaction-free measurement) must be reversed too. Once we took care to make the time reversal thus complete, the photon would indeed return to the lamp from which it was initially emitted. Penrose, of course, believes that this would not happen, for he regards "collapse of the wave function" as a real process. However, no experiment is known today that can favor this interpretation over other, time-symmetric ones. For example, the "guide wave" or the "many worlds" interpretations assume that some hidden variables, in the form of empty waves or parallel universes, remain after the measurement, preserving all the seemingly-lost information (see Unruh [17] for another objection to Penrose's argument).

Quantum mechanics, therefore, just like classical physics, allows any process to be time-reversed under the appropriate initial conditions.

3 Hawking's Information-Loss Hypothesis

It is black holes, however, that seem to provide what we are looking for. As noted in the introduction, Hawking claims that all the in-falling matter's information, save the conserved

quantities M , Q , and J , is obliterated by black hole evaporation. While a detailed review of the debate concerning Hawking's hypothesis is beyond the scope of this paper, we shall briefly mention the hypothesis and the counter arguments and then, without taking a stand, we shall point out the bearing of this hypothesis on the question of time asymmetry.

Due to the Hawking effect [10, 11], black holes must eventually evaporate. Since the resulting radiation comes from quantum vacuum fluctuations at the black hole's horizon, it seems to be absolutely thermal, being unrelated to, and preserving nothing of the black hole's content. This gives rise to entropy that is not due to coarse graining, as in classical physics. Rather, the entropy seems to be absolute.

Naturally, Hawking's claim has raised several objections, yet none turned out to be decisive. Especially the loss of unitarity seems disturbing. Among the most radical attempts to preserve unitarity is t'Hooft's [18] S-Matrix approach, which assumes that a pure state of a complete system would always go to a pure state, hence no information is lost. But as t'Hooft himself admits, the model is still hypothetical (see also Page [19]). Other authors pointed out that, for external observers, nothing really crosses a black hole's horizon; the gravitational time-dilation red-shifts the fallings objects to the point where they "freeze" on the horizon, never really appearing to cross it. However, for a freely-falling observer, the horizon is devoid of physical significance; it will be crossed soon, and no "frozen" object would appear. The case is similar to that of black-hole formation: here too, the imploding matter was believed to "freeze" before reaching the critical circumference. Yet Finkelstein [20] has shown how to reconcile the two accounts, that of the external observer and that of the freely-falling one, into one, self-consistent account. Arguments based on reference frames are therefore insufficient for dismissing Hawking's paradox [21].

Preskill [22], initially Hawking's opponent, has thoroughly reviewed all the proposals to avoid the information loss paradox and found all of them deficient. "The information loss paradox," he concludes, "may be a genuine failing of 20th Century physics, and a signal that we must recast the foundations of our discipline."

We submit that, if Hawking's argument is sound, then its most immediate bearing has gone unnoticed so far. It reveals a fundamental origin of time symmetry.

Consider, then, the following thought experiment. Let a closed system undergo a normal evolution, such that its entropy increases with time. Also, let the system have enough mass and time to allow a black hole to form and evaporate. Opening the system after sufficient time, we find that its entropy has increased. This is not surprising: If Hawking's hypothesis is correct, the particles into which the black hole has evaporated could not preserve the positions and momenta

of the objects swallowed earlier by the black hole. Hence, the black hole has only added to the system's entropy, in a way similar to that of the event in Fig. 2a where the causal chain was interfered with.

Consider next the time-reversed system. Let there be a similar closed system, with the positions and momenta of all its particles pre-correlated with great precision such that its entropy would decrease with time. And here too, the amount of matter and the time allocated to the system suffice for the formation and evaporation of a black hole. Opening the system at the end of the experiment, we find that the time-reversal has failed: Entropy has increased in this case too.

The reason is clear: The black hole's information destroying effect has ruined the pre-arranged correlations with which the initial state has been prepared. This parallels the simplified case shown in Fig. 2b, with the difference that the failure of determinism entailed by the black hole effects not only one but *numerous* particles. Let us put this failure in physical terms. Preparing a black hole in a time-reversed system amounts to preparing a *white hole*, i.e., a singularity from which light as well as macroscopic objects are ejected. But this is precisely what we cannot do. In order to create a white hole, numerous thermal particles must be directed towards one point. This is the time-reversal of the black hole's evaporation. With a sufficiently huge number of particles a singularity will indeed form, which will later evaporate. However, when it evaporates, then, by Hawking's hypothesis, it evaporates again into particles whose spectrum is *thermal*; no objects with complex physical attributes can emerge from it. Although Hawking seems to be unaware of it, his hypothesis provides a perfect explanation for the absence of macroscopic white holes.

A normal system, then, increases its entropy when an information-erasing event is formed within it, but so does a time-reversed system. The conclusion therefore follows: *In any closed system that gives rise to an information-erasing singularity, an intrinsic time-arrow emerges that disregards the system's boundary conditions, but complies with the time-arrow of the universe, of which closed systems are supposed to be shielded.*

4 Summary

In mainstream physics, the Second Law is not a real law but rather a consequence of the universe's initial conditions; under special initial conditions, the Second Law can be reversed.

We have shown that this assertion is correct only under absolute determinism. With even the slightest failure of determinism, an intrinsic arrow of time must emerge in any closed system, regardless of its initial conditions, but with perfect accordance with the time arrow of the entire

universe, despite the system's isolation.

The implications of this inherent time arrow for the nature of time are very far-reaching, and discussed in detail elsewhere [4]. If future events are indeed devoid of causal efficacy on past events, then the awkward possibility mentioned at the beginning of this paper, namely, that we live in an entropy-decreasing universe while unable to observe it, would be ruled out at last. But then, the very definition of time as a dimension in Minkowski's 4-geometry requires revision.

Our conclusions equally apply to all other theories that assume genuine indeterminism. Thus, although proponents of the indeterministic interpretations of quantum mechanics are generally unaware of it, their interpretations imply that causality itself is the origin of time asymmetry.

5 Acknowledgments

This work was supported in part by The Stewart and Judy Colton Foundation. It is a pleasure to thank Yakir Aharonov for many illuminating discussions.

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