The Arrow of Time

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Abstract

The foundation of irreversible, probabilistic time -- the classical time of conscious observation -- is the reversible and deterministic time of the quantum wave function. The tendency in physics is to regard time in the abstract, a mere parameter devoid of inherent direction, implying that a concept of real time begins with irreversibility. In reality time has no need for irreversibility, and every invocation of time implies becoming or flow. Neither symmetry under time reversal, of which Newton was well aware, nor the absence of an absolute parameter, as in relativity, negates temporal passage. Far from encapsulating time, irreversibility is a secondary property dependent on the emergence of distinct moments from the ceaseless presence charted by the wave function.

Keywords: Irreversibility; Wave function; Decoherence; Relativity of simultaneity; Bergson

Introduction

Despite our innate sense of time as unidirectional flow, scientific investigation compels us to consider the possibility that temporal passage is illusory. Every solution of a dynamical law is accompanied by a time-reversed solution, and initial conditions can always be reformulated as final conditions. Moreover the laws of physics say nothing about our experience of time as a moving "now." If these laws capture the essential characteristics of nature, time must be subjective, a mere shadow cast by the light of consciousness.

Yet physics is troubled by numerous "arrows of time." Entropy rises in forward time but not reverse. Light carries information about the past, not the future. Only in reverse time do objects appear from black holes. The universe expands in one temporal direction and contracts in the other. Darwin's theory of descent with modification, which inspired both Clausius and -- ironically -- Boltzmann, seems inexplicable in the context of time symmetry (Prigogine 1997, 18-19).

The rise of entropy in a gas obscures the underlying time-reversible determinism of the motions of the molecules comprising it. The one-way entropic drive to equilibrium rests on statistics and is therefore reversible in principle even if not (very often) in practice. Given Boltzmann's success at accommodating thermodynamics to time-reversible law by way of statistical mechanics, solutions might be found for other arrows of time. Whereas Planck saw no way around the electromagnetic arrow, Boltzmann thought it could be explained according to improbable initial conditions, much as improbably low entropy in the very early universe presumably set the stage for subsequent rise (Zeh 2010, 19).

Despite the enthusiasm of certain theorists, skepticism remains the natural response to the idea that the arrow of time -- verified in diverse phenomena including our own continual experience -- is a projection of the psyche. According to H. Dieter Zeh, what is truly subjective is not the directionality of time but our sense that the time is now. "The concept of a present," he writes, "seems to have as little to do with the concept of time itself as color has to do with light" (2010, 13). The task is not to explain away the arrows of time but to identify the "master arrow" from which the rest are descended. While he believes this achievement might have to await the completion of a theory of quantum gravity (2010, 177), the real answer is right under his nose. The origin of the arrow of time is already described in the process of decoherence. Zeh, who has been instrumental in the decoherence program, misses this insight because he denies the reality of temporal presence and therefore overlooks the role of time in the quantum. On the basis of this misunderstanding, he quite logically dismisses the possibility of the "emergence of a classical concept of time from a timeless quantum world" (2010, 202).

Physical theory typically treats time as an abstract quantity that takes on apparent substance only in the context of irreversible processes, which in turn can be written off as statistical mirage. I propose that time is a fundamental property of nature in no way dependent on irreversibility. The classical time of irreversible moments emerges from the reversible time implicit in the wave function.

The Two Aspects of Time Expressed in Wave Evolution and Decoherence

Time comes to us as presence without end. Whereas past and future are inferred, direct experience is limited to continuous presence. Even the instant, central to the treatment of time in physics, is conceptual elaboration. What we actually experience is not a current instant but a flowing current. From this we infer that our previous experience of ongoing presence is now "past" and that our subsequent experience of ongoing presence is, as of now, "future." Of course, when the anticipated moment arrives, it is no longer future but present. Prior to conceptual thought, we have only ceaseless presence.

Our intuition of time as unbroken presence entered the domain of physical inquiry with the formulation of quantum theory and the concept of the wave function. The solution of the Schrödinger equation for a given circumstance, the wave function charts the trajectory of a microphysical system across its probabilistic states. As long as the system remains unmeasured, the number of its potential states typically increases. According to von Neumann, when an observer intervenes in the system by making a measurement, the wave function "collapses," taking with it all but one of those possible states. Whereas the system previously occupied a superposition of states, at the moment of observation it consists of well-defined particles in a classical state.

The problem is that the Schrödinger equation stipulates only the continuous evolution of the wave function, making no allowance for its abrupt and irreversible collapse. Von Neumann sought to get around this problem by invoking psycho-physical parallelism (Zeh 2010, 130). From a physical standpoint, the wave function must proceed in accord with Schrödinger's time-reversible equation. Running parallel to physical reality, however, is the consciousness of the observer, which acts as a clinamen introducing a random classical outcome to an otherwise deterministic quantum process.

If we are to explain the quantum transition without recourse to dualistic philosophy, we must identify the physical reality that underlies quantum theory. As Penrose points out, any such attempt begins with the wave function (2005, 508). In contrast to a classical probability wave, which merely expresses our ignorance of the true situation, the wave function -- or rather the evolving superposition of possible states it calculates -- *is* the true situation. The Schrödinger equation describes temporal continuity. How do we reconcile this with the discontinuity in wave evolution upon measurement?

Whereas wave evolution situates the quantum system in continuous presence, a definite event requires a definite period of time emergent from ongoing presence. The properties of a quantum system take on determinate values when a discrete moment crystallizes from the general flux. The meaning of collapse is that the wave function *momentarily* decouples from the system, which exhibits classical properties before reverting to its usual wave state.

What, then, causes the fundamental time of the wave function to "cough up" a distinct moment? The answer according to the experimentally successful decoherence program, is the interaction between the quantum system and its local environment (Zeh 2010, 112). In the case of human measurement, the source of a classical world from the quantum foundation is not the consciousness of the observer but the large-scale intrusion inherent to the measurement process. Environmental interaction occurs on a regular basis without the need for human intervention. The absorption of a photon by an atom, with the resulting orbital jump of an electron, constitutes an intervention into that atom and therefore a momentary discontinuity just as if it had been measured in a laboratory. As Penrose says, nature continually produces the effect that we produce through measurement (2005, 593). Zurek calculates that a mass of one gram has so many potential local interactions that it ought to decohere every 10^{-23} seconds, with or without measurement (2002, 14). Schrödinger's cat would decohere at least as rapidly. By contrast, an isolated electron can remain wave-coherent for a billion years or more (Bohm and Hiley 1993, 329).

Just as nothing prevents a train of thought from repeating in reverse order, nothing prevents a succession of quantum superpositions from reversing all the way back to its origin. Once a decision is actualized via muscle, however, it cannot be undone. Likewise, when a quantum system undergoes environmental intervention, its properties take on definite values. Irreversibility, the arrow of time, arrives with the emergence of a definite state from multiple possibilities -- that is, the emergence of a distinct moment from continuous presence.

Whereas Newton's time-reversible laws of motion idealize an irreversible classical world, Schrödinger's time-reversible equation captures the content of wave mechanics on its own terms. The irony is that the Copenhagen interpretation makes no claim about quantum reality, merely stating that the object of measurement and the macroscopic measuring device require different descriptions (Whitaker 2006, 176-77). Until an electron is measured, it has no determinate properties and constitutes a wave rather than a particle. Probability wave and definite particle are complementary descriptions of the same phenomenon.

Though Zeh (2010, 105) grants that classical properties "emerge from the wave function and are maintained by a process that cannot be reversed," he cannot recognize that irreversible classical time emerges from ongoing presence because he has denied temporal presence, the now, from the outset.

The emergence of classical definitude from quantum potentiality signifies the extraction of a definite period of time from the indeterminate present of the microphysical system in its undisturbed state. The past is defined first by the relation of the completed moment to ongoing presence and then by the relation of each completed moment to its successor. Not only the emergence of each moment but the sequence of moments constituting classical time is irreversible.

Lacking a temporal model of the transition from wave mechanics to classical mechanics, Zeh must reject the claim that decoherence eliminates the measurement problem. Since "the measurement problem," he writes, "can only be resolved if the Schrödinger dynamics is supplemented by a non-unitary collapse," and he cannot account for such collapse, he appeals to an Everett-style solution (Giulini, et al, 2003, 21). In Everett's Many Worlds interpretation, every possible classical outcome takes place in a nonlinear "branching" process, each branch constituting a "world" corresponding to a conscious observer. In this way Everett preserves von Neumann's model of psycho-physical parallelism without resorting to wave function collapse (Zeh 2010, 132).

Yet Zeh's embrace of infinitely branching consciousness is unnecessary given that decoherence lends itself equally well to the vastly simpler model of fundamental time yielding sequentially to momentary time. The Schrödinger equation is incomplete insofar as it leaves out the irreversible time that periodically "buds off" from fundamental time. Limited to the time of reversible presence, it accounts for the wave function but not its collapse.

Key to the quantum transition is differing timeframes between macro- and microphysical systems. An electron occupies such a miniscule spatio-temporal expanse that its existence does not require a complete moment set apart from ongoing presence. If it decoheres from its wave state, the cause is external to it. As a large-scale event dependent on a succession of distinct moments, a measurement cannot help but translate the electron from a superposition of possible values to a determinate state. By contrast, a macroscopic object such as a protein decoheres by necessity, for it cannot exist *as such* in anything less than the timeframe of a completed moment, distinct from both ongoing presence and previously completed moments. As Zeh himself puts it, decoherence is "unavoidable for all macroscopic objects" (2010, 102).

The wave function is a kind of clock. When a quantum system decoheres, its wave function resets and continues evolving from that point until enough time has passed that the macroscopic object of which the system is a small portion comes into being as such, triggering the next decoherence and consequent updating of the wave function. For the isolated electron, time is simply continuous presence, endless now. For the macroscopic object, *now* is always collapsing into *then*, clearing the way for the next *now*, and so on.

Implicit in this process is Wheeler's concept of pre-space. Defined in accord with Planck length (10^{-33} cm) and Planck time (10^{-43} seconds), pre-space is beyond the boundary of measurability in the small (Griffin 1986, 192). It is time-zero, the ever present starting point. The decoupling of the quantum system from ongoing presence, signified by decoherence, causes the wave function to reset at the inner boundary of space-time, from which wave evolution commences anew. By 10^{-15} seconds the atom comes into being as such (Nichol 2003, 34). By a billionth of a second, a sugar molecule exists not just as a collection of particles but *as a sugar molecule* (Zeh 2010, 106). The emergence of scale, however, triggers another decoherence and the capping off of the moment, which therefore ceases to be *the* moment but only *a* moment, specifically the most recent past moment -- past insofar as it no longer participates in ongoing presence.

Though Zeh highlights the apparent incompatibility of a deterministic wave function and the "fundamental indeterminism of the future" implicit in probabilistic classical outcomes

(2010, 5, 92), this conflict dissolves with the realization that quantum theory deals with different aspects of time. Whereas continuous presence is reversible and deterministic, the fleeting presence that periodically emerges from it is irreversible and probabilistic.

Bohr's principle of wave-particle complementarity took shape in conjunction with Heisenberg's "uncertainty" relation, according to which the precise values of position and momentum cannot be simultaneously established (Folse 1985, 91). Implicit in position is a distinct moment. A particle -- say, a photon -- has a definite position at a particular time. Though momentum is also expressible as a given value at a given time, by its nature it spills over from previous moments. Whereas position is simply a snapshot -- a single instant in a sequence of instants -- momentum is the current that runs through them, converting snapshots into cinema. The more precisely the positions of a system's components are established at an instant, the greater the indeteminacy of its future state (1985, 93).

Einstein came into the 1927 Solvay Conference with the intention of proving that position and momentum could be determined in the same measurement. He was soon compelled to concede the point to Bohr (Whitaker 2006, 205-09). But Bohr could offer no fundamental explanation for why Einstein’s seemingly sensible approach was faulty. Perhaps the reason is simply that time cannot be revealed as both unbroken flow and a sequence of discrete moments *at the same time*. The genius of complementarity is that the contradiction is only in our measurements, not the underlying reality. Momentum and position -- wave and particle -- express flux and instantiation as the two faces of time.

Denial of Time in Physics

By rejecting periodic collapse of the wave function, the Many Worlds interpretation denies the reality of moment-to-moment existence. The sensorial world turns out to be information carried on a wave. In place of tangible reality, we have an eternally branching set of possible outcomes of a moment that never completes. Without distinct moments that successively individuate it, ongoing presence is no longer the foundation of time but its tomb, a timeless eternity.

The denial of time has deep roots. In the West the preference for "being over becoming" typified the earliest philosophers and constituted the defining feature of the Eleatic school of Parmenides, whose student Zeno offered four paradoxes designed to demonstrate the unreality of time according to the impossibility of motion. In his paradox of the arrow, Zeno argued that if time is composed of minimal units of time, i.e. instants, an arrow could not actually be in motion because motion during an instant would imply its divisibility into smaller units, leaving only the "time" between instants for the arrow to move, an impossibility if time is confined to each successive instant. The flight of the arrow -- and time itself -- is illusory (Durie 2000, 22).

The arrow paradox resolves insofar as time is ongoing presence periodically rounded out into a completed moment. Each moment, rather than simply succeeding the previous moment, expresses the underlying flux, the open-ended time of the wave function. This is essentially Aristotle's two-fold view of the "now," which holds time together in a single flow while distinguishing "before" and "after" (Durie 2000, 18). Whereas the wave function expresses continuous presence, local interaction triggers a fleeting present that divides off everything already determined from that which remains potential.

Bergson observed that the philosophy underlying modern physics is more Platonic than Aristotelian, though instead of a multitude of eternal Ideas serving as models for actualities, a small set of mathematically fixed Laws suffices to give phenomena their form. In the modern view, time is regarded as a "confused form of the rational. What we perceive as being a succession of states is conceived by our intellect, once the fog has settled, as a system of relations" (1946, 124).

According to Popper, the idea of time as an illusion obscuring a timeless reality reached its "highest fulfillment in the continuity theory of Einstein" (Ansell Pearson 2002, 48). Assimilated into a four-dimensional continuum, time is stripped of all temporality. Passage from one moment to the next, rather than intrinsic to time, indicates only the movement of our own consciousness across the continuum, a mere trick of the mind. Though credited with providing the basis of time dilation, the actual effect of Einstein's special theory of relativity is the establishment of time as a static system of relations.

As is well known among physicists and laypeople alike, time dilation takes place for an object traveling at a higher speed -- that is, closer to the speed of light -- than another object. Yet this is not at all how Einstein explained relativistic effects such as time dilation and length contraction. Instead he based his account on a principle known as the relativity of simultaneity. Because events that are simultaneous in one inertial frame of reference are successive in other frames, the present moment in one frame is past or future in other frames, eliminating a definitive time-present and rendering incoherent the classical notion of time as the orderly passage of moments. Minkowski's reduction of time to the fourth axis in a space-time continuum was merely the icing on the cake.

The trouble with the relativity of simultaneity is that its effects are reciprocal between frames, which is why Bergson dismissed it (Capek 1971, 240). In the absence of an absolute frame or "ether," an observer in each frame by necessity perceives the other frame as the one in motion. This illusion, combined with the fact that the speed of light is the same in every frame, causes each observer to mistake a past moment in the other frame for its present moment. Hence each observer thinks the other frame is undergoing time dilation (Takeuchi 2010, 132-37). Yet it cannot be the case that each frame dilates in time relative to the other. Bergson rejected time dilation, characterizing it as an illusion of perspective, precisely because he took Einstein at his word that relativistic effects are caused by the relativity of simultaneity.

As Milic Capek pointed out, the reality of time dilation in no way denies the reality of time itself. Since each frame remains contemporary to the other frame regardless of how much one or the other undergoes time dilation, no actual displacement in time occurs. Bergson overlooked the compatibility of differing rhythms of local times with underlying universal duration (1971, 248-49).

The expulsion of relative simultaneity as a causal factor in special relativity has no bearing on the proven phenomenon of time dilation (Bailey, et al, 1977). Nor does it negate Einstein's two postulates of relativity: the frame-invariance of physical law and the lawfulness of the propagation of light. Time dilation follows directly from these postulates without the intermediary of relative simultaneity. Among a pair of reference frames, time dilates for the frame traveling closer to the speed of light because the speed of light must remain constant regardless of the speed of the observer.

We know that when we travel at high speed away from a luminous object, its red shift in no way means the wavelength of its radiation has actually increased. Conversely, as we approach a luminous object at high speed, its blue shift does not mean its radiation has intensified. Either way the only shift is in our perspective. Likewise, when simultaneous events appear to take place at different times, the effect results from our motion relative to those events. So why is the relativity of simultaneity considered objectively real, though the Doppler effect is merely an artifact of perspective?

Unlike the Doppler effect, which has no ideological implications, the relativity of simultaneity advances the program of vacuuming temporality from physics and establishing the supremacy of timeless deterministic law. Given the dependence of physics on seemingly eternal mathematical formulae, the embrace of relative simultaneity is entirely predictable. Indeed, by attributing the quantum transition to observer-induced wave function collapse, von Neumann and Wigner served the bias against time by safely sequestering irreversibility -- a troublesome indicator of temporality -- in the strictly subjective domain of human consciousness (Prigogine 1980, 66).

Conclusion

Given that laws of physics are formulated on the basis of timeless mathematical equations, should we be surprised that these laws apply in reverse time as well as forward time? In no way does the time-reversibility of abstract laws have any bearing on the one-way flux of tangible existence.

For Bergson the best way to understand time is simply to listen to music. Though time is traditionally characterized in terms of either multiplicity or unity -- either pulverized into a "dust of instants" or unified into an "eternity of death" -- music reveals multiplicity and unity as complementary aspects of time (Capek 1971, 120, 147). Though a piece of music can be surgically divided into a particular set of sounds at any given moment, what makes it musical is the continuity of sounds over time. Music is heterogeneous insofar as it consists of changes from one moment to the next but unified insofar as the current moment is infused with previous moments. Hearing the chorus the second time is not the same as hearing it the first time. Even as it changes, a melody remains a single movement, as does wave evolution in the absence of local interaction. With time conceived as heterogeneous continuity, Bergson anticipated Schrödinger's continuously evolving wave function.

Moreover, by characterizing physical existence according to *ebranlements*, "shakings," Bergson anticipated the rapid-fire repetitions of wave collapse upon which the classical world is discontinuously built (Capek 1971, 205, 331). This is the aspect of time that defines a distinct moment, demarcating it from both ongoing presence (*durée réelle*) and prior temporal discontinuities.

Macroscopic existence is the successive emergence of completed moments from ongoing presence. Zeh's model of time, which concedes objective directionality of moments but consigns temporal presence to the status of mere subjectivity, is incoherent. If not in contrast to the present, how is a given moment defined as past? A sense of "now" without an actual present is like a sense of color without objective wavelengths of light.

"Now" has two meanings, one continuous and the other discontinuous. One defines presence as perpetual re-beginning; the other indicates a fleeting present always just *now* concluding. Irreversible time is the moment-to-moment crystallization of continuous presence. Because presence moves -- because it is not static like an instant but flows -- whatever emerges from the flux is defined as past relative first to ongoing presence itself and then to subsequent projections from wave evolution, the all-flowing background of tangible existence.

The project of deriving the arrow of time from timeless principle is doomed to failure. Irreversibility follows not from the laws of nature but the nature of time.

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