TIME'S ARROWS POINT BOTH WAYS

THE VIEW FROM NOWHEN

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Suppose you are in a closed room full of people. Somebody opens the door and all the air rushes out of the room and everyone inside explodes and dies. Of course, we have all been in closed rooms many times and this has never happened. Based on that experience, and the experiences of everyone else throughout history, we have no reason to fear closed rooms. And you probably think that physics confirms that trust.

Most of us were taught in school that certain physical processes are irreversible, that is, can only happen in one time direction. In the absence of an external energy source, heat never flows from lower to higher temperature. Broken glasses do not spontaneously reassemble and people do not get younger. And, air inside a chamber never rushes out of an aperture, leaving behind a vacuum. All these processes are forbidden, we were told, by one of the basic laws of physics: the second law of thermodynamics. Well, we were mislead. Reverse processes are not strictly forbidden by any known principle of the mechanics of particle motion. A broken glass can reassemble if its molecules just happen to be moving in the right direction. A dead man can even rise. The air molecules in the room can be moving in the direction of the door at the instant the door is opened and kill everyone inside.

True these are all highly improbable events and not likely to happen in the age of the universe. But, technically they are not impossible. As Ludwig Boltzmann proposed over a century ago, the second law of thermodynamics is not a deterministic law of physics but rather a statement of probabilities. In 1928, Arthur Eddington introduced the expression "arrow of time" to represent the apparent one-way property of time that has no analogue in space. He associated the arrow with an increasing random element in the state of the world, as expressed by the second law. Eddington recognized that molecular motions were intrinsically reversible, but that they tend to lose their organization and become increasingly shuffled with time. He regarded the second law as a fundamental principle of the universe, saying it occupied "the supreme position among the laws of Nature."[1] However, he did not address the basic issue of why the molecules were organized in the first place.

THE COSMOLOGICAL ARROW

The entropy of the universe today is about 100 orders of magnitude higher than it was in the very early universe and at least 23 orders of magnitude lower than it will be eventually as the universe approaches heat death. This huge entropy difference defines a cosmological arrow of time. Oxford mathematician Roger Penrose has argued that the existence of the cosmological arrow requires a new law of physics and that quantum gravity is about the only place left to look for such a law.[2] However, the cosmological and thermodynamic arrows of time are clearly related. In each case we have fully or partially isolated systems where the entropy increases along the same time direction. We choose the positive time axis to point in that common direction. As philosopher Huw Price points out, the issue is not that an entropy gradient leads to an arrow of time, but explaining the source of that gradient.[3]

Why is the entropy so low at one end of the time axis and so high at the other? Davies and Twamley have suggested that the exponential inflation now believed to have occurred in first tiny fraction of a second of the big bang provides the way out.[4] Price, however, objects that they are applying a double standard in assuming a time direction to begin with and then having it appear as a result.[5] However, I think the Davies and Twamley basic idea can be made to work.

The idea is to maintain underlying time symmetry while allowing "localized" violations, a trick that has worked for other symmetries in particle theory. Like those symmetries, time symmetry becomes a global rule that is locally broken, where by "local" here I am referring to the region of spacetime occupied by our universe since the beginning of the big bang. Let the big bang begin at an arbitrary point on the time axis we label $t = 0$. According to the inflationary big bang model, the universe was empty of matter and radiation at that time. However it was not nothing. A quantum fluctuation in the presumably pre-existing nothing produced a non-zero curvature that appears in. Einstein's general relativity equations as the infamous cosmological constant.

The simple solution of the equations in this case, the de Sitter solution, yields an exponential expansion e^{Ht} in which H is proportional to the square root of the cosmological constant. This is inflation, which is eventually (in 10^{-35} second or so) brought to a halt by particle production and a corresponding entropy generation.[6] The traditional big bang expansion then follows. Now the square root of a number can be negative just as well as positive. Thus, technically, the solution of Einstein's equations must contain a term with a negative H as well. This will lead to exponential deflation instead of inflation on the positive side of the t-axis. That is, the total effect is a superposition of inflation and deflation. However, the deflationary term can be neglected since it will be quickly overwhelmed by the inflationary term.

Let us ask next what happens on the usually-ignored negative side of the t-axis. There, because of the negative value of t, the positive H factor term will deflate and become negligible, while the negative H factor term will inflate. Thus we get a completely time-symmetric inflation on both sides of the t-axis: two universes (really the same universe), one with its time arrow forward in conventional time and one with its time arrow going in the opposite direction. The universe as a whole is then time-symmetric. Although a huge "local" asymmetry exists on our side of the t-axis, it is matched by a similar local asymmetry on the other side.

What about this other side, the side in our past—before the big bang? We would not expect it to be an exact mirror image of ours, given quantum indeterminacy, but we will probably never know. All the information about that part of of our universe would likely have been destroyed in the chaos near t = 0.

THE RADIATION ARROW

A third suggested arrow of time is provided by radiation. Like the other equations of physics, Maxwell's equations of electromagnetism show no preference for a direction of time. The usual solutions are called "retarded," with electromagnetic waves arriving at the detector after they left the source. However "advanced" solutions which arrive at the detector before they leave the source are also allowed. These are usually eliminated in practice by asserting, as a "boundary condition," the fact that they are not observed. This apparent asymmetry is identified as the arrow of radiation.

In 1956, philosopher Karl Popper wrote that the simple observation of water waves provides evidence for a temporal asymmetry other than the thermodynamic variety.[7] Toss a rock in a pond and you will see circular waves radiating outward. The time-reversed process of waves converging on a point is never observed. However, Davies[8] and Zeh[9] have both disagreed, arguing that the radiation arrow follows from the thermodynamic one, which is basically statistical. In principle, waves could be generated around the edge of the pool resulting in a converging wave front, but this would require coherence all the way around which is statistically very unlikely. But, that is just what the thermodynamic and cosmological arrows are all about—the low probability for certain phenomena to be seen running in reverse direction from which they are normally observed.

Price, however, criticizes these arguments as again applying a double standard by assuming that we only have diverging but no converging radiation in nature.[10] Looking in reverse time we see converging waves and we have to explain why we see no diverging ones. The problem, in other words, is not with the convergence or divergence but with the highly special circumstances that exist in the center of the pool where the rock hit the water. As was the case for the thermodynamic and cosmological arrows discussed above, in order to explain the evident asymmetry we have to explain why, in our world, we have these special regions where entropy is exceptionally low.

Price relates the radiative arrow to the difference between sources and absorbers in the macroscopic world. Microscopically we see no difference. An oscillating charge is a source of a coherent electromagnetic wave that propagates through space and sets another charge at a different location oscillating with the same frequency. This is indistinguishable from the time-reversed process in which the second particle is the oscillating source and the first is the receiver.

Macroscopically, coherent sources of radiation, whether water or electromagnetic waves, are far more prevalent than coherent absorbers. The rock dropped in the pool sets up a coherent wave in which many atoms in the water are set oscillating in unison. The atoms in the wall around the pool are rarely oscillating in unison so that they can emit a single coherent wave that converges back on the original source.

When we look at phenomena at the quantum level, the distinction between source and absorber disappears. A photon emitted by a quantum jump between energy levels in an atom can travel in a straight line and excite another atom in a nearby detector. This process can be readily reversed, with the second atom de-exciting and emitting a photon that goes back along the same path re-exciting the source. For quantum events then, the processes of emission and absorption are perfectly reversible. As with the cosmological arrow, the arrow of radiation is indistinguishable from the arrow of thermodynamics. Again it represents an arbitrary choice we make based on the fact that most macroscopic, or more precisely, most many-body processes exhibit an entropy gradient that arises from the large contribution that randomness makes to these phenomena. And, as I have shown, we can attribute the large entropy gradient to the huge cosmological asymmetry that exists on each side of the t-axis to inflation in the early universe.

THE QUANTUM ARROW

Now let us consider the arrow of time that seems to be associated with quantum phenomena. We will see that it, too, is an artifact. Furthermore, we will see how time reversibility at the quantum scale makes it possible for us to understand some of the puzzling features of quantum mechanics. Indeed, quantum events seem to be yelling at physicists that the universe has no intrinsic arrow of time, but most refuse to listen.

Roger Penrose is one of the strong proponents of a fundamental arrow of time. As discussed above, he has sought an arrow of time in cosmology. He has also looked for one in quantum mechanics, claiming that the quantum mechanical process called *wave function collapse* is inherently time-asymmetric.[11] He claims to illustrate this with a simple example that I have redrawn in Figure 1. A lamp L emits photons in the direction of a photocell (small photon detector) P. Halfway between is a half-silvered mirror M arranged at forty-five degrees so that the photon, with fifty percent probability, will go either straight through to P or be reflected toward the laboratory wall in the direction W. The paths are indicated by the solid lines in the figure. The lamp and photocell also contain registers that count the photons emitted and detected. Penrose then asks: "Given that L registers, what is the probability that P registers?" His answer follows from quantum mechanics: "one-half."

Penrose then considers what he calls the "reverse-time procedure" in which a backwards-time wave function represents a photon that eventually reaches P. This wave function is traced "backwards in time" to the mirror where it divides, implying a fifty-fifty chance of reaching the lamp L. He then asks: "Given that P registers, what is the probability that L registers?" His answer: "one." His reasoning is as follows: "If the photo-cell indeed registers, then it is virtually certain that the photon came from L and not the wall!" The conventional application of quantum mechanics thus gives the wrong answer in the time-reversed direction and so, Penrose concludes, that the process must be time-asymmetric. While this is correct for the process Penrose describes, note that this is not what you would actually see watching a film of the event being run backwards through the projector. This, more literal reverse-time process is indicated by the dashed lines in Figure 1. There the photons that are absorbed in the lamp come from two sources, the detector P and the wall. All the photons registered at P also register at L, as in Penrose's example, but the lamp also receives additional photons from the wall.

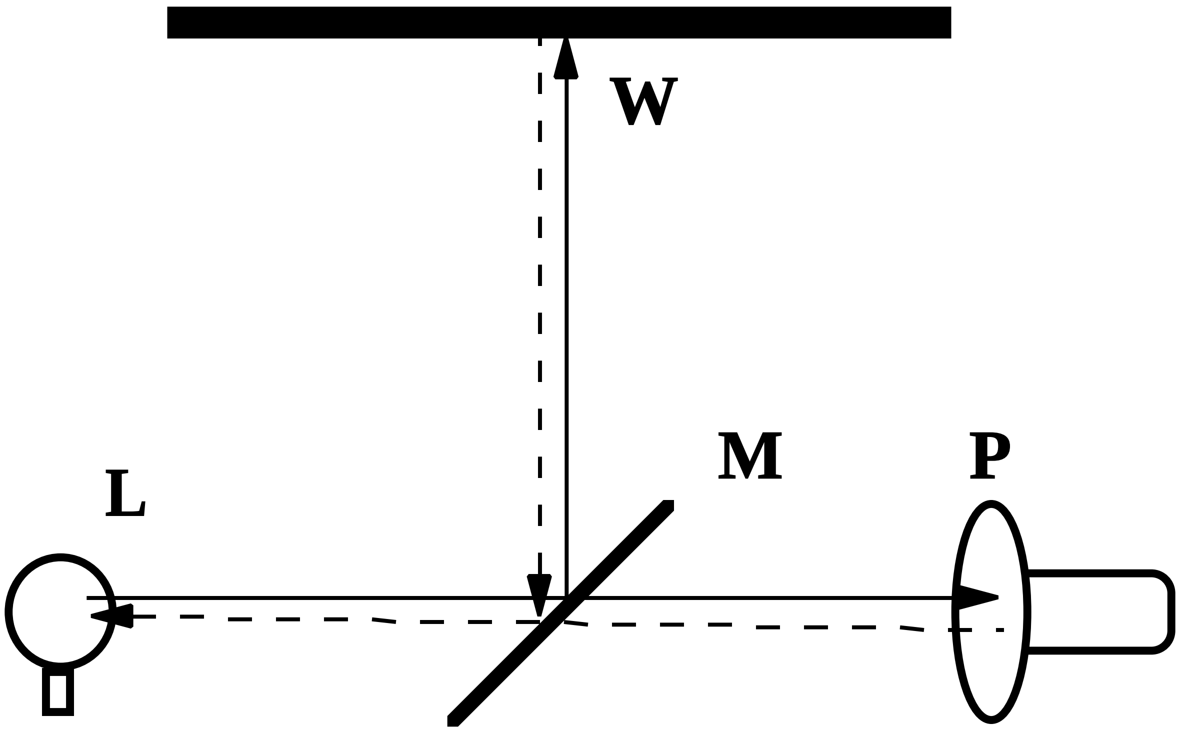

Figure 1 . Photons from lamp L have a fifty-fifty chance of either going through the mirror M to the photodetector P or reflecting from M and being absorbed by the wall at W. In the time-reversed process, as imagined in a film run backward through the projector, half the photons are emitted by P and half by the wall, all returning to the lamp at L. At the quantum level, sources can act as detectors or absorbers, and detectors or absorbers as sources. Irreversibility occurs at the macroscopic level because macroscopic sources and detectors are not in general reversible. This figure is based on Figure 8.3 in Penrose 1989 (ref. 2).

If the experiment were a purely quantum one, with single atoms as sources and detectors, then it would be completely time reversible. The irreversibility that Penrose sees is exactly the same irreversibility I talked about earlier, an effect of the large amount of randomness in macroscopic many body systems. Now, Penrose argues that the actual experiment is done with a macroscopic lamp L, macroscopic detector P, and macroscopic walls and so it is irreversible. That is, L is not normally a detector and P or the wall is rarely a source.

True, but this is the situation I described above while discussing the arrow of radiation. There I showed that the radiation arrow results from the asymmetry between macroscopic sources and detectors in our particular world. That is, they are part of the boundary conditions of the world of our experiences and nothing fundamental. Most lamps are not reversible as detectors, although lasers, being quantum devices, are in principle reversible. Most macroscopic detectors, like photographic film or photomultiplier tubes, cannot be reversed into sources, or, at least, very efficient ones. Furthermore, walls do not emit the kind of narrow beam of visible photons we are assuming in this experiment, although they do emit incoherent thermal radiation. Lamps, detectors, and absorbing walls do not look the same in the mirror of time. However, like the face of the person you see when you look in the bathroom mirror, which is strangely different from the one you see in a photo, what is seen in a mirror is not strictly impossible.

Let us peer more deeply into the lamp, detector, and wall. Consider the primary emission and absorption processes that take place at the point where the photon is emitted or absorbed. In "forward time," an electron in an excited energy level of an atom in the lamp drops down to a lower energy level, emitting a photon. This photon is absorbed in either the wall at W or the detector P in Figure 1, with an electron being excited from a lower to a higher level in an atom at either place. In "backward time," the wall or the detector emits a photon by the same process as the lamp in forward time while the lamp absorbs the photon.

It is true that in actual practice the wall and detector will irreversibly absorb photons, converting their energy to heat and gaining entropy. But if we could do the experiment with a purely quantum lamp, detector, and wall composed of a single atom each with the same energy levels, as say a hydrogen atom, then the process would be completely reversible.The irreversibility in the Penrose experiment is still statistical and the result of asymmetric boundary conditions imposed on the experiment, not the result of any fundamental principle of physics. The quantum arrow is the same as the thermodynamic/cosmological/radiation one. And so, time symmetry remains deeply embedded in both classical and quantum physics.

SOLVING THE QUANTUM PARADOXES

At the quantum level, information flows readily in either time direction. Indeed, this is exactly what has been demonstrated in a number of now-famous quantum experiments. Perhaps the best known is that of Aspect and his collaborators that tested the Einstein-Podolsky-Rosen paradox.[12] This has been described in many books so I will not go into the details here.[13] Basically, quantum experiments of this genre indicate that changes in the arrangement of the detection apparatus seem to act back in time to affect the earlier state of the system being observed.

I must comment that while these experiments have received much media attention, most physicists have generally been underwhelmed. The results always come out in perfect agreement with quantum mechanics, which has been around now for 75 years. Thus the typical physicist reaction has been "What else is new?" The continuing debates over quantum mechanics that one reads about concern its philosophical or even metaphysical interpretation, not its ability as a mathematical theory to describe the data. So, speaking metaphysically, to the undoubted disgust of most of my colleagues, time reversibility easily accounts for many of the observations in quantum experiments, such as the backward causality in EPR experiments, that many people regard as paradoxical. Indeed, the Aspect et al experiment is almost trivial when viewed in reverse conventional time and one can only wonder what the big deal is all about.

Other strange features of quantum systems, such as apparently instantaneous quantum jumps or particles appearing to be at different places at the same time, can be readily understood. Just as you are able to be in the same place at two different times by walking up the street and back, an electron or photon can be two places at the same time by starting at one place, going back in time and then forward again to a new place. Indeed, this "zigzagging" in spacetime was introduced by Richard Feynman in 1949 and is now built into modern particle theory.[14] However, Feynman never pushed the idea of time reversibility and most physicists preferred the less economical, though admittedly equivalent, view that two kinds of matter exist, both going forward in time, rather than one kind that can go either way.

The idea that time reversibility can help resolve the apparent paradoxes of quantum mechanics has been floating around for about half a century, so no parenthood is being claimed here for that notion. In 1953, Olivier Costa de Beauregard suggested that the EPR paradox can be understood in terms of time reversibility and thus not require-the nonlocality (superluminality) that seems otherwise unavoidable.[15] However, influential figures, like John Bell, were dissuaded from incorporating time reversal into interpretations of quantum mechanics by the causal paradox implied by time travel.[16] If the time travel paradox can be resolved at the quantum level, then the way is open for time symmetry to be a part of any quantum interpretation.

SOLVING THE TIME TRAVEL PARADOX

The time-reversible picture presented here should not be interpreted as implying that macroscopic objects, such as human beings, will ever be able to travel back in time. As with a dead man being resuscitated, it can happen, but we should not expect to see it in the lifetime of the universe. The familiar arrow of time applies to incoherent many body systems, including the human body, and is defined by the direction of most probable occurrences. Because of the large number of particles involved, this probability is very highly peaked in one direction, which is then defined as the direction of time.

The time travel implied by the very unlikely but in principle possible processes that can happen in the opposite direction are not to be confused with some of the other types of macroscopic time travel about which people speculate. For example, cosmological time travel might occur when the time axis is bent back on itself in the vicinity of strong gravitational singularities, or cosmic wormholes are used as time machines.[17]

Human time travel would appear to allow you to go back in time and kill your grandfather when he was a child, thereby eliminating the possibility of your existence. This is the famous time travel or grandfather paradox. The quantum situation is as if you went back in time to look for your grandfather and kill him, but found that he was indistinguishable from all the other males in the world (only two, in the photon example). All you can do was shoot one at random, which you do not have to be from the future to do. Since no information from the future is needed, no paradox occurs.

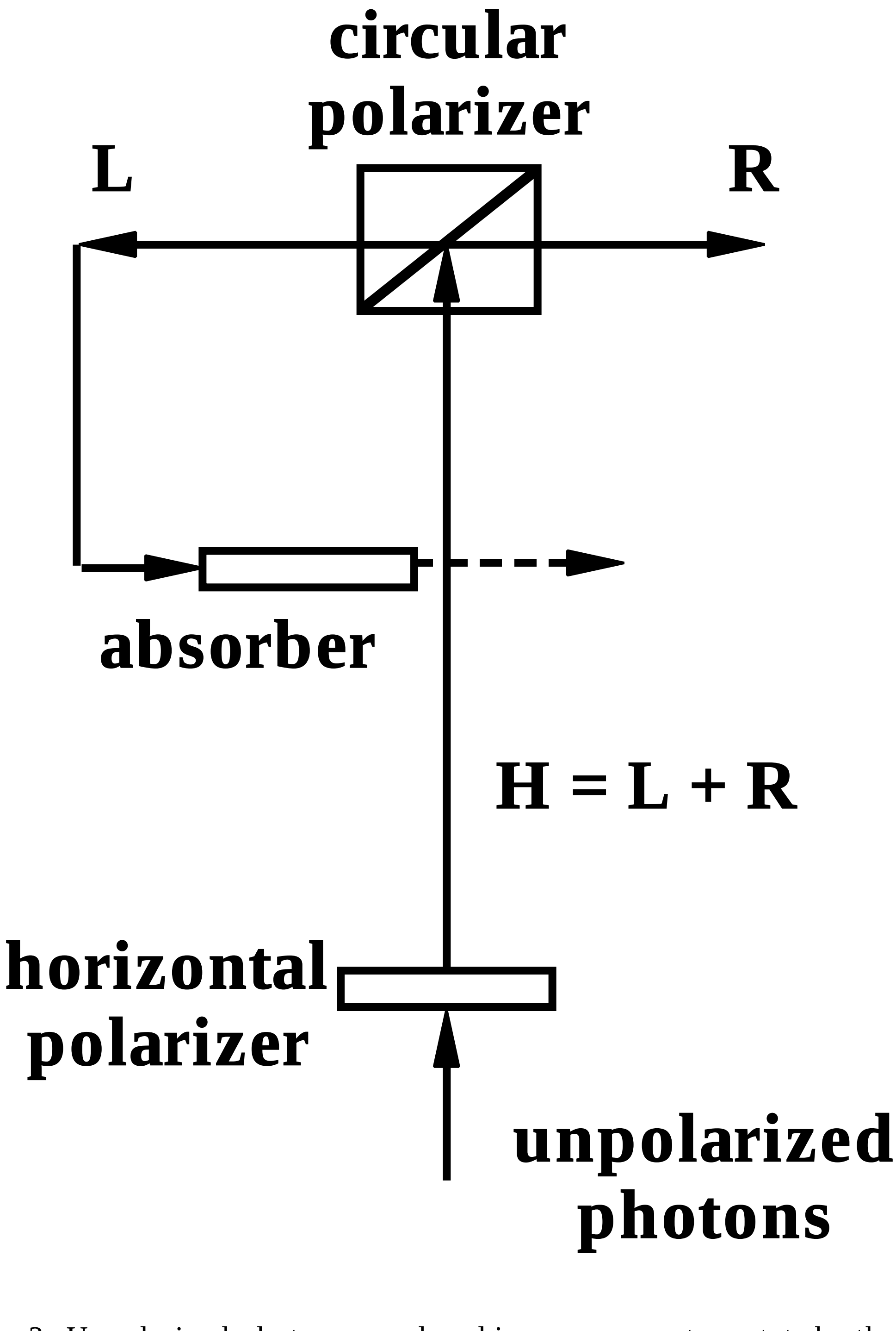

Figure 2 . Unpolarized photons are placed in a pure quantum state by the horizontal polarizer. The circular polarizer separates the beam into two circularly polarized beams L and R. When an L is detected, a signal is sent back in time to place an absorber in the beam and prevent the photon from proceeding, thus producing a causal paradox. However, the paradox is not present when the state H is a coherent superposition of L and R, only when it is an incoherent mixture.

Let me explain this precisely in terms of an experiment with coherent photons rather than macroscopic bodies like grandfathers (see Figure 2). Suppose we pass initially unpolarized photons through a horizontal linear polarizer H, so that we know their exact state, and thence into a circular polarizing beam splitter. Two beams emerge from the latter, one with left polarization L and the other with right polarization R. We set up the apparatus so that when a photon is detected in the L beam, a signal is transmitted back in conventional time (it need only be nanosecond or so) to insert an absorber that blocks the photon before it reaches the L polarizer. This is analogous to going back in time and killing your grandfather, or yourself for that matter.

Now, each photon that has passed through the H polarizer is in a coherent superposition of L and R states. As a result, we will sometimes block photons that would normally end up in the R beam. That is, we cannot identify an L photon to absorb since that L photon is part of the pure state H. If we act to absorb the photon anyway, we will be killing an H state, not an L state. This action is as if the absorber were randomly inserted in the beam, killing off on average half the photons that will end up in the L and R beams. Again, since we can achieve the same result without the signal from the future, we do not have a causal paradox. That is, the killing of the photon was not necessarily "caused" by an event in the future.

You might wonder what would happen of, instead of the H polarizer we had an L one. Then we always have L photons and kill them all off. Or, if we have R photons we don't kill any. Again, this can be done without a signal from the future and we have no paradox. The same situation obtains if we try to measure the circular polarization before taking action. To do this we would have to insert a right circular polarizer in the beam, which would produce a beam of pure R. But this can also be done with no information provided from the future.

To appreciate the role quantum mechanics plays in avoiding the grandfather's paradox, consider what happens when H is removed. Then we have an incoherent mixture of L and R photons from the original source, analogous to a macroscopic system. The absorber will only block the L photons that are destined to be in the L beam. The R photons pass unhindered to the right beam. Now we indeed have a causal paradox, with the signal produced by a particle in the future going back in time and killing the particle. While this example certainly does not exhaust all the possibilities, it strikes me that the causal paradox will be hard to defeat for macroscopic time travel, unless that travel is to a parallel universe.

In the clever *Back to the Future* films, the young time traveller Marty (played by Michael J. Fox) had to take certain actions to make sure his father became his father. He had to watch over him, protect him from bullies, and make sure that he dated Marty's future mother (who found Marty strangely attractive).

Time travel may be impossible in the classical world, without the parallel universes that these and other films and science fiction tales assume, but time travel in the quantum world appears to remain logically possible. In this article, I have implicitly assumed a direction of time as defined by convention and spoken of "backward" or "advanced" causality from that perspective. However, we have seen that the conventional direction of time is set by the direction of increased entropy, and we might wonder where that enters in these examples. Actually, it enters in an interesting way. Backward causality involves the use of information from the future that is not available in the past. But this implies that the future has *lower* entropy--more information--than the past, a contradiction. The past is by definition the state of lower entropy.

On the other hand, the flow of information from the past into the future is allowed. So no logical paradox occurs when a signal is sent to the future (as it is in everyday experience--far in the future if we send it third class mail), just when it is sent into the past. In the quantum case, since the same result as backward causality can be obtained without the signal from the future, no information flows into a lower entropy past and no causal paradox ensues.

NOWHERE TO RUN, NOWHEN TO GO

We now know that the Copernican Revolution did not imply that the sun was the center of the universe. It meant that there was no center, no special point in space. Philosopher Thomas Nagel has called this the view from nowhere.[18] Similarly, no special point in time exists and philosopher Huw Price has called this the view from nowhen.[19]

Copernicus forced us to discard our anthropocentric prejudices about our place in the universe. The result was a simpler picture of the universe. Similarly, we need to discard our prejudices about time. Time reversibility provides us with a simpler and more economical picture of the universe than is possible when we insist on the common view that time changes in only one direction. And it is on that basis, not proof, that we can rationally conclude that ultimate reality is time-symmetric. With no special present, past, and future at the fundamental level, we exist in a *timeless reality*.

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