The Garden of Forking Paths: Time as an Expanding Labyrinth

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The gifted 20th century Argentine writer, Jorge Luis Borges, once described time as the "one essential mystery." Indeed our mundane experience of time can be baffling. Moments slip away—sometimes in a trickle, other times in a stampede—and it is impossible to return to the past. Through our memories and dreams, distant times sometimes seem clear and immediate, and other times foggy and remote. Years sometimes fly by; days sometimes drag on.

For physicists, eager to pin down elusive properties and assign measurable parameters to natural phenomena, the nature of time offers many fundamental enigmas. Various subfields of physics provide clashing visions of time's behavior. Classical mechanics offers a clockwork view of a steady rhythm of causes followed by effects. It is eminently deterministic and fully reversible. Complexity theory advices us, however, that a wide range of systems, even ones modeled by only a few parameters, can be deterministic in principle yet as hard to predict in practice as a coin toss. Edward Lorentz, for example, brilliantly showed why long-range weather forecasting is tricky; a minute discrepancy in one parameter can lead to overwhelming differences over time [1]. Yet this is not a violation of causality and determinism; rather it represents a statement of the imperfection of measuring devices. In principle, with absolutely precise instruments, the future could be predicted indefinitely.

Another vision of time is as something akin to space. Einstein emphasized that by setting time as a parameter by which motion is measured—along with three spatial coordinates—Newton effectively rendered it a kind of fourth dimension (without saying such). Indeed, as early as 1754, a French encyclopedia entry written by the mathematician Jean d'Alembert discussed the idea of duration being the fourth dimension [2]. D'Alembert's definition, and a similar statement by Joseph Lagrange found in his 1797 text, <u>The Theory of Analytical Functions</u>, clearly drew this idea from Newtonian physics.

Special relativity, particularly in the version framed by Hermann Minkowski, solidified the concept of time as being on par with space as members of a dimensional quartet—what became known as a spacetime manifold. Through general relativity, Einstein showed how mass and energy rendered this manifold dynamic—its geometry responding to the matter-energy distribution. This dynamics is fundamentally different from the Newtonian succession of moments, as it incorporates the past, present and future on equal footing. In other words, while Newtonian mechanics allows, in principle, for complete knowledge of the past and future (given access to all information about the present), general relativity implies a far more rigid determinism by freezing all of history into a solid immutable block. The reason is that the division of spacetime into space and time is arbitrary. If one could somehow step outside of the spacetime manifold, all moments would be as accessible as all locations. In its purest form this "block universe idea" offers the startling conclusion that travel through time ought to be as simple as traveling along any spatial direction, and that the passage of time is an illusion. Such implications clash with our intuition, placing us in the situation of either denying the framework of Einstein's elegant theory, slicing in a manner it to reflect our own experience of time (such as in the ADM formalism of Arnowitt, Deser and Misner [3]), or proclaiming that our feeling of moments passing is fallacious.

Curiously, modern cosmology, though fully consistent with general relativity (give or take a cosmological constant term), breaks the time invariance symmetry by offering an empirical definition of past, present, and future. We can define three-dimensional spatial slices, isotropic (likely flat) in their geometries on the largest scale, and objectively order them based upon the size of their metric components (determined by distances between points). The universe today, for example, is much more dispersed than it was 10 billion years in the past. From evidence gathered from surveys of distant supernovae, astronomers have determined that the universe is currently accelerating in its expansion. Therefore it will likely be even more spread out 10 billion years from now. This prescribes a cosmological arrow of time.

Another arrow of time derives from a thermodynamic principle known to hold true for closed systems and speculated to apply to the universe as a whole—namely the law of entropy. Natural processes occur in the direction of maintaining or increasing, but never decreasing the total disorder. A measure of the lack of uniqueness of microstates in assembling a macrostate, entropy also has an astrophysical definition through Jacob Bekenstein's black hole area formula [4]. Based on the holographic principle—proposed by Gerard 't Hooft and Leonard Susskind—that encodes information pertaining to a region on its boundary, Bekenstein subsequently identified profound connections between information content and area entropy. He found that the maximum capacity for information of a volume of space depends on its surface area [5].

Yet another directional arrow of time pertains to quantum measurement. According to the Copenhagen interpretation of quantum mechanics, whenever an observer measures a particle's property, its wave function collapses into one of a spectrum of eigenstates corresponding to a particular eigenvalue pertaining to that property. For example, measuring an electron's spin forces it into one of its two spin states, each matched up with a different spin eigenvalue. Such wave function collapse is generally irreversible; that is, one cannot directly "undo" the measurement to restore a mixed spin state. The famous cat paradox of Schrödinger in which a cat "collapses" from a mixed state into either a state of life or death, aptly demonstrates the time irreversibility of quantum measurement.

A leading alternative to the Copenhagen interpretation, that cleverly removes any involvement by the observer in quantum measurement, is the Many Worlds interpretation proposed by Hugh Everett [6]. Each quantum decision point, Everett speculated, causes the universe to bifurcate into a number of near identical copies. The only difference is the particular result of the quantum state being determined—with each outcome represented by a different parallel universe. To take a simple case, if an electron's spin is being measured by its placement in a magnet field, the two possibilities, "spin up" and "spin down" correspond to different universes. The researcher conducting the measurement would simultaneously bifurcate as well, such that each replica would experience a different outcome—unaware of other versions of him- or herself witnessing alternative conclusions.

As in the Copenhagen interpretation, the Many Worlds interpretation prescribes an arrow of time. In the case of Everett's hypothesis, time's arrow relates to the number of parallel universes. Presumably, close to the time of the Big Bang, there would have be far fewer quantum bifurcations than in recent times. The state of the universe would have occupied a much smaller subset of the space of all possibilities. Thus if one defines a measure of the complexity of the set of parallel universes—a kind of information entropy based on the multiplicity of the multiverse (set of parallel universes)—such would have a growing value from the Big Bang forward.

The multiverse can be encoded as a kind of information space, representing the full spectrum of the wave function of the universe (a composition of all of its component fields). Each time the universe undergoes a bifurcation (that is, a quantum decision is made), the spectrum of alternatives would enlarge, and this information space would grow slightly in volume. Following Bekenstein's conjecture, this growth would correspond to an increase in the bounding area of the information space and thus of the total entropy. In other words, quantum processes that result in alternative outcomes would lead to a growth of the information space, an increase in entropy, and an irreversible arrow of time.

Note that most quantum processes are manifestly reversible. These would not lead to an increase in the information entropy. However, even scattered incidents of bifurcation into distinct states would correspond to a gradual overall growth of the complexity of the Hilbert space corresponding to the amalgamated wave function of the universe. Moreover, CP (charge-parity) violation in some forms of kaon decay and other weak processes would represent examples of microscopic time-irreversibility that could manifest themselves in an expansion of the information space.

We now wish to connect this vision of an expanding information space to general relativity and cosmology. We speculate that there is a dynamic, deterministic reason for the growth of the information space that describes the various possibilities of the multiverse, similar to the dynamic reason for the expansion of the physical universe itself. As Einstein found, in the absence of a cosmological constant, cosmological solutions of general relativity are unstable—a finding that matched up well with Hubble's subsequent discovery of cosmological expansion. Similarly, we conjecture that an information space obeys a physical law that mandates (or at least permits) its growth in tandem with the growth of the physical universe. These dynamics could be governed by an extension of general relativity into the domain of the information space—in the fashion of Kaluza-Klein theories positing extra, unseen dimensions—or they could be set by different physical laws.

There has been a longstanding interest in identifying a connection between general relativistic dynamics and the arrow of time. In his "Weyl curvature hypothesis," Roger Penrose speculated that the Weyl tensor (components of the Riemann tensor that are not directly linked to the stress-energy tensor through the Einstein equations, but rather represent additional degrees of freedom) is connected to cosmological entropy [7]. By constraining a function of the Weyl tensor to be identically zero at the Big Bang, but not so later in time, its growth could offer an explanation for time's arrow. Our speculations offer an alternative picture in which it is the information space that expands and hence provides a temporal arrow. It is conceivable, however, that cosmological entropy increase is due to a number of factors.

In representing a dynamic explanation for entropy increase and the entropic arrow of time, the natural growth of the information space could also possibly explain the human sense of time moving forward. As Hawking suggested, the direction of the entropic time could set the direction of human consciousness, because we must consume orderly material (nutrition) and convert it into disorderly material (waste) in order to think [8]. However, given that the information space's expansion opens up more and more alternatives—choices on the quantum level that can lead to macroscopic effects—there may be much more to the picture.

Instead of considering time as a straight arrow, it is more instructive to think of it as an ever-growing network of possibilities—that is, an expanding labyrinth of diverging world lines.

This concept of time as a labyrinth was suggested in fiction as early as the 1940s in Borges' classic tale "The Garden of Forking Paths." The story represents time as a book in which all possibilities are realized. Every plot twist that can happen does happen. Through the voice of one of his characters, Borges insightfully refers to this concept of time as an alternative to the absolute time of Newton.

Imagine, then, time as a book of information about all the alternative possibilities for interactions between matter fields in the universe—for example, particular particles can either decay or not decay at any given moment, offering different outcomes. The salient feature of this book is that it is continuously expanding and adding new pages in a predictable fashion. This new information means that more and more alternatives are available as the universe progresses.

One of the key features of consciousness is the possibility of choice. Choices on a macroscopic level ultimately correspond to myriad transitions on the quantum level. For example, choosing to put on gloves in the wintertime raises the temperature of molecules in one's hands, increasing the likelihood of these being in higher energy states. Thus, the choice represents a splitting of possibilities between higher and lower energy states of the molecules in question. It is interesting that we make choices only in the direction of time in which quantum alternatives are growing. Therefore the direction of conscious experience—choice-making— is identical to the growth of the complexity of parallel timelines within the expansion of the information space.

A profound mystery about time is why do we experience its progression at a certain speed. Perhaps this feeling of moving forward pertains to the rate of the growth of the information space, allowing us to engage in the processes of thought and choice. Our mental activity progresses as new alternatives open up. It is like a train slowly chugging along as new tracks are laid down ahead of it.

Einstein was famously troubled by the role of chance in quantum mechanics. If time is indeed a growing labyrinth, it could well be the case that the construction of this maze could be completely predictable. Just as the planners of garden mazes sometimes draw careful blueprints before completing their projects, it is possible that the labyrinth of time's development is similarly methodical—governed by certain dynamical equations. Yet just as garden maze planners cannot anticipate which routes those who enter their creations embark on, the labyrinth of quantum alternatives allows for numerous paths and possibilities—growing as the information space expands. If each of these paths represents a parallel universe, then there is no contradiction with determinism—because all possibilities that can occur will occur.

The sociologist Herbert Spencer once wrote of the law of “multiplication of effects” as an explanation for progress. Each cause, he argued, leads to numerous effects and thereby increases complexity. In the vision of time as an expanding labyrinth, it is the expansion of the range of possible effects that drives the forward movement of choice, both on a macroscopic level—conscious-decision making—and on a microscopic level—the differentiation of wave functions into alternatives (for example, “spin up” and “spin down” states).

In his later years, physicist John Wheeler pondered the role of information in the universe. Could information, he speculated, be even more fundamental than matter and energy? Quantum physics certainly suggests that not all that can be known about particles resides in physical space, but rather that some of this information is embedded in an “abstract” Hilbert space. It is a profound mystery where this unseen information—hidden aspects of wave functions—actually lies. Could a separate information space exist that is physically real yet inaccessible? Alternatively, could this information reside in the variations among alternative parallel universes? Either way, the burgeoning of quantum information since the era of the Big Bang would offer a fundamental clue about the nature of time.

The labyrinth model of time has the philosophically interesting feature of allowing for free will within the context of a deterministic material framework. While the labyrinth of possibilities could be delineated through as mechanism such as field equations, conscious beings could choose to embark upon unique, individual paths. The character of this choice is similar to the modern world-wide-web which offers myriad routes through cyberspace, predetermined by programmers, but individually chosen through the links users happen to select. Heisenberg once suggested that the philosophy of physics often bears the imprint of particular times, such as the uncertainty principle being developed during the turbulent inter-war era. Thus perhaps this age of the internet and cyberspace complexity is ripe for the notion of time as an intricate network.

Historically, models of time often reflect the philosophical ideas of their proposers. When Kepler set out to describe planetary motion, his preconception was that planets move in simple circles. This belief arose in part from his study of ancient Greek ideas, particularly those of Pythagoras (and also conveyed by Plato, Aristotle and others). The concept of the planetary system as a “harmony of the spheres” reflected a belief that time always runs in cycles. For the ancients, cyclical time was the most natural way of thinking about the cosmos given that many observed astronomical phenomena were repetitive and predictable.

In many cultures, cyclical time corresponded to a pseudoscientific belief in the repetition of historical events and the ability to forecast human, as well as natural, occurrences. Our fate, many ancient peoples believed, is determined by the behavior of the stars and planers—hence the word "disaster," meaning "bad stars." Interestingly, such beliefs were still prevalent during the time of Kepler, who sold astrological forecasts to earn extra income.

Although Newton was also personally interested in mysticism, he did not combine such beliefs in his scientific work. Rather, he developed laws of motion that follow an objective, deterministic course. They predict the elliptical planetary orbits Kepler had found from astronomical data collected by Tycho Brahe. Thus Newtonian time retains a cyclic quality.

In the 18th century, drawing from the results of Newtonian mechanics, the French mathematician Pierre-Simon Laplace proposed a kind of rigid determinism governing the states of objects in the universe. Laplacian determinism posits that by knowing the positions and velocities of all bodies in the universe one could use Newton's law of motion, along with knowledge of the forces between them, to exactly predict all future positions and velocities. Such strict determinism held sway among many thinkers during the decades that followed, influencing the emergence of a deterministic psychology that essentially denied free will. Indeed it is hard to reconcile free will with a strictly clockwork cosmos.

While in religious belief, linear time replaced cyclical time in the West, particularly in Biblical accounts of a unique creation and a single end-of-the-world, science would not embrace an arrow of time until the 19th century. The discovery of the second law of thermodynamics demonstrated that even the most efficient machines would run down over time. Through the insights of William Thomson (Lord Kelvin), Hermann von Helmholtz, Rudolf Clausius and others, science arrived at the grim realization that even the stars in the sky, once believed to be eternal, would eventually burn out. Ultimately, disorder (encoded by Clausius in the concept of entropy) would reach a maximum and the universe would reach a state of uniform temperatures and absolute lifelessness called "Heat Death." Thus, at least within the realm of those familiar with thermodynamics, entropic time replaced cyclical time as the model for ultimate cosmic destiny.

Intriguingly, it was a contemporary in another field, Charles Darwin, who developed the revolutionary notions in biology that spurred a very different belief in linear time. Darwinian evolution, as interpreted in particular by Spencer, led to the concept of a "law of progress." In physics, such a notion corresponds to idea that complex forms can spontaneously emerge from simple structures. The evolutionary arrow of time, pointing toward progress and complexity, therefore constitutes an optimistic alternative to the entropic arrow of time, pointing toward decay and uniformity.

One of the grand tasks of the late 19th centuries was trying to reconcile these disparate notions of time – cyclical (or at least mechanistic) on the level of simple bodies and forces and linear (but in opposite ways) for thermodynamic systems and life. A pioneer in attempting such unification was Ludwig Boltzmann, who ceaselessly tried to unify classical mechanics and thermodynamics, and find ways of linking these with Darwinian evolution. Boltzmann made major strides in showing how applying statistical principles to mechanistic systems could lead to definitions of macroscopic quantities such as entropy. Much later, Claude Shannon would make use of this work in defining information entropy [9].

In the mid-20th century the seeds for a labyrinthine concept of time would emerge through the application of quantum principles to electrodynamics. Feynman's introduction of the concept of "sum over histories" demonstrated that electromagnetic interactions between charged particles followed not just one path but rather a combination of alternative trajectories weighed by probabilistic factors. Somehow, the end results of interactions seemed to possess a hidden awareness of the full gamut of possible intermediate steps. Could the abstract space of wave functions be more fundamental that the physical universe itself? Or could there be, in the fashion of Everett's hypothesis, parallel worlds that record all these alternative trajectories?

As physicists began to grapple with the ideas of applying quantum theory to gravitation, an important question arose about the role of observers. For example, an early formulation of quantum gravity, the Wheeler-DeWitt equation, posited a quantum space in which the states are various geometric configurations. James Hartle, along with Hawking, proposed a candidate wave function solution to the equation to represent the universe itself. As Bryce DeWitt pointed out, a quantum description of the whole universe could not realistically depend on the measurements of conscious observers. Such reasoning lent support to the Many Worlds hypothesis as a more suitable alternative. Consequently, it favored a description of time as a bifurcating network of rivulets rather than as a steady stream.

The possibility of alternative timelines could help resolve a number of longstanding enigmas. Foremost among these is the question of whether or not causality paradoxes would plague any form of backward signaling or past-directed time travel. These paradoxes hearken back to Richard Tolman's speculation in 1917 that faster-than-light signals would circumvent the natural order of cause and effect. A 1970 paper by G. A. Benford, D. L. Book, and W. A. Newcomb, "The Tachyonic Anti-telephone," published in Physical Review D, examines a hypothetical system for sending signals back in time and the ensuing breach in causality [10].

Various proposals in the late 1980s, spurred by work by Kip Thorne and others, considered the possibility of traveling through spacetime wormholes in which one end moved at a high velocity relative to the other, and hence induced time dilation. By journeying into the static end and emerging from the rapidly moving end (in which time had passed more slowly) one could theoretically travel backward in time. Richard Gott proposed a related scheme based on energetic cosmic strings. In each case it seemed that the historic flow of events could be altered through past-directed travel.

To combat such conundrums several proposals were suggested. Hawking formulated the "Chronology Protection Conjecture" as an attempt to forbid backward time travel based on the laws of physics [11]. Igor Novikov took a different tact and proposed a self-consistency principle that permitted past-directed travel as long as it was fully consistent with what already had transpired [12] . For example, if a spaceship traveled one hour back in time through a wormhole, intercepted an earlier version of itself, and forced that version one hour later into the same wormhole, there would conceivably be no disruption to the chronicle of events. The whole chronology would be perfectly aligned. Yet, given human free will, it would be hard to imagine why conscious navigators would enact such rigid scenarios. Self-consistency thereby rests on a perfectly deterministic view of human fate.

The model of time as an expanding labyrinth of possible states provides a potential answer to the question of time travel. We speculate that because new states would open up along with the growth of the information space, future-directed would be far easier than past-directed time travel. Past-directed time travel would be permitted, consistent with general relativistic anomalies such as wormholes, in so far as the information space in the past possessed available "slots' to accommodate the material traveling back in time. As a result, those attempting past-directed time travel would be forced into alternative timelines rather than those already occupied by actual events. Effectively, therefore, they would be unable to interfere with existing structures (such as anything familiar), making it a rather meaningless excursion.

An analogy is venturing into the future or past of an ever-expanding hotel. While in traveling into the future, there would likely be extra rooms available, in going back to the past there could well be no vacancy. Thus if such past-directed travel were possible, one would have to find hitherto unoccupied space.

In summary, we have proposed a model of time based on an ever-expanding labyrinth of alternatives embedded either in an information space or in a network of parallel universes. Our goal is to reconcile some of the diverse properties of time gleaned through various subfields of physics, including reversibility in certain microscopic processes, irreversibility in others (such in collapse upon quantum measurement and in certain weak processes), and manifest unidirectionality on a macroscopic scale following the second law of thermodynamics. An advantage of describing time as a network is that physical reality could possess causal, deterministic aspects while accommodating a multiplicity of quantum paths as well as the free will of conscious beings. The expansion of such an information space could offer a natural arrow of time, explain the forward-time direction of decision-making, and help justify why future-directed time travel would be more straightforward than past-directed excursions. Although our model is hypothetical, some of its elements could conceivably emerge through a fuller understanding of quantum gravity, particularly of possible connections between general relativistic dynamics and the nature of quantum information.

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