Science Fact

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

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In Part I of this essay, we briefly surveyed classical/Newtonian mechanics, relativistic/Einsteinian mechanics, quantum mechanics, and thermodynamics (or, if you require your lists to exhibit parallel construction, its close relative: statistical mechanics). Each of these disciplines offered its own conclusions about the nature of time. Left for this concluding half of the essay: how we might travel in time and the implications of such a venture.

Not to keep you in suspense: physics suggests time travel *is* possible—but (a) only through incredible feats of engineering (b) amid great skepticism that something important (e.g., the need for causality) is missing from that physics, and (c) even then, seemingly with major restrictions on what eras can be visited.

As usual in this essay series, we'll also see where SF has anticipated the possibilities.

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To the far future . . . if not easily

We *can* travel into the future at other than at our accustomed second-per-second pace.

Option one, previously touched upon: travel fast for a while before resuming a normal (or no) speed. Voilà! You're in your own future.

Getting far into the future this way, oddly enough, takes time. Suppose you set the goal of traveling twenty years into the Earth's future. Suppose your ship can accelerate to about 86% of light speed (which will require rather advanced tech—no human has ever achieved 1% of light speed). At that pace, time aboard your ship passes only half as quickly as back on Earth. To simplify matters, we'll ignore the periods spent accelerating to, or decelerating from, that breakneck speed. You will need to spend ten years aboard your ship before twenty years pass on Earth. Even if you could achieve 99-plus percent of light speed, you'd need to spend more than a half year of ship's time to get a ten-year jump on Earth.

It takes a great deal of energy to achieve those near-light velocities! In Newtonian mechanics, the kinetic energy of an object with velocity v and mass m equals $1/2mv^2$. Doubling the ship's velocity entails four times the energy, tripling the ship's velocity takes nine times the energy, and so on. As velocity increases, relativistic effects become manifest and Newtonian mechanics understates the required energy. The bottom line: the ship's mass to be accelerated grows exponentially with velocity. Let's just say that significant time travel by starship isn't (hah!) in our immediate future.[1]

Option two: loiter deep within a significant gravity well—near a neutron star, say—and (relative to those of us in comparatively flat space-time) clocks again run slower.[2] Make sure to pick one among the subset of neutron stars that *isn't* (like a pulsar) a deadly radiation zone. In orbit around the neutron star, you'd be in free fall, like an astronaut circling the Earth. You'd have the time-slowing benefit of the intense gravity without feeling that gravity. (But don't orbit too close, or—as befell characters in Larry Niven's 1966 Hugo Award-winning short story "Neutron Star"—you'd feel the tidal effects. Only *tidal effects* is so understated. The more descriptive term for what would you'd experience is "spaghettification.")[3]

But if gravitational time dilation is the road to the future, there's yet another difficulty. The closest known neutron stars to Earth are hundreds of light-years distant. *Making* a neutron star (presumably out of a nearby sun) might be no more of a challenge than traveling to a naturally occurring neutron star. And if your engineering skills are really advanced? Perhaps you can assemble sufficient mass into a shell *around* yourself. Tidal effects, like gravitational attraction, go to zero at the center of a uniform sphere.

The do-it-yourself, wraparound neutron star has its own limits. Lest the constructed shell collapse into a black hole—with the would-be time traveler within—Brian Clegg has calculated the best that can be achieved is one year elapsed inside for every five years passing outside.

Speaking of black holes,[4] if you want to slow time to an absolute crawl, find a suitably sized one and "loiter" just outside its event horizon.[5] (Spaghettification doesn't become problematical until you're well inside the event horizon, in which case you have *lots* of problems.)[6] Of course, no black holes are known to exist in the interstellar neighborhood, either.

I *did* say about travel to the future: not easily.

Perhaps someday, when quantum mechanics and general relativity have been reconciled, physicists will learn to *artificially* warp space-time. Among the applications of such knowledge might be the formation of compact regions of slowed time that—unlike the neighborhoods of neutron stars and black holes—would not be deathly radiation environments. Such space-time warping technology plays a part in my Campus Award-winning 2015 novel *InterstellarNet: Enigma*.

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What's past is past. Or is it?

Everything we've discussed so far deals with carrying oneself, one way or another, into the future: *Rip Van Winkle* improved with high tech. But what if you wish to visit the past? What if, having explored the future, you desire to return to report on what you've seen? That is a much tougher challenge (although we've already covered much of the underlying physics).

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A matter of some gravity

A full understanding of the world around us involves mathematical skill and the computational arts as much as physical insight. As a case in point, consider gravity.

In 1686, Newton described the gravitational interaction between any two masses (say, Earth and Sun) with a simple quadratic equation. This description served astronomers well for centuries; it suffices to this day for most NASA mission-planning purposes. But add a third mass (say, the Moon) to the picture, and Newton's theory of gravity lacks a general solution. It was almost a century after Newton published his findings until Euler and Lagrange demonstrated special circumstances in which the three-body problem *can* be solved exactly.[7] It wasn't until 1887 that Bruns and Poincaré proved that no exact general solution exists for the three-body problem. Approximations have been, and remain, necessary.

The analogous representation of the modern, more complete description of gravity—Einstein's 1915 theory of general relativity—is a system of ten nonlinear partial-differential equations. All you need to know about that characterization is (a) that's seriously heavy-duty math and (b) the Einstein field equations (like Newton's far simpler equation) have yet to offer many exact solutions. It wasn't until 1949 that mathematician Kurt Gödel, applying the Einstein field equations to the Universe as a whole—a spinning Universe, at that—showed that exact solutions exist that allow "closed time-like curves."

A space-time curve represents an object's experience: the path the object has taken through time and space. An interval on that history is delimited by two nonsimultaneous events. Recall from Part I that across a time-like interval no possible observer can witness the second (possibly, effect) event occurring before the first (possibly, causal) event. That precedence is maintained for as long as the watcher's observations and travel—as we're so often told must be true—happen at or below light speed. Remember that caveat.

What, then, is a closed time-like curve (CTC)? It's an object returning to a place *and time* already experienced. It's history meeting up with itself. Like an Escher stairway, no matter how ordinary each step appears, the whole seems wrong.

"CTC" is highly circumspect physics-speak for time travel to one's past.

No wonder that, when Gödel presented his proof to his friend on his seventieth birthday, Einstein briefly doubted general relativity.

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Time travel is such a drag

Familiar (within these pages, anyway) considerations of relativity tell us that the faster one travels, the slower one's clock ticks, until, approaching light speed, the shipboard clock—viewed from an external/at-rest frame of reference—slows to zero. It makes intuitive sense that, upon exceeding light speed, one's clock—and time itself—would change direction. Would run backward relative to a sub-light speed observer.

Alas, a moving object's mass increases in inverse proportion to its time dilation. When shipboard clocks are ticking at half the stay-at-home rate, the ship's mass (compared to its at-rest mass) has doubled. As the clock rate (from the at-home perspective) slows toward zero, the ship's mass (in the at-home perspective) approaches infinite. You just *can't* accelerate an object to, much less past, light speed.

If I'm not pages too late to write this: here's where matters get tricky.

The mere presence of a massive object like the Sun curves space-time—that's a basic conclusion of general relativity. The influence of that curvature on the trajectory of other objects, like the planets, is what we know as gravity. Less well-known—but another implication of the Einstein field equations—is that the *rotation* of massive objects further distorts space-time. Specifically, the rotation drags space-time around with it. When the object is massive enough, and/or rotating fast enough, the dragging effects can be substantial. A ship moving at sub-light speeds within a dragged region of space-time (physicists refer to "frame dragging") can be moving *faster* than light in regions where space-time is not being dragged. In the process, the ship is also—compared to that non-dragged region—spiraling backward in time.

Circling the Universe, à là Gödel, isn't the easiest way to go backward in time.[8] In 1974, Frank Tipler came up with a solution to Einstein's field equations showing that a closed time-like curve—travel backward in time—could be accomplished with the frame dragging of a massive object smaller than the Universe. His 1974 paper, "Rotating Cylinders and the Possibility of Global Causality Violation," suggested one such time-travel mechanism. Tipler tamed the math with the simplifying assumption that the cylinder was of infinite length—not something we finite humans are likely ever to construct—but asserts that a finite object of sufficient mass and rotational velocity would suffice.[9] His density and mass estimates roughly correspond to ten neutron stars. Disassembling neutron stars, reassembling all that mass into a cylinder, and spinning it up sounds like a challenge. So does maintaining all that mass in a cylindrical shape against the tug of its own gravity. (That much mass would normally pull itself into a sphere—and then collapse into a black hole.) Ditto approaching near enough to benefit from frame dragging without getting spaghettified.

Another class of exotic celestial object might serve our purposes: cosmic strings.[10] Richard Gott described how two cosmic strings could sufficiently distort space-time to also allow for a backward-in-time spiral. Just: find and straighten two cosmic strings; wrestle them into parallel positions; set them moving apart—despite their gargantuan masses and mutual attraction—at near light speeds; loop around the (rapidly separating) strings at near-light speeds. That sounds like another engineering project too ambitious to take on anytime soon.

Physicists keep finding solutions to Einstein's field equations. Here on Earth, a ring of intense light—light has energy; energy is a form of mass (and vice versa)—might demonstrate frame dragging and time travel. That's the assertion, anyway, of Ronald Mallett. Compared to Tipler's super-massive cylinders and Gott's cosmic strings, Mallett's approach has the virtue of permitting a near-term test.[11]

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Once more, black holes

A popular pedagogical device for presenting the general-relativity explanation of gravity is to liken (a) space-time to a taut, horizontal rubber sheet and (b) any large mass such as the Sun to a bowling ball set onto the sheet. The weight of the bowling ball causes the sheet to sag. Objects anywhere on the sheet, influenced only by the local tilt of the rubber sheet, are drawn toward the dip. This is an imperfect analogy, of course. For one thing, the rubber sheet is two dimensional, and space-time has four dimensions. For another, the analogy relies upon gravity tugging on the bowling ball to explain . . . gravity. Nonetheless, the mental image can be instructive.

The bowling ball/Sun stretched the sheet a bit. Imagine, instead, how the sheet would stretch beneath something really massive and really compact: into a deep, conical, distortion. *That* is the simplified model of space-time near a black hole.

Suppose you dive into that deep, deep pit. You might suspect you won't get out. In general, you'd be right . . . but what if at the bottom of this pit you encountered the bottom of another pit. Might you go in one side and come out the other?

That space-time construct is an Einstein-Rosen bridge, more commonly known as a wormhole. It's a tunnel that in theory provides a shortcut between widely separated regions of the Universe. (In more speculative physics, a wormhole might interconnect different universes within the Multiverse. For our time-travel discussion, we don't need to explore the latter possibility.)

Things get eerier. A voyage through a wormhole at sub-light speed—bypassing lots of intervening flat space-time—can exceed light speed with respect to the *non-wormhole* distance between the two endpoints. And supra-light speeds, as we've seen, suggests travel backward in time.

In its simplest version, a black hole is a dimensionless point, to which everything that approaches within its event horizon must inevitably and fatally be drawn. If so, to dive into a black hole is suicide. Then Roy Kerr reapplied the Einstein field equations to a new scenario, in which the star collapsing into a black hole (like most objects in space) is spinning. In this case, the "singularity" of a black hole, rather than a point, becomes a *ring*. With the correct angle of approach to a suitably sized Kerr black hole, a spaceship might fly *through* the singularity without get spaghettified. But any such ship would *still* be trapped inside an event horizon.

So: rather than the "pits" of two black holes meeting up, we need our black-hole entrance to be matched with its antithesis: a white hole. White holes, if they exist, and the Einstein field equations permit them, spew out matter and energy.[12] If white holes, too, can spin, a spaceship might exit through *its* annular (ringlike) singularity.

Permitted is hardly a compelling proof. Astronomers have never spotted a white hole—which, unlike black holes, should be very obvious. One might argue the Big Bang itself was a white hole, but that hardly makes the prospect of emerging through one very attractive.

A black-hole/white-hole tunnel sounds (a) incredibly dangerous and (b) one-way. If we could round up two white holes, and link them, in theory the link could be two-way. Which may not matter, because the math predicts wormholes are incredibly unstable. Try to traverse a wormhole, and it collapses faster than anything can make the crossing. Unless, that is, you artificially reinforce the mouths of the wormhole with—choose your engineering challenge: antigravity, exotic matter, negative energy.

Exotic matter, you ask? It would be to familiar matter as a white hole is to a black hole. Exotic matter is as hypothetical as are white holes. Negative energy? That's a synonym for dark energy, the mysterious stuff that is presumed—somehow—to be driving the accelerating expansion of the Universe.

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Building a wormhole time machine

If contemplation of wormholes hasn't yet dropped you down Alice's rabbit hole, consider this: *making* a wormhole. For that, we need black and white holes.

Physicists regularly use particle accelerators to collide high-speed atomic nuclei. Interestingly, sometimes short-lived particles emerge from such collisions, teaching us about the quantum world. The typical collision debris is subatomic bits and electromagnetic radiation. Sometimes the debris includes matter/antimatter pairs, like an electron and a positron. At energy densities far beyond the capacity of current particle accelerators, collisions can—in theory—produce black holes. If white holes exist, they, too, could be produced by a collision process. Ditto black/white hole pairs. Rather than dwell on the hazards of, and safety precautions for, such manufacturing, we'll assume the factory for black and white holes is located safely far from Earth. We'll further assume the holes come out spinning, so that their singularities are annular. Wasn't that easy? Now:

- Separate black and white holes before they meet and mutually annihilate.
- Feed matter to the holes quickly enough to prevent them from evaporating.[13]
- Inject the black and white holes with charged particles until the holes are easily manipulated using electric or magnetic fields.[14]
- Manipulate a black hole and a white hole close enough to one another to (somehow) induce formation of a wormhole between them. Stabilize the ends (waves hands even more furiously) with antigravity, exotic matter, or negative energy. Separate the ends.
- Return the white hole to a particle accelerator. Sling the white hole around and around . . . and *a round,* accelerating it to very close to the speed of light. Through old-fashioned time dilation à là special relativity, the two ends of the wormhole will develop a significant time differential.[15] Or park the white-hole end in a deep gravity well to rack up gravity-based time dilation.
- Separate the wormhole's white-hole end from its black-hole end by a sufficient distance. (What distance is sufficient? Past where light connects the two endpoints as quickly across regular space-time as through the wormhole.) The white hole can be moved by shooting it out of the particle accelerator or by spaceship.
- As necessary, manipulate the wormhole-mouth stabilization mechanism, expanding the entry/exit holes to accommodate whatever will be passing through.
- Go through the tunnel and start to take on cause-and-effect paradoxes (a topic to which we *will* come).

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Richard A. Lovett employed essentially this technology in his novelette "The Wormhole War" (in the June 2015 *Analog).* It might have taken five years to transport a wormhole end deep into space—but researchers back on Earth could then send stuff through the wormhole in more like one year. *Someone* (we get only musings about whom) built a wormhole time machine in the

2014 movie *Interstellar,* which also showcased time dilation à là general relativity.[16]

It's only a bit more speculative (read: mind-bending) to contemplate daisy-chaining or looping two or more wormhole time machines. Or carrying a wormhole through a wormhole. Or constructing tunnels made from two white holes, and so (in one theory, anyway) bidirectional.

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Not your grandpa's time machine

That's pretty neat! We've designed—reliant upon future/exotic tech and some as-yet untested implications of general relativity—a time machine that can carry us into the past. It remains far from what your average SF reader (or author) would ask for in a time machine.

It only lets you go back so far. The time separation between ends of the wormhole comes from time dilation. One end has proceeded more slowly into the future than the other. If a five-year separation has been achieved, you can go back five years. When the at-home end of the wormhole is a year old, you still can travel back five years—but that's now four years after the wormhole was created.

If an end of the wormhole is carried away from Earth at relativistic speeds, or is parked deep in the gravity well of a neutron star, the separation between ends of the wormhole can continue to grow—but under no circumstances can a wormhole time machine transport you back before the creation of the time machine. (In my novella "Time Out," January/February 2013 *Analog,* it was expressed as any time-travel transmitter requires a matching receiver. You can't travel back before the first receiver.) Forget your plan to drop in on ancient Rome.[17]

On the bright side, we may have discovered the answer to the time-travel variant of the Fermi Paradox. We don't find ourselves tripping over time travelers because—our era having failed to invent backward-going time travel—they can't get here.

It can't be set for arbitrary dates. Mr. Peabody of *Rocky and his Friends,* aka *The Rocky and Bullwinkle Show* (1959), may have a dial on his WABAC (say it aloud) machine, but that was cartoon physics. There's no tweaking the dial on our wormhole time machine. If the WABAC machine is like a helicopter, able to deliver you anywhen (and anywhere) in the past, the wormhole time machine is more of a railroad. It takes you to when/where its "tracks" end—and only then/there. And ("Play it again, Sam") as time goes by, the "past" end of the wormhole time machine—the train depot—keeps sliding forward in time.

To travel far back in time, you also must go far away in space. Our wormhole won't take us to the past until the end-to-end trip at light speed would be shorter through the wormhole than through uncontorted space-time. That is, until the wormhole's ends are sufficiently separated, they remain connected through regular space-time. In relativity-speak, communication between insufficiently separated ends of the wormhole is by a space-like curve, not a time-like curve.

In a word: bummer.

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Cause and effect

Still and all, we've seen reason to believe that—with sufficiently massive engineering efforts, and subject to constraints—travel to the past *is* possible. We may not have our grandpa's time machine, but we still have the Grandfather paradox.

Suppose I build a time machine, with which I travel to the past and shoot my grandfather before he ever reproduced. Then I could never have been born. Obviously, I never went back in time. So Grandpa *did* reproduce, and I *was* born, and . . .

Theorists and SF authors have imagined several resolutions to cause-and-effect dilemmas that travel to the past might otherwise provoke.

Such as: the past can't be changed. Something must foil every such attempt. The 1995 movie *Twelve Monkeys* relies on that premise. Travelers to the past can hope only to locate a plague virus in its unmutated state, the better—in the time traveler's present—to engineer a vaccine. Any attempt retroactively to stop the plague must be futile. *(12 Monkeys,* the 2015 version, rests upon the opposite premise. Episode by episode the TV series changes the time traveler's past—although, to keep the series going, none of the changes yet shown have stopped the plague.)

A past that can't be changed—no matter the reassuring affirmation of our everyday notions that cause and effect ever occur in that order—begs the question: *why?* Perhaps time is simply fixed. Our efforts to change matters may fail because they always have and always will.

An interesting type of unchangeable past arises from a cause linked with its effect in a closed loop. Such a loop underpins the novelette "By His Bootstraps," by Robert Heinlein (writing as Anson MacDonald, in the October 1941 issue of *Astounding).* The time travelers who manipulate the story's protagonist are later versions of himself. That is: a Bob from the far future coerces the earlier Bob to go to that far future, from whence he returns to the earlier Bob to . . . With neither beginning nor end, but plenty of loopedy loop, everything hangs together in a mind-bending way.

Heinlein was back at it in his (oddly punctuated) 1959 short story "'—All You Zombies—'" (the basis of the 2015 movie *Predestination)* in which the time-traveling protagonist eventually becomes both his own parents.

Perhaps the Universe acts as its own enforcer, preventing paradoxes by precluding changes to the past—a speculation whose academically understated name is the cosmic censorship principle. Maybe the resolution of the Grandfather paradox is as boring as the Universe (somehow) returning you to your own time before you can pull the trigger. Stephen Hawking has speculated that any wormhole into the past creates a feedback loop. Through that loop, background radiation—the frothing of the quantum foam—builds up to destroy the wormhole (sort of like background noise endlessly amplified by a poorly positioned microphone blowing out a loudspeaker). He dubbed such cosmic censorship the "causal ordering postulate." Time COP.

A more ruthless Nature is at work in Larry Niven's short story "Rotating Cylinders and the Possibility of Global Causality Violation" (in the August 1977 *Analog).*[18] Setting off a nova to stop intelligent aliens from completing work on their Tipler cylinder? That seems pretty ruthless to me.

Suppose, as unproven as the assertion may be, that cause must always precede effect. That would preclude chrononauts from *some* activities in the past—the Grandfather paradox sort of thing. We can surely imagine jaunts that avoid triggering such conflicts. Simply to observe, perhaps as—in theory—is all that Connie Willis's time-traveling historians do. Having observed, perhaps it would be safe to remove items no one will miss (as in John Varley's 1983 novel *Millennium,* basis of the 1989 movie).

And having scouted out the moment when specific dinosaurs will die anyway, why *not* escort big-game hunters to the Cretaceous, as in Ray Bradbury's 1952 short story, "A Sound of Thunder" (basis of the 2005 film). What could possibly go wrong?

Maybe the Universe itself doesn't prevent changes to the past—but (ideally) wise minds do their best to achieve the same end. Officialdom takes on that task in Poul Anderson's Time Patrol series and the 1994 movie *Timecop*. In John G. Cramer's 1997 novel *Einstein's Bridge,* physicists exploit a time-like loop through a wormhole to undo an unfortunate First Contact (and in the process, create the history we know). In Nancy Kress's 2012 Nebula Award-winning novella "After the Fall, Before the Fall, During the Fall," Gaia herself enables limited meddling with a very messed up past. And maybe your grandfather must act in self-defense, as in my short story "Grandpa?" (in the July/August 2001 *Analog*, and basis of the 2006 short film *The Grandfather Paradox*[19]*).*

Having said all this, it remains possible—ages of human impressions notwithstanding—that cause-and-effect is a human delusion. Nothing in known science requires cause to precede effect.

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A split decision

Among the conundrums of quantum mechanics—a probabilistic description of reality—is what exactly happens when a measurement is taken or an observation is made. Up until the observation, a particle has, rather than a location, a probability of being in various locations. For simplicity, we'll consider a 50-50 probability of being in places A or B. Upon the act of measurement, we find the particle in *one* of those places. A common explanation is: don't ask.

A less common, but still academically respectable explanation, is: the Universe split. There-after, in our universe (it being non-unique, I've switched to lower case), the particle is at A. The observer in that other universe finds the particle is at B. In this Many Worlds Interpretation, proposed (without the catchy name) by Hugh Everett in 1957, every possible past and every possible future exists. At each moment, for each possible event, a universe splits. A moment later, for each possible event, each of those universes again splits. . . .

There's no Grandfather paradox, because Grandson splits off a new universe by attempting his trip to the past. In one universe, the trip to the past failed. In the second universe, the grandpatricide can succeed—Grandson didn't come from that universe.

Many Worlds Interpretation adds a dimension(s) to space-time. In the Multiverse, with the proper technology (just don't ask me what it is), one can travel across time both like a clock changing *and* across world lines. The farther one goes in that latter dimension, the farther apart the world lines are from their common ancestral universe.

Is the Many Worlds Interpretation valid? Unknown. Can universes arise from nothing? Cosmologists say it happened once, so why not repeatedly? That suffices to make multidimensional time—and multidimensional time travel—fair game for science fiction. Keith Laumer's Imperium novels and H. Beam Piper's Paratime series alike put time cops in a multiverse with multidimensional time. James P. Hogan's 1985 novel *The Proteus Operation* and Harry Turtledove's 1992 novel *The Guns of the South* have factions on the losing side of (local) history making and shaping getaways to elsewhere and elsewhen.

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Odds, Ends, and Tropes—
and the SF that illustrates them

Energy-time uncertainty. In one of its more absurd predictions, quantum mechanics allows particle/antiparticle pairs to appear from nothingness, to mutually destruct a (very) short while later. Odder yet, pair production happens. If nature can borrow energy to produce matter, if only for a brief time, perhaps supplied energy can move objects through time.

Geoffrey Landis's Nebula Award-winning 1988 short story "Ripples in the Dirac Sea" relies on this time-travel mechanism. (Geoff threw in a twist on the *you-can't-change-the-past* trope: in his story, no matter how you change your past, the present from which you departed won't change.) So, in a slightly different manner, did my 2010 novel *Countdown to Armageddon.*

Tachyons. Beyond the purview of the wildly successful Standard Model of particle physics, some have theorized about particles, called tachyons (from the Greek, *tachy,* meaning rapid), that always travel faster than light. Familiar particles can't be accelerated to light speed because their mass approaches infinite at light speed. But faster than light? Above light speed, mass *decreases* the faster an object travels—which wouldn't even be a tachyon's most counterintuitive property.

There's no evidence that tachyons exist. There's no theory for if/how—should they exist—tachyons might interact with normal matter. It would seem difficult to construct a time machine (or anything else) from stuff that comes at you from out of the future and that vanishes before you can see it coming (both consequences of tachyons traveling faster than light.) Always up for a challenge, physicist Gregory Benford used tachyons for backward-in-time communications in his 1980 John W. Campbell Memorial Award-winning novel, *Timescape.*

FTL travel. FTL travel (the math of relativity tells us), would mean travel backward in time. As it happens, FTL *might* be possible. This article has considered shortcuts: wormholes that can be transited faster than light travels between the same endpoints outside the wormhole. Other dimensions, as yet undiscovered, might also offer such shortcuts. Light speed is a property of the material (or vacuum) traversed; some future discovery may teach us to create a bubble of altered space-time within which light speed is faster than natural.[20]

But perhaps nature, pardon the anthropomorphism, won't be fooled.[21] If, for example, a starship uses a wormhole, won't light, too? If so, the regions at both ends of the wormhole remain causally linked. We won't know if shortcuts mean FTL—or only a stapling close together of previously distant regions—until we're able to perform the test. No FTL, no backward-in-time travel.

When more isn't better. In *Timecop,* (melo)dramatically, a time-traveling villain and his younger self touch—and are thereby mutually destroyed. Connie Willis's time-traveling historians can visit before their births—but anyone careless or unlucky enough to overlap in time with another instance of himself will be canceled out. In Rysa Walker's Chronos Files series, overlapping with oneself in time is brain-muddling, the more so the geographically closer the two versions approach. In Don Sakers's short story "Double Exposure" (May 2015 issue), time-transported matter decays at the atomic level with a half-life of hours.

The overarching trope suggests a sort of conservation rule: that versions of a particular item from different times—somehow, to a story-convenient level—are incompatible when brought to the same moment. The nature of this conflict is seldom explained. I speculate that the trope originated in the (not universal) interpretation of antimatter particles as normal particles moving backward in time, because an antimatter particle and its normal-matter equivalent mutually destruct, if they meet, in a flash of energy. Other time-travel stories dispense with this trope: the various versions of Bob in "By His Bootstraps" *do* meet; Bob Two even shoves Bob One through a time portal without physical harm to either.

Timeline changes and latency effects. So: you've gone back in time and changed history. Does the change rewire your brain to erase the memory? Alter libraries and digital archives? How soon do such changes take effect?

In the original (1985) *Back to the Future,* Marty McFly carried a family photo into his past. Siblings—and then Marty himself—fade from his photo as his actions in his past look to keep his parents from marrying. In Robert Silverberg's 1966 short story "Needle in a Timestack," people retain memories of a rendered-null timeline briefly longer than do digital archives. I've never seen a rationale given for such variable latency.

If timeline changes *do* happen, how quickly do they progress from the altered past to the altered present? Stories differ in their treatment, often leaving the progression unseen. In *Countdown to Armageddon,* I stuck with what we (think we) experience about time sans time travel: any event's implications ripple into the future at a second per second.

Self-dampening (or not) changes. The jostle of a random air molecule or a collision with a wayward gnat won't have much effect on a falling piano. That's inertia for you. Does history—however metaphorically—exhibit inertia? Is history robust against small perturbations? If so, how small is small enough? In "A Sound of Thunder," a time traveler stepping off a trail suffices to bring disaster.

It often seems implausible that a time traveler's actions can avoid inadvertent effects. With merely an ill-timed stroll, the time tourist might block a passerby's view of something that would have been life altering. Then again, that passerby may see the *whatever* the next time they happen to pass by, and the slightly changed timeline converges to what would have been. It *also* seems implausible that a photon from our time, transported, say, a billion years into the past, into some void deep between distant galaxies, would produce any ill effects. Then again, that out-of-time-and-place photon, falling a billion years later into a telescope, might interfere with what would otherwise be an epochal cosmological insight. Absent a working time machine, we simply can't know the implications of interacting at any level with the past.

Never mind physical changes wrought by time travelers. What changes might the thoughts and knowledge of a time traveler wreak? Does human history resist change? Do the masses of humanity—as Tolstoy, Marx, and Harry Seldon in separate ways would have it—swim in all but irresistible historical currents? Or do people follow the lead of great men and women? H. Beam Piper explored that question in the paratime stories "Gunpowder God" (November 1964 issue) and "Down Styphon" (November 1965 issue). Between these extremes, at moments when competing trends all but balance, are stories (like my *Countdown to Armageddon*) in which events are at a tipping point and one person's actions do matter.

Are changes to history necessarily changes for the worst? Orson Scott Card's 1996 novel *Pastwatch: The Redemption of Christopher Columbus* takes a good look at that question.

When time really is money. Time travel, as we've seen, will be complicated. Read: *expensive.* Perhaps the answer to the time-travel variant of the Fermi paradox is: it's just too expensive to build time machines.[21]

* * *

Conclusions

What can we—or, at least, what do I—conclude from all this? That time, in the context of space-time, exists. That in a Universe without simultaneity, past, present, and future can coexist (not necessarily at the same spatial coordinates). That's not to say past and future are set, or that any aspect of the Universe is deterministic—but neither can I disprove determinism. That we can travel to (some) future, by moving fast enough, or sitting in a gravity well deep enough, or with Really Good Medicine—but that the possibility of travel into the past is less compelling. That time travel is fair game for the hardest of SF—not that every time-travel mechanism in the genre rises to the level of plausibility. That the subgenre is rife with questionable sub-tropes.

That if you me ask what *is* time, I'll refer you back to Saint Augustine. "Provided that no one asks me, I know. If I want to explain it to an inquirer, I do not know."

Acknowledgments

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To read further

The Nature of the Physical World, Sir Arthur Eddington, 1928. (In elegant, entirely nonmathematical language, Eddington tackles many of the more interesting implications of quantum mechanics and relativity. Read this with care, however, because later discoveries—the neutron; expansion of the Universe—negate some of Eddington's discussion.)

The Arrow of Time: A Voyage Through Science to Solve Time's Greatest Mystery, Peter Coveney and Roger Highfield, 1990.

Science Fiction and Science Fact: An Encyclopedia, Brian Stableford (editor), 2006, articles on time and time travel.

How to Build a Time Machine: The Real Science of Time Travel, Brian Clegg, 2011.

The Time Traveler's Almanac, Ann VanderMeer and Jeff VanderMeer, 2014. (Almost seventy stories, plus essays, on the theme of time travel.)

Footnotes

1 For a more detailed look at the energy requirements of relativistic travel, see my "Faster than a Speeding Photon: The Why, Where, and (Perhaps the How) of Faster-than-Light Technology," in the January/February 2012 *Analog.*

2 A neutron star is the collapsed remains of a "regular" star after it has gone supernova. Neutron stars are super-dense; each packing the mass of a Sun-like star into a sphere only a few miles across. (Stars more massive than about ten of our Sun collapse, post-supernova, yet further—forming black holes.)

The extreme conditions of the collapse transform most of the star's post-explosion mass into neutrons. A neutron star is, on average, about a hundred *trillion* times as dense as liquid water (less—but still incredibly—dense toward the surface; yet denser toward the core). Lead, the densest material most of us ever encounter, is a mere eleven times as dense as water. At neutron-star densities, all of humanity would fit into a teaspoon.

All of which is to say: the gravity near such a massive, tiny object is ferocious. On the star's surface, the gravity would crush you.

3 In "Neutron Star," Niven chose not to dwell on the clock-slowing consequences of the close encounter. But whether or not the hero of the story realized it, he got past his near-spaghettification faster than an outside observer observing his peril.

4 A black hole is an object so massive that it has collapsed into infinite density (not always into a dimensionless point—a complication we'll save for later). To become a black hole is the ultimate fate of large stars once their fusion fuel runs out and heat-driven expansion can no longer counterbalance the inward tug of gravity.

A black hole's gravitational field is so intense that not even light can escape—hence the object's metaphorical blackness. The point of no return upon an approach to a black hole is called its event horizon.

Why *metaphorical* blackness? Because black holes typically aren't black; they are often surrounded by light sources. In-falling matter, attracted and accelerated by the intense gravity, often encircles the event horizon.

This "accretion disc," superheated by compression and friction, produces a bright radiation environment.

[5] Why the quotes around *loiter?* Because there's no aimless dawdling involved! In sufficiently curved space-time—as is found close to an event horizon—orbits aren't stable. A ship in that region can follow a closed course around the event horizon, or can hover, but in either case only by thrusting mightily against the singularity's gravity. See "Centrifugal Forces and Black Holes," John G. Cramer, November 1992 *Analog, http://www.npl.washington.edu/AV/altvw55.html*.

(At least this complication arises with *static* black holes. Close-in stable orbits seem possible near a sufficiently massive *rotating* black hole, due to another aspect of general relativity that we'll soon discuss: frame dragging.)

[6] As does the hero's girlfriend in Frederik Pohl's 1977 Hugo and Nebula Award-winning novel *Gateway*.

[7] These special cases, relevant to a small object in the vicinity of two much more massive bodies, involve the Lagrange (or libration) points. At five specific locations, dubbed L1 through L5, the gravitational attractions of the massive bodies and the centrifugal force acting upon the much smaller body, come into balance. Spacecraft are sometimes intentionally stationed at (or set to orbit around) various Lagrange points. See *http://en.wikipedia.org/wiki/Lagrangian_point*.

[8] "Beyond Space and Time" (1938), by Joel Townsley Rogers, has a starship circling the Universe at very great speed, such that the pilot returns to the place *and time* of his departure. Rogers beat Gödel to the punch by more than a decade. (Unless . . . Maybe Gödel traveled a CTC to give Rogers this idea? Nah.)

[9] Remember Superman turning back time, changing history, and saving the girl (Lois Lane) by flying around the world really fast, in the 1978 movie *Superman?* For comic-book science, that wasn't bad.

[10] Cosmic strings take some explanation.

Start with the Big Bang "fireball." Everything in the very early Universe was super-hot and expanding. Expansion cools things, just as expanding water vapor can cool and condense into liquid water. Vapor condensing to water is a phase transition. Cool further, and water's next phase change is from liquid to ice. Now picture frost on a winter window, forming from condensation. Picture the random lines and curves that crisscross the icy coating.

Each fracture line in the frost marks the collision between expanding regions of spontaneous phase change: water turning to ice. Where matters get hand-wavy is in analogizing collisions between cooling space-time regions with ice-fracture lines. In the early, rapidly expanding Universe, energy—in theory—could have been trapped in such interstices. Lots of energy. Energy and mass are (remember $E=mc^2$) two forms of the same thing. Once formed, the ongoing expansion of the Universe will have stretched such fracture lines to light-years (or longer) in length. So: we're considering one-dimensional objects of extraordinary length, incredibly dense (an Earth mass or more per kilometer), and prospectively—as so often happens to threads—tangled.

Theorists call these objects cosmic strings. To date, none has been detected.

Side note: the strings theorized by cosmologists and the strings theorized by quantum-gravity theorists are, despite the name similarity, quite different.

[11] "A Physicist Is Building a Time Machine to Reconnect With His Dead Father," Tom Moroney, March 27, 2015, *Bloomberg Business*, *http://www.bloomberg.com/news/articles/2015-03-27/a-physicist-is-building-a-time-machine-to-reconnect-with-his-dead-father*.

[12] A white hole can be interpreted as the time reverse of a black hole. White holes may emerge from the equations of general relativity only because that theory is indifferent to time's direction.

[13] For quantum-mechanical reasons, all black holes radiate. If the mass-equivalent of such radiation is less than the mass falling into a black hole, it shrinks. The smaller a black hole becomes, the faster it evaporates until—with a *very* unpleasant *poof!*—it is no longer a black hole. White holes may also self-radiate; they are, regardless, by definition in a state of permanent disgorgement.

[14] How does one keep electrons, or anything else inside a matter-and-energy spewing white hole? That's a puzzler.

[15] Will slinging around one end of the wormhole disconnect the wormhole? What happens when a wormhole snaps? We won't know till we try. Kids: don't try this experiment the first time anywhere near your home planet.

[16] There's much else about that movie we'll do well to ignore. For example, the gravity implied by the indicated time dilation should have spaghettified the first alien planet Our Hero visited.

[17] A loophole: finding a wormhole time machine left behind by ancient aliens.

[18] Niven took his title from the Frank Tipler's earlier academic paper.

[19] *http://www.nsi-canada.ca/2012/04/the-grandfather-paradox/*

[20] For much more on possible FTL technology, see my "Faster Than a Speeding Photon: The Why, Where, and (Perhaps the) How of Faster-Than-Light Technology," January/February 2012 *Analog*.

[21] If you are of a certain age, that should evoke from the depths of memory—time travel of a sort—a certain margarine commercial.

[21] Of course you can make investments before a trip to the future, hoping to have amassed a fortune before you arrive—but that's no slam-dunk. Inflation happens. Companies, and even countries, fail. And if you're justified in your optimism? You don't have the money *now* to build the time machine.

Yes, you might bring foreknowledge into the past, to invest in stocks and horse races—but until you *have* done so (without, in the process, changing matters in a disastrous way), and returned to your time of origin, you don't have that money. It's another grandfather paradox.

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. Ed's website is *www.edwardmlerner.com*.