Science Fact

Here We Go Loopedy Loop: A Brief History of Time Travel (Part I)

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Who among us, from the age we first noticed that events happen one after another, has led a life so perfect and free of unpleasantness as to not ponder, occasionally, a do-over? Who among us, from the age we first distinguished the now from the not-yet, has not wondered what might come to befall us? From such basic human instincts, surely, arises our fascination with the notion of traveling through time.

Time travel has long been a common theme of popular culture. There's Washington Irving's 1819 short story "Rip Van Winkle,"[1] Charles Dickens's 1843 novella "A Christmas Carol," Mark Twain's 1889 novel *A Connecticut Yankee in King Arthur's Court* and, of course, H. G. Wells's 1895 novel *The Time Machine*. Time travel has likewise been a staple of science fiction since the dawn of the genre, as when Buck Rogers awakened from centuries of suspended animation in 1928's story "Armageddon 2419 A.D.," by Philip Francis Nowlan writing as Anthony Rogers.

And more recently?[2] Time travel abounds in the popular culture. On-screen, consider: *Doctor Who* (the original BBC series in 1963, and its many reboots); The 1966 TV series *The Time Tunnel; Star Trek,* from many an episode in the original series (1966) to *Star Trek IV: The Voyage Home* (1986) to the 2009 movie reboot; The *Back to the Future* trilogy (1985, 1989, 1990); *Peggy Sue Got Married* (1986); *Bill & Ted's Excellent Adventure* (1989); *Timecop* (1994); The *Terminator* movies (1984, 1991, 2003, 2009, and 2015) and the related *Sarah Connor Chronicles* TV series (2008); *Hot Tub Time Machine* (2010); *Looper* (2012); *Edge of Tomorrow* (2014);

And the ultimate in popular culture: Super Bowl XLVIII's *Doritos* time-machine commercial (2014).[3]

Despite time travel's enduring mass appeal, modern SF is often as hand-wavy as to *how* such transportation might be possible as were the earliest speculations. This avoidance is as characteristic of literary SF as of the video kind. Jack Finney's 1970 novel *Time and Again* uses self-hypnosis, with characters living in the era that they convince themselves to experience. Diana Gabaldon's Outlander series, begun in 1991, uses circles of standing stones for its time travel. Audrey Niffenegger's *The Time Traveler's Wife* (2003, then a 2009 movie) calls upon a rare mutation—just don't ask how a mutation makes someone bounce around in time. Connie Willis's time-traveling historians (first seen in the Hugo and Nebula Award-winning 1982 novelette "Fire Watch") never consider *how* they are transported, only whether their actions might trigger cause-and-effect paradoxes.[4] Irving Belateche's 2014 novel *Einstein's Secret* has a wormhole conveniently linking Pennsylvania and Virginia, and offers no more explanation than "time travel is messy." Even many an SF story in *this* magazine, rightly renowned for rigor, merely posits that a time-travel mechanism—somehow—exists. "Trust me" is about as scientific as the conk on the head that conveyed the Connecticut Yankee to Arthurian times, or Merlin's spell by which he snoozed through a return to his present.

In summary, even recent time-travel fiction often depends upon reader/viewer acceptance of an SF trope (science used other than literally). Must such forbearance be the case? Perhaps. Perhaps not.

It's time for us to talk about . . . time.

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Son of the Fermi Paradox

Every day, it seems, astronomers announce the discovery of another planet orbiting some other star. As techniques mature for observing exoplanets, more and more of these worlds are found to be Earth-like in one or more respects, whether in size, mass, or an orbit within the local "Goldilocks" zone. And so, an earlier essay in this series[5] delved extensively into the matter of why, in a Universe rife with prospectively life-hospitable worlds, we might anticipate finding ourselves overrun by alien visitors. Since aliens visitors *aren't* underfoot, it's fair to ask instead why we don't detect their radio broadcasts or encounter abandoned artifacts of their past visits.

Refuting this appeal to large numbers, Nobelist Enrico Fermi asked: where are they? We call this succinct rebuttal the Fermi Paradox.

Time travel raises similar questions. That is: if time travel is possible, then why—out of the eons that surely stretch before us—are we not tripping over time travelers? Would Fermi, if confronted with speculations about time travel, similarly rebut: where are they?

* * *

What *is* time? The great philosophers

Can one travel through time? If not, the apparent absence of time travelers ceases to be mysterious. Before we can hope to answer that question, surely there's a more basic question to address: what *is* time?

We're sure we experience time, but we don't necessarily agree on what we experience. What is time, beyond something approximated by the operation of our clocks?[6] Is time fundamental? In what objective sense can we confirm the existence of time? Is time cyclical, as days, months, years—our natural measurement units of time—suggest? Is time linear, as in our journey from birth to death? Did time begin with the Big Bang? Will time end?

It's not just SF readers who struggle with such concepts. Philosophers, it turns out, disagree on what time is—and whether it truly even exists.

"Time is a sort of river of passing events," said the Roman emperor and stoic philosopher Marcus Aurelius, "and strong is its current; no sooner is a thing brought to sight than it is swept by and another takes its place, and this too will be swept away."

If time is about the sequence of events (a perspective shared with many a dictionary), such as successive stages of motion, what have philosophers had to say about *that?*

The ancient Greek philosopher Zeno of Elea is well known for his paradoxes. Consider the race Zeno imagined between the famously fleet-footed Achilles and an ordinary tortoise. Achilles, after graciously giving the tortoise a head start, quickly reaches the tortoise's starting point. By then, of course, the tortoise has moved forward a short distance. Achilles soon crosses *that* distance, as well, only to find the tortoise has crept a bit farther still. It seems that Achilles can never—quite—catch up.[7] Or consider the flight of an arrow. At any particular instant, the arrow is motionless. But time, surely, is nothing more than a succession of instants. How, then, can the arrow *ever* move? Through such reasoning, Zeno decided that motion, being the change of position with time—and time itself—are illusions.[8]

Aristotle reached the opposite conclusion. Contrasting the logic of the arrow paradox with his certainty that motion *is* observed, Aristotle asserted that more than a present moment must exist. If there are past, present, and future, then there is time.

Do the past and future exist, or is there only an ever-changing present? Philosophers continue to argue that point, as well. The past, no matter that we remember it, might cease to exist, instant by instant, as we cease to experience it. And if the future is that which has yet to happen, in what sense can the future be said to exist at all? But perhaps, as the "block theory" of time has it, past and future always exist, just as left and right do. If the block view is correct, we journey along a time continuum, experiencing an ever-changing "now."

Is time a sort of cosmic backdrop, apart from events? Or is time the consequence, somehow, of events, without independent existence? Plato and Aristotle disagreed. Two millennia later, on the very same point, Newton and Leibniz also disagreed.

Despite all the philosophical hair-splitting, we *experience* time. We're born, we age, and we die. We remember the past but only imagine the future into which we steadily advance by a second every second.

So what is time? Perhaps no philosopher has put it better than Augustine of Hippo, also known as St. Augustine. "What then is time? Provided that no one asks me, I know. If I want to explain it to an inquirer, I do not know."

Making this the time for us to abandon philosophy and seek the guidance of physics. . . .

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What *is* time? Newtonian mechanics

Isaac Newton's laws of motion ascribe a machine-like determinism to physical events—so machine-like that in common metaphor the Universe *became* a mechanical clock. God's role post-Creation (and Newton was a highly religious man) seemed reduced to winding the clock.

Of particular interest to our present topic, the Newtonian universe presumed two absolutes: (a) an invisible grid against which one ascertains locations and measures distance, and (b) consistency of time across that grid. Knowing the laws of motion and the position of an object at any single instant, it became possible—in principle, in any event—to calculate the position of that object at any *other* time.

Newtonian equations of motion, moreover, are indifferent to the direction of time. We can as readily derive from whence an object came as to where it will go. Prediction or retrodiction? The distinction is merely a matter of the sign, plus or minus, of the time parameter plugged into the equations.

If time is in some sense reversible, what does that say of cause and effect?

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What *is* time? Quantum mechanics

Quantum mechanics (QM), as discussed elsewhere in this essay series, characterizes the behavior of matter and energy at very small scales. Where Newtonian mechanics describes the behavior of particles with clockwork-like, theoretically infinite precision, quantum mechanics teaches that nature itself limits the precision with which a particle's velocity or position can be known. Quantum-mechanical uncertainties aren't discernible in macroscopic objects (like Newton's falling apple), but at tiny enough scales, these effects are routinely observed.

Due to its inherent uncertainties, quantum mechanics allows one to calculate only the probability that a quantum particle is here (or there, or anywhere else), those probabilities changing with time. The time-varying probabilities are mathematically embodied in what physicists call the "wave function."

We're not accustomed to encountering an object that is, say, 10% here, 20% percent there, and 70% smeared out all over. We simply find a particular object—whether a car or an electron—in one place. Theorists call the instantaneous localization upon the act of measurement "collapsing of the wave function," and they have argued for a century about what the collapse process physically means. Theorists even argue about whether it's meaningful to discuss the question.

No matter its strangeness, quantum mechanics shares a basic property with Newtonian mechanics: equations that are indifferent to the direction of time. Flip the sign of the time parameter, and QM's equations work as well as before the reversal. (That said, whatever happens when the wave function collapses undoes QM's indifference to the direction of time: applying QM methods to retrodiction from a particle's *measured* position gives incorrect results.)

* * *

But are you certain?

In the preceding section, I oversimplified somewhat. Quantum-mechanical uncertainty applies not strictly to position, but to the mathematical product of position and momentum. (Momentum, in turn, is the mathematical product of velocity and mass.) The more precisely we know a particle's position, the less precisely we can know its momentum. The uncertainties of an object's position and momentum are thus linked and complementary.[9]

The mathematical product of an object's energy and duration (a quantity characterized by the same units of measurement as the product of position and momentum) are likewise linked and complementary, are likewise subject to quantum-mechanical uncertainty. Pretty esoteric, eh?

Perhaps. But also very real.

Mass and energy being forms of the same thing (as expressed in perhaps the best-known equation in all of modern physics: $E = mc^2$), the energy X duration uncertainty suggests that particles can pop out of nothingness if they persist for only a sufficiently brief interval. And particles do! A particle and its antiparticle, such as an electron and a positron, will form spontaneously. When they encounter one another (or a different antiparticle and particle pairs) the unlike particles mutually annihilate. It all works out as long as the energy "loan" to create something from nothing is brief enough—within the irreducible window of uncertainty. Some physicists call this ceaseless froth of emerging and disappearing particles the quantum foam.

And in good time (cough, cough) we'll come to why I brought up this wrinkle. . . .

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What *is* time? Special relativity

Quantum Mechanics isn't the end of counterintuitive physics.

If I'm driving a car at sixty mph and (never mind why) hurl a ball straight forward out the window at ten mph, an observer standing on the sidewalk sees the ball moving at the sum of those speeds: seventy mph. Light, according to experiment (and Albert Einstein), doesn't work like that. Headlight beams from a moving car travel no faster than those emitted by a stationary car. More generally, light speed is the same (within a particular medium, such as air, water, or vacuum) wherever you measure it, whatever your velocity.[10]

That's less than intuitive.

Once we accept that light speed within a particular medium is constant, the implications are astonishing. Instead of light beaming *from* a vehicle, consider a flash of light set off *within* a vehicle, such as at the midpoint of the cabin of a clear-walled spaceship. The shipboard observer says the flash reaches the ends of the cabin simultaneously.

The spaceship, however, is coasting away from Earth. What does the Earthbound observer (with a Really Good Telescope) see? That as the flash moves toward Earth, the aft wall of the cabin—from Earth's perspective—zooms toward the light. Our Earthbound observer insists the light reaches the aft wall (as that wall races toward the flash) *before* light reaches the bow wall (as that wall races away from the flash). And yet, both observers claim that the inside-the-ship flash travels at the same speed. And both are correct!

It gets weirder. The Earthbound observer sees (a) the ship foreshortened in the direction of its flight, and (b) a shipboard clock ticking slower than an identical Earthbound clock. *(Clock* here stands in for any dynamic process, whether dust bunnies accumulating under a bed, milk going sour, or human aging.) The shipboard observer experiences neither length contraction nor time dilation, any more than the passenger in a car moving at a steady pace experiences any sense of motion.

As familiar from our SF reading as are these consequences of special relativity, they still battle with our intuition of how the Universe works. That's too bad for our intuition, for these effects have been confirmed again and again. Take, for example, muons. Muons are short-lived subatomic particles created in the upper atmosphere when high-energy cosmic rays collide with gas molecules. Everything known about muons says they ought to decay long before reaching Earthbound detectors into (typically) an electron and two neutrinos—only often muons don't. The muons are, in effect, tiny spaceships careening through the atmosphere at relativistic speeds. Their decay proceeds according to their internal, time-dilated "shipboard" clocks, not any clock set on Earth's surface. When a downward-streaking muon reaches Earth's surface, it remains, in some sense, in what you and I would consider the past. And from the muon's point of view? It has sped ahead into its future.

When the length of a ruler, the rate of a clock's ticking, and the meaning of simultaneity all depend upon from whence you look, then—Newton notwithstanding—absolute space and time do not exist. There is, instead, four-dimensional space-time, and nothing about *it* is absolute. As Einstein concluded, "Time has no independent existence apart from the order of events by which we measure it."

On the bright side, this mind-bending state of affairs answers one question for us: is there more than an instantaneous, ever-evolving present? Emphatically, yes! Simultaneity being relative precludes the notion of any universal instant in time. My present—if one of us is moving relative to the other—may be in your future or your past.

* * *

The twins paradox

If you don't care to entrust yourself, *Futurama*-style, to freezing and eventual thawing, or, *Buck Rogers*-style, to suspended animation, you can *still* travel to the far future by Going Really Fast. True, accelerating an object as massive as a human body to near-light speed isn't practical, nor is that feat apt to be feasible any time soon, but it *is* allowed by physics. We see an extreme example in Poul Anderson's Hugo-nominated 1970 novel, *Tau Zero*. Larry Niven's 1976 novel *A World Out of Time* does a time-travel two-step: the hero first jumps ahead as a corpsicle and then (much) farther during a long relativistic trip.[11]

But wait! If all motion is relative, why isn't it the Earth traveling really fast, the spaceship at rest, and the Earth leaping into the ship-and-passenger's future?

All motion *is* relative, but there's more to the story. (If you want a story, that would be Robert A. Heinlein's 1956 novel *Time for the Stars.)* As for the physics, it's time we look at the famous twins paradox, a form of which was first posed by Paul Langevin in 1911.

Consider twenty-year-old twins, whom we'll call Alice and Bob. Alice is the traveler of the pair. Aboard her spaceship, she: accelerates to about 99.995% of light speed; coasts for a month; decelerates to a stop; turns around; accelerates back toward Earth, again to 99.995% of light speed; coasts for a month; decelerates to a stop; and lands. She steps off her spaceship two months older.[12] Stay-at-home brother Bob is on the tarmac to greet her.

How old is he?

We've seen that speed makes clocks tick slower, so we might expect Bob to have aged more than Alice. But while Bob, with his Really Good Telescope, saw Alice's ship zoom away and come back, it's also true that Alice, with *her* Really Good Telescope, saw Earth—with Bob on it—zoom away and return. But clearly each twin can't be younger than the other.

It turns out that Bob, come to greet his peripatetic sister, is middle-aged. For him, almost seventeen years have passed and he's pushing thirty-seven. The difference between the twins?

Alice's bouts of acceleration and deceleration. Each time Alice accelerates, decelerates, or changes direction, she changes her "frame of reference." Bob has remained—to the first approximation—in a single frame of reference. Their situations are not equivalent.[13]

And so, upon close examination, the twin paradox isn't a paradox at all.

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The fourth dimension—sort of

Articles aimed at a general audience sometimes refer to time simply as "the fourth dimension." It's a natural enough idea. An object without persistence—vanished in an instant—is as much of a physical abstraction as an object that lacks breadth or depth or height.

We move left and right, forward and back, up and down, and we move forward in time. It's not seemingly much of a mental leap to suppose that we could—although we have yet to discover the means—(as in H. G. Wells's *The Time Machine)* also move backward in time. We don't notice the fourth dimension, Wells's nameless Time Traveler explains, because our consciousness moves along with it.

But time as a pure dimension, as distinct from space as left/right are distinct from up/down, is *not* the four-dimensional space-time of which Einstein wrote. Time and space, as Einstein realized, are different depending upon who is observing and from where they're observing. Hence: space-time.

Time, now conflated with space, remains different than purely spatial dimensions. That's another implication of light setting a speed limit. That the speed limit exists means that some pairs of events might have a cause-and-effect relationship, while others—too far separated by space for even light to traverse in the available time—cannot be related in that way.

Since soon after Einstein introduced special relativity, physicists have spoken of time-like and space-like intervals separating events in space-time. Across a time-like interval, no possible observer can see the second (possibly effect) event before the first (possibly causal) event. Past and future in this scenario are unambiguous. Across a space-like interval, however, matters are quite different. Which event of the interval-delimiting pair a particular observer perceives as first and which as second depends upon the events' and the observer's relative motion. Across space-like intervals, past and future *are* ambiguous.

But wait! There's more.

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What *is* time? General relativity

Special relativity suggests that the time aspect of space-time is complicated—but not yet what that time aspect is. Well, when Einstein developed that theory, he wasn't done. The "special" in special relativity limits the theory to particular points of view, what physicists call reference frames, that move at constant velocities, where (as we've seen) velocity combines speed with direction.

General relativity involves accelerating reference frames (that is, situations in which speed *or* direction changes) and—here comes the truly interesting part—the insight that acceleration and gravitational attraction are equivalent. An object dropped in a spaceship accelerating at one gee falls *just* like an object dropped while standing still on the Earth's surface. What's going on, and what has it do with time?

Special relativity is uncomplicated compared to general relativity. Averting our eyes from quite complex math, we'll jump straight to a few important implications.

If the malleability of space-time and the relativity of simultaneity haven't already convinced you that the Universe lacks some unchanging, multidimensional grid/backdrop, consider this: neither does space-time reflect dimensions at right angles to each other. That geometry you studied back in secondary school, the product of Euclid, another ancient Greek, is merely another approximation to reality.

Recall how flat/two-dimensional maps satisfactorily represent small areas—while grossly misrepresenting the overall Earth. That's because (setting aside that Earth isn't quite a perfect sphere) the two-dimensional surface of a sphere curves.[14] Space-time itself curves, the local curvature dependent (general relativity tells us) upon the distribution of mass.

Newton struggled to explain—no matter the obvious utility of his mathematical equation for gravitational attraction—*how* widely separated objects could influence one another's motions. Consider the Moon as it orbits the Earth. How do the Moon and Earth "know" that the other exists—on average 238,000 miles (384,000 kilometers) separate the two worlds—much less how do they gauge their influences one upon the other?

Via his theory of general relativity, Einstein did away with such "non-local" interaction. Objects *don't* sense other objects at a distance; rather, objects interact with the local curvature of space-time. Or, as physicist John Wheeler so elegantly (if anthropomorphically) expressed the essence of General Relativity in twelve words: "Matter tells space how to curve. Space tells matter how to move."

What has this to do with time and time travel? Everything. Because it's space-*time* that warps in the presence of matter. The stronger the local gravitational field (i.e., the more curved the local space-time), the slower a clock ticks in that field. Conversely, the atomic clocks overhead in GPS satellites—because they're a bit removed from the Earth's mass—tick *faster* than an identical clock does on our planet's surface.

And so, our time-travel toolkit includes velocity-induced *and* gravitational time dilation.

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What *is* time? The slings and arrows of outrageous entropy

The video of two billiard balls colliding is as believable run backward as forward. Ditto the (admittedly harder to produce) video of two really hard spheres colliding at relativistic speed. Same for an alpha particle, say, scattering off an atomic nucleus.

The video of the making of an omelet? Not so ambiguous.

Mechanics—classical, relativistic, and quantum—is governed by equations that are indifferent to the direction of time.[15] Why, then, do you and I experience a direction of time? For a possible answer, we must turn to yet another branch of physics.

Thermodynamics, as its name suggests, deals with the evolution of heat-driven systems. It was developed to better understand and optimize steam engines. Thermodynamics *can't* undertake to see the world as individually modeled, sometimes colliding, particles, because the problems thermodynamics seeks to solve encompass enormous numbers of molecules. Instead, thermodynamics uses statistics and probability to reduce the overall complexity. *Temperature*, as an example, is a measure of the average energy of a set of particles—like the water molecules comprising all the steam in a boiler. That single number is often more useful than the (impossible to determine, much less to compute with) details of every molecule's position and kinetic energy.

Entropy is another highly abstract parameter from thermodynamics. Entropy, loosely speaking, is the measure of disorder within a system. We'll use a standard deck of playing cards, of four suits and thirteen cards per suit, to examine entropy.

Playing cards leave the factory arranged in numeric order by suit, with the suits ordered by customary rank: clubs, diamonds, hearts, spades. Imagine we separate out the four suits, then shuffle the four-element deck made of the thirteen-card-thick stacks (think of each stack as a very thick card). The deck can end up in any of 24 ways (four possibilities for the front suit; times three possibilities from among the remaining three; times two possibilities between the remaining two; times one, the remaining suit: 4 X 3 X 2 X 1 = 24). We'd be surprised, but not incredulous, if after shuffling we found the deck in factory order.

In a normal shuffle, the cards within a suit won't stay together. Instead, when we shuffle the deck, any of 52 cards might wind up first, any of the 51 remaining cards wind up second. . . . After a lot of multiplication (or a simple spreadsheet), it turns out that there are more than 8 X 10^{67} possible outcomes. That's 8 followed by 67 zeroes!

It's still possible for a shuffled deck to come out in factory order—just *extremely* implausible. While the toss of a fair coin has a one-in-two chance of coming up heads, a shuffled deck has less than one chance in 8 X 10^{67} of coming out in factory order.

The second law of thermodynamics, paraphrasing, says that entropy—the disorder within a closed system—tends to a maximum. *Entropy*—and our everyday experience with the natural tendency to disorder—suggests a cause for the perceived "arrow of time."

Billiard balls colliding, then rebounding, are a simple system. We see no difference between the video of their collision run forward and backward because the trajectories in either case appear equally likely. Not so, the deck of cards picked up, shuffled, set down, then shown to be in factory order. Not so, the omelet seen reassembling itself into eggs. Or as Arthur Eddington put it, almost a century ago:

* * *

> The law that entropy always increases, holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the Universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

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How, then, is it that we often see order emerge from disorder? How is it I can re-sort a deck of cards? How is it nature can assemble scads of stray molecules into potatoes and people? The short answer: the tendency toward disorder applies to *closed systems*. A deck of cards ceases to be a closed system when I'm sorting; the energy I supply can overcome the deck's tendency toward disorder. More broadly, *Earth* is not a closed system; the unending flood of energy from the Sun makes possible the ongoing biological processes that would seem the antithesis of entropy. But the Sun is a pretty good approximation of a closed system . . . luckily for us, its evolution is a very gradual thing. And bigger picture: the *Universe*—or the Multiverse, if you find that sort of thing convincing—is the ultimate closed system.

If we were to examine our colliding billiard balls closely enough, even here time reversibility would disappear. Perfectly elastic collisions on perfectly frictionless surfaces are abstractions. In the real world, a little kinetic energy (the energy of motion) is lost to friction between billiard balls and tabletop. At the moment of collision, a tiny amount of kinetic energy transforms to slightly raised temperatures of the balls themselves. In physical, rather than idealized, processes, some energy is *always* dissipated in heat.

And so, before and after become distinguishable.

Does time have a direction, or just the illusion of one? Will the Universe have reached the end of time once the state of maximum entropy has been reached? Or will time continue, only its direction be forever lost?

Wouldn't it be nice to know?

* * *

What *is* time? The recurrence theorem

Preindustrial societies were attuned to the cycles of nature: day and night, the "moonthly" phases of our world's natural satellite, and the annual cycle of the seasons. It's no wonder that some societies saw time itself having cyclic properties.

We "moderns" tend to find such a cyclic view of time quaint: a relic of a simpler, naturalistic society. Thermodynamics seems to confirm what our senses tell us: that there is a direction to time. Surely, time is linear, not cyclical.

Or not. Mathematician Henri Poincaré demonstrated in 1890, in what has become known as the Poincaré recurrence theorem, that any finite isolated system must, after a finite amount of time, return to its initial state. In an infinite amount of time, the cycle must repeat an infinite number of times.[16]

* * *

What *is* time? The astronomical evidence

In 1924, astronomer Edwin Hubble published his finding that the Universe is expanding. The same data, considered in reverse, gave rise to a startling implication: at earlier times, the

Universe was smaller. Keep rewinding that conceptual movie, and the retrodiction was of a *singularity:* conditions of infinite density and temperature. In such conditions, physical laws as then (and still) understood fall apart.

Was the Big Bang the beginning of time? Perhaps. If anything existed before the Big bang, physical science offers no opportunity to glimpse it.[17]

For decades, astronomers and cosmologists wondered: did the Universe contain enough mass that its mutual gravitational attraction would eventually overcome the outward momentum from the Big Bang, bringing expansion to a halt, then bring everything crashing back together to erupt again in another Big Bang (perhaps to repeat again and again and again . . .)? If so, the Poincaré recurrence theorem would be more than a mathematical curiosity.

In the 1990s, however, it became clear that the expansion of the Universe is *accelerating*. Far from everything falling back together in some very distant future, the Universe will continue expanding—possibly until even atoms, and then their constituent parts, are ripped apart. Physicists say that "dark energy" drives this accelerating expansion—although that's merely a label, not an explanation. But whatever is happening, the Universe doesn't seem cyclical.[18]

Astronomy, like thermodynamics, most definitely exhibits an arrow of time.[19]

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What *is* time? Reflections

A century of effort has failed to reconcile the two greatest theories in modern physics: quantum mechanics, whose prescriptions so accurately describe subatomic realms, and general relativity, whose prescriptions so accurately describe very large and/or very massive domains. These two theories are, at their cores, inconsistent in their underlying assumptions. The equations of general relativity assume that space-time is continuous. The QM worldview is inherently *dis*continuous, with matter and energy coming in discrete, indivisible chunks called quanta. Moreover, GR is deterministic while QM is probabilistic.

Can the Universe be continuous *and* discontinuous, deterministic *and* nondeterministic? It would appear that one of these great theories—and perhaps both—suffers from a foundational shortcoming. When, someday, the two theories are unified, or superseded, we may get an explanation for the arrow of time.

But even that grand unification may fail to explain time's arrow. QM and GR alike are *reductionist* in approach. Both undertake to explain the very complex through an ever-deeper understanding of ever fewer, ever more fundamental, constituent parts. For certain lines of inquiry—such as the nature of time?—reductionism may stand in the way of an answer.

Thermodynamics sees—as do you and I, as do (at a quite different scale) astronomers—an arrow of time. And thermodynamics alone, of the physics disciplines we've surveyed, *embraces* the messiness of molecules in their myriad multitudes.

A few atoms seen (or modeled) jostling and jittering about don't suggest that—within a crystal—they form part of an overarching order. A few ants spotted wandering about don't suggest the purposeful behavior of the colony. A few neurons detected firing don't suggest that among an ensemble of billions, they can create art, literature, and science.

Time's arrow—like crystals, ant colonies, and human thought—might be an emergent property of large numbers of objects. If so, the reductionist models of QM and GR could be as unsuited to fully explaining time as the study of single neurons is to explaining the human mind. And if time's arrow is an emergent property, what other characteristics of time might QM and GR theories have omitted?

Coming up next (cough cough) time: the many uncertainties surrounding the prospects for, and the possible implications of, time travel.

Footnotes:

[1] A similar idea, casting a different Irving character (Ichabod Crane)—awakening after two centuries, not two decades—underlies the 2013 TV series *Sleepy Hollow*.

[2] He says (in the present context) ironically. Or maybe the parenthetical made it doubly ironic.

[3] *https://www.youtube.com/watch?v=Y-P0Hs0ADJY*

[4] Paradoxes, loops, and the like are a whole major topic. We *will* get there. All in good (cough cough) time.

[5] See my "Alien AWOLs: The Great Silence," in the October 2014 *Analog*.

[6] A clock counts events or measures processes believed to change in a predictable way with respect to time. In the course of history, clocks have made use of water dripping into a bowl, the burning of candles, the shadow cast by the Sun, the swinging of a pendulum, the oscillations of electrically stressed chunks of quartz, even the properties of the light emitted by atoms.

Not one of these mechanisms measures *time*. No one knows how to do that directly. We are left to trust that our stand-in measurements are valid analogues.

[7] That some infinite series (such as 1 + 1/2 + 1/4 + 1/8 . . .) can be proven to converge doesn't resolve the paradox—because other infinite series (such as 1 + 1/2 + 1/3 + 1/4 + . . .) can be shown *not* to converge.

[8] Was Zeno wrong? If so, how?

The Achilles-and-tortoise paradox presupposes that time and distance are infinitely divisible. If there is some smallest possible distance, eventually only one indivisible unit of distance will separate man from tortoise—and the man is faster to cross it.

Many physicists now believe that space and time, like matter and energy, are composed of indivisible quanta. The suspected fundamental unit of distance is far too small for any present-day technology to confirm. The fundamental unit of duration is, presumably, the amount of time that light (in a vacuum) would take to cross the quantum of distance.

[9] If an object were at perfect rest, its velocity, hence its momentum, would be zero. Zero times anything finite is also zero. If the object's position X momentum were zero, there would be no uncertainty—and we can't have that. Even at absolute zero, therefore, an object has a minimal amount of jitter.

[10] Contrary to familiar usage, *speed* and *velocity* differ. *Speed* is a rate, such as ten miles per hour. *Velocity* is both a rate and a direction, such as ten miles per hour due north. An object tracing a circle at a constant speed has a constantly changing direction—and hence a constantly changing velocity.

The "special" in special relativity limits the theory to particular points of view, what physicists call inertial frames of reference, that move at constant velocities.

We'll come to the more general case.

[11] A point of grammar: in customary usage, *farther* refers to increased physical distance and *further* to an increase in something else—often something metaphorical. In a time-travel context, time offers a type of distance. With premeditation, I chose *farther* to characterize our hero's time shift; while you may disagree with my usage, I'll ask that you not hassle me *further*.

[12] For simplicity (or because some advanced technology protects Alice from what would otherwise be extremely high levels of gee forces) we'll assume that the periods of acceleration are extremely brief. This is, after all, a thought experiment! We can then find the time dilation strictly from the long periods spent coasting, and I get to avoid doing calculus.

[13] Strictly speaking, Earth doesn't provide an inertial frame of reference. Earth orbits the Sun and the Sun orbits the galactic core, but these ongoing changes in velocity are insignificant compared to Alice's maneuvers. Ditto the effects, which we have yet to discuss, of Earth's gravity. We could simplify our thought experiment by starting out Bob and Alice on a tiny habitat adrift in space. Stay-at-home Bob wouldn't much like that, of course.

[14] Notwithstanding many maps you've likely seen, Greenland *isn't* larger than South America! South America, in fact, has an area of about eight times that of Greenland. Greenland appears huge on many world maps because it lies so far to the north—and the Mercator projection commonly used on world maps distorts more and more the farther one gets from the equator.

[15] Quantum mechanics deals with the probabilities of where an object may be, not its actual position, but nonetheless, the equation remains time-reversible.

[16] *Is* the Universe a finite system? Unclear.

The finite speed of light and the finite elapsed time since the Big Bang combine to limit observations to a finite, if extremely large, observable Universe. Limits on the observable Universe, however, don't preclude the overall Universe from having infinite extent.

[17] Cosmologists still speculate. If this essay hasn't provided enough food for thought, see *Before the Big Bang: The Prehistory of Our Universe,"* Brian Clegg (2009).

[18] The data remain inconclusive whether and how the density of dark energy changes with time. The Big Rip will happen only if that density grows as the Universe expands, creating a positive feedback loop, stretching space-time itself ever faster and faster. See "The Big Rip at the End of Time," John G. Cramer (March 2005 issue), *http://www.analogsf.com/0503/altview.shtml*.

[19] For completeness—but without further elaboration—I'll note that an arrow of time is also glimpsed in a rare decay mode of a type of kaon (a subatomic particle) and in the absence of backward-in-time electromagnetic waves (which would be consistent with Maxwell's equations but are not observed in nature).

About the author

A physicist and computer scientist, Edward M. Lerner toiled for thirty years in the vineyards of aerospace and high tech. Then, suitably intoxicated, he began writing science fiction full time. When not prospecting beneath his sofa cushions for small change for his first spaceflight, he writes technothrillers like *Energized* (powersats), the InterstellarNet adventures of First *and* Second Contact and, with Larry Niven, the Fleet of Worlds series of space operas.

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