Donald Kingsbury

THE JANUS-HEADED ARROW OF TIME:

ENTROPY AND TIME TRAVEL

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It is remarkably liberating to realize that time in itself does not exist except as an abstraction to free us from always having to talk about this clock or that. The discovery that there is no time—only clocks—has deep and surprising consequences for many very simple things we tend to take for granted because of our almost instinctual conviction that time has a reality that transcends the behavior of clocks.

N. David Mermin, from his book *Boojums All The Way Thru*.

We all know in our hearts that time travel is impossible—much as we'd like to chat with our younger father or fight the lions in the Colosseum with our trusty AK-47. But the proof of such a mundane intuition is not easy to come by. We listen to convincing time paradoxes—yet retain an uneasy feeling that paradoxes are logical constructs that may be telling us more about our untenable basic assumptions than about the nature of the physical world.

So why *is* time travel impossible?

CLOCKS AND ENTROPY

"Kingsbury's Entropy Theorem," which I have modestly named after myself because of its elegance, states that **it is impossible to build a clock which can distinguish between backward or forward time flow**. This is because all clocks are entropic in nature. If we could build a clock that ran backwards simply because we reversed the flow of time, we could also build a perpetual motion machine to generate as much power as we might ever want—for free. A two-way clock necessarily transcends the laws of thermodynamics.

Time travel is *not* impossible because physics prohibits time-reversal. Time travel paradoxes are cute but irrelevant. Time travel is impossible because no conceivable clock would ever be able to reverse itself even if we did have a machine that could alter the direction of time.

Reverse time—and the sand in an hour glass will continue to pour from the top chamber to the bottom chamber. The sand will *not* start to flow upward in such a way that entropy begins to decrease. Even time-reversal cannot put Humpty-Dumpty back together again.

Reverse time—and the velocity of a pendulum will reverse. But the grandfather clock's hands will continue to rotate *clockwise*. To get the hour and minute hands to run counterclockwise would require us to redesign the clock so that in normal operation its entropy would be decreasing. We'd have to ensorcell a Maxwell Demon. The driving weights would have to suck energy out of the air, lowering the ambient temperature, then store that energy in the weights by raising them. By the Known Laws of Physics, no such design for a grandfather clock can exist.

Let me stop you in your tracks before you rush to inform me that if we reverse time, and thus the velocities of the air molecules, the whole super-complex "billiard-ball" system will start whacking the grandfather clock's ratchet in such a way that the surrounding air is cooled and the power weights begin to rise and the hands creep backwards. *Classical mechanics* can reverse entropy in this way but classical mechanics is the wrong tool with which to attack such a problem. Given a billiard-ball shot of this complexity, "nature" would have to measure its angles and velocities and momenta with an accuracy enormously greater than quantum mechanics allows.

Einstein notwithstanding, God shoots dice. God's Gambling House, being honest, always gives you exactly the same *odds* from day to day, but you'll never get the same event in response to the same input. A mathematician would say that "the initial conditions do not determine a unique solution."

Too many people make the mistake of assuming that all the physical probabilities either have to be "zero" or "one" before we can have a useful causality. But physicists have long been comfortable with error-bars; errors of measurement have never stopped them from making useful predictions. Why should we expect God to record his data down to an infinite number of decimal places? I suspect that even God cannot remember the number of hairs that once grew in Julius Caesar's left armpit or the details of the death of a London sparrow in the summer of 1832.

Consider a radium clock that tells time by counting alpha particles. Reverse the time flow. Classical mechanics tells us that the radium remaining at the moment of reversal will cease to be radioactive (since a radium atom which has not yet decayed cannot decay if it is only retracing its past). Classical mechanics tells us that the dispersed radon gas will magically return to its point of origin in the radium crystal just in time to capture an opportune alpha particle of the right energy to convert it into radium. Quantum mechanics predicts a different story. *Even under time-reversal* it insists that the radium must continue to decay into radon by alpha emission.

What kind of nonsense is this? Am I daring to say that if we backtrack through time, our footsteps won't fall into the same tracks? Absurd, Mr. Kingsbury—such rude behavior would imply that our Universe has a history of alternate pasts! But that is exactly what I am saying. The past that we remember is not the only past that we have.

Common sense—as well as the physics establishment, 1994—tells us that the Universe has only one past. (If you believe this, I can probably convince you that an electron is a particle.) Follow me in a bit of simple Aristotelian logic:

(1) Quantum mechanics tells us that the Tree-of-Now branches up into alternate futures—see Wheeler and Everett.

(2) The equations of quantum mechanics, for example, Dirac, circa 1929, are time symmetric.

(3) *Therefore* the Tree-of-Now *must* root down into alternate pasts.

Contrary to everything you have ever been told, there is no entropic arrow of time. Entropy turns out to be Janus-faced, peering both into the future and into the past. We find a second arrowhead where we were told that the feathers would be.

You can't go back in time and kill your youthful grandfather because you wouldn't be able to find your grandfather among the plethora of alternate pasts. It is even worse than that. To locate your grandfather, a time machine must be able to effect a *decrease* in entropy. Because events are all entropically "downhill" from your grandfather to you, to get from you to your young grandfather is an "uphill trek" involving an increase in orderliness—a *decrease* in entropy. Discouraging.

It gets worse. Not only do you have to reverse entropy to reach your grandfather but there are zillions of "uphill" alternate pasts for you to choose from, only a microscopic few of them leading to your grandfather.

And all of the easy paths into your past, the ones that don't involve violating the laws of thermodynamics, the vast-vast majority of your alternate pasts, lie "downhill" in a direction directly away from your grandfather. Read your family letters and sigh. Stare at those old Kodaks and weep. Entropy forever bars you from those worlds just as effectively as it bars you from enjoying the fruits of a perpetual motion machine.

But what a concept! A universe of alternate pasts sounds like a great idea for a science fiction story. In Larry Niven's *Flight of the Horse* a time machine visits the "past" and brings back a unicorn. Unfortunately, it wouldn't be that interesting. Atlantis? Mu? Fairyland? Most of your alternate pasts wouldn't amuse you at all.

Do you commute to work along the New Jersey Turnpike? Imagine 10,000 cars, moving at 110 kph, tailgating each other and weaving across lanes at 8:45AM, all in a desperate hurry to get to Manhattan. You are one of them. Someone throws the switch on his time machine control panel. Time reverses. You are suddenly racing backwards down the New Jersey Turnpike at rush hour with 10,000 other cars hightailing it back toward breakfast, facing the wrong way.

Will you soon be regurgitating your coffee into a cup, and watching it convert itself into clear boiling water and coffee beans as you get sleepier and stagger backwards toward bed? Not at all! A fraction of a second after time does its flip, you (with your heart in your mouth) will be trying to remember which way to turn the steering wheel to stay in control. Sadly, entropy isn't going to be nice to you. Listen to the mayhem of a 10,000 car crackup!

In one of your alternate pasts, you weren't born of your mother; you were assembled out of blood and guts and splintered bone, put at the wheel of an unwrinkling steel car and sent off to work in New York's publishing industry. Given a time machine, you are much more likely to find such a broken past in a ditch than to meet your grandfather.

Preposterous? Am I pulling your leg? Let us retreat to the physics lab. We've been shooting electrons, one at a time, through a double slit and charting their impact. The hits form a diffraction pattern characteristic of waves. But we've been firing the electrons off one at a time and they have been hitting one at a time, just as if the electrons were particles. How can one electron pass through both slits? But if we run the quantum equations backwards, we see that the electron had many alternate pasts. In some of them it passed through slit one; in the others it passed through slit two. Simple. Recall that no physicist ever promised you that quantum mechanics was going to provide you with palatable answers.

When Erwin Schroedinger published his wave equation in 1926, it was in the form we call the retarded solution which tells us what we can expect to happen as time is increasing. Dirac very soon afterwards derived the full time-symmetric form of the Schroedinger wave equation which gives both retarded and advanced solutions for the wave equation. The advanced solutions describe what we can deduce about the past.

It is important to note that both Newtonian and quantum mechanics are time-symmetric. This means that you can be shifted from a universe in which time is increasing to one in which time is decreasing and you will not be able to detect any changes in the rules of physics.* Planets still orbit in ellipses. Water still freezes and boils. Vibrating* electrons still emit electromagnetic radiation. Does this "sameness" make sense? If time is reversed won't we be seeing things like scrambled eggs decooking in the skillet and popping back into their eggshells while swimsuited beauties are being ejected upward from the

*(To be on the safe side we might have to pass you through a looking glass and switch your electric charges, too, but I don't want to go into that.)

swimming pool to land spectacularly on the high diving board?

No. Time is a tree, not a linear sequence of movie frames. We wouldn't see such oddities as Humpty-Dumpty reassembling himself for the very same reason we don't see entropy decreasing (and broken eggs reassembling themselves) as time runs *forward*. Mechanics tell us that it is possible, but not very probable, for entropy to decrease as we move into the future. Because of symmetry, mechanics tells us that it is possible, but not very probable, for entropy to decrease as we run backwards into one of our alternate pasts. It does not even help to finagle the initial conditions; quantum mechanics will not guarantee us the same outcome for the same initial state, either backwards or forwards.

Did the Universe start with the Big Bang? Which Big Bang?

THE MEMORY OF THE UNIVERSE—DOES GOD HAVE ALZHEIMER'S?

A universe must have memory if it is ever to support any kind of time travel. There has to be a past or a future to go to.

Does our seemingly mindless Universe have any memory at all?

We know that *some* kind of minimal memory must be present because causality requires it. Using causality we can read from our sky vague memories of a "big bang" some 16±6 billion years ago. On the Moon enough fossil information survives to tell us about events four billion years ago. Hints of bacterial life on Earth three billion years old exist in stone that was once mud.

At low resolution, with pixels the size of planets, causality can tell you the structure of the Solar System for thousands, even millions of years into the past or future. At high resolution, with pixels the size of atoms, causality has a very short range view of the past, but memory is there and experimental nuclear physicists and chemists know how to exploit that short glimpse into time's fog. At super high resolutions, with pixels the size of the Planck length, causality doesn't seem to be able to recover much of anything.

Our own wetware memories would be useless if there were no analogs of them in the real world. Predictions of the future depend upon our memories of the past. Every day we stay alive by means of our predictions—for instance, we jump out of the way of buses before they hit us. The weather bureau can predict the weather up to a week ahead with reasonable accuracy and the President of the United States can predict the economy reasonably well for the next three days, and both can tell you that the Sun will rise tomorrow.

Acid rain is a memory of the coal-generated electricity we sucked from those plugs along the baseboards of our houses. The dry fields of the Texas Panhandle are a memory trace of water taken from a deep aquifer. The TV you watch is a memory of the time young Farnsworth was plowing the field and saw plowing as a way to paint pictures on a screen. You are a memory of a time when your parents were in each other's arms.

But all of these ephemera are only *partial* memories. They are fossils. They can tell you the shape of the bones but not the howls of distress. Information has been lost.

If we were able to roam through the past (or future), there would have to exist somewhere in the structure of the Universe a *perfect* memory of all past (and future) events. Imagine trying to go back to Rome and finding that Rome had been forgotten? Or overwritten? Or half forgotten so that Romans sometimes didn't have mothers or faces, or stuttered over their Latin declensions? Suppose the DNA in the

Italian microbes lacked cytosine and the stinks in the street were wrong?

The universal memory state we need is a very strict condition. Any universe which permits time machines can be allowed to forget *nothing*. Abbreviations, loss of resolution, image compression, memory condensation—none of this is allowable. If the universe forgets, even has minor lapses like disremembering a telephone number, then time travel becomes impossible. Try going back in time and killing your grandfather in a universe that has forgotten things like the color of your grandfather's tie or how many eyes he has.

Does our Universe have a perfect memory? Physicists certainly used to think. so. Most of them still do.

Under the roof of differential geometry we have classified mechanics, classical electromagnetism, and General Relativity, even Schroedinger's wave equation. All of these theories are executed, with calculus, on a stage called a differentiable manifold. Differentiable manifolds have very nice properties which I have no intention of explaining here. (Just think of such a manifold as a "rubbery" set of points which have not been assigned a measure for the distance between two points. Once we assign to our manifold such a measure, called a metric, we get a space—Euclidean if our metric is Pythagorean, non-Euclidean if our metric bends "straight" lines.)

These methods do indeed provide us with the tools to describe a universe-wide, perfect memory. The storage device for this staggering information capacity is a set of real numbers called "initial conditions" by the priests of differential geometry. (For the non-initiate just think of a real number as a non-terminating decimal. No matter how many integers are placed after the decimal point, there are always more.) An infinite amount of information can be stored in each real number. Indeed, if all the books and junk mail and grocery lists ever written by human hand were transcribed onto one real number we would still have room for, say, things like a list of unique nicknames for every atom in the known Universe, etc.

The machinery of Newtonian mechanics and general relativity store "the memory of the universe" in such "initial conditions." Take, as an example, a very simple universe of one particle of mass m, located at a position x and moving with a velocity v. Then m, x, and v are the initial conditions of the particle. Given a system of mechanics, we could then use these initial conditions to find the past and future behavior of the particle.

Simulating our *physical* space upon the framework of a mathematical manifold, plus metric, simplifies life for physicists appreciably taller than 10^{-33} centimeters, the Planck length. But—as convenient as the concept is—do not make the mistake of assuming that space *is* a metricized manifold. Such a construction is only a model and models break down. When we try to insert things like "epsilons that can be assigned *any* magnitude greater than zero" and "a minimum Planck length" in the same model we are in deep trouble. We are mixing apples and oranges.

With that caveat aside, let me say that many physicists still believe in a "universal memory"—mainly because it is a property of their most powerful tool, differential geometry. After merciless years in graduate school, studying bleary-eyed for their prelims, they no longer know how to think about space as anything else.

For instance, there is a whole group of present day physicists who are disturbed by the fact that black holes seem to swallow and destroy information about the past. These souls want to be able to run their equations of motion backwards and have the books that have fallen into the black hole pop out again, whole and legible. They cannot tolerate the idea of a whole slew of alternate pasts popping out instead in a kind of Hawking cornucopia. My only suggestion is that they study communication theory, and look at the Universe, not in terms of differentiable manifolds, but as a place in which the past communicates with the future via a "lossy" transmission. Information about the past is continually being lost. Physicists already understand the concept and call it "entropy."

How did such a crazy idea as "universal memory" become part of science? Nobody invented the concept; it just grew like some orphaned prodigy. The mother was a headstrong Newtonian mechanics and the differential equations which served her. The unknown father was probably religious conviction—"a universe that remembers everything" is comfortably similar to an all-knowing, all-seeing God.

Let me go back to the eighteenth century, which is when the trouble began, and quote from Pierre Simon Laplace's *Theorie Analytique Des Probabilities*. A master Newtonian mechanic, Laplace was profoundly influenced by the power of Newtonian law. Accurate astronomical predictions could be made far into the distant future and far into the past. (We can accurately date ancient Chinese documents by knowing that they were written during a particular eclipse.)

In a moment of effusion Laplace tells us this: "Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective positions of the beings which compose it ... nothing would be uncertain, and the future as the past would be present to its eyes."

In modern terms he is saying that given the laws of mechanics and a sufficiently powerful computer, plus boundary conditions at a time t=0 which consist of all the positions, momenta, and forces of the Universe, any event from the past or future can be computed to any level of desired accuracy. This is another way of stating that "the now" contains a total memory of the past and the future.

Why was Laplace's confidence so sweeping?

The classical physicists came to believe in a universal total memory because every law of physics that they used was time-symmetric and *uniquely* solvable. The *mathematics* which is at the foundation of geometry attaches to the Universe a "fast forward" button and a "fast rewind" button. No matter how many times one runs the Universe backwards or forwards, the *same* events flash by.

During the heady eighteenth century days of mathematical breakthroughs, the dogma of scientific determinism was founded. The present fixes the past and the future.

A hundred years after Laplace, rational determinism was all the rage. Everyone was jumping on the bandwagon. Marxism was a deterministic theory of history based on a causal mechanics. He spoke of *social forces, of the masses*, of the *energy* of nations. Freudian psychoanalysis was a deterministic theory of the psyche. A young H. G. Wells built his time machine upon the deterministic foundation laid down by nineteenth century science. The <t> for time was just another coordinate in the equations of the universe. <x, y, z, t> determined a *unique* event.

Such influence was long lasting—the early Asimov's psychohistory of the 1940s, in which Hari Seldon could make deterministic historical predictions over a period of a thousand years, via mathematics, was part of that philosophical wave. Unlike Marx, Asimov incorporated statistical mechanics analogies into his scheme.

There is no doubt that classical mechanics is deterministic. (1) Every dynamical situation is reversible and (2) has a unique solution. Since real numbers are used in the computations there are no errors. A computation can be carried indefinitely far into the future or the past without error. Mathematicians of the eighteenth and nineteenth centuries worked very hard to get this result. Basically they succeeded by overlaying their mathematics on top of a very smooth space that gives you no surprises no matter how small a region you chose.

In talking about "the universal memory" the classical physicist will offer only one reservation. When he mentions "singularities" it may be with the same terror that a computer aficionado feels about the accidental reformatting of his hard disk drive. The singularity, you will be told, is a memory wipe. You'll be warned not to zoom your time machine through the "big bang singularity." Therein lies amnesia—all information about any "prior" universe was wiped when, like toothpaste, we were squeezed out of the Original Point Source. There is nothing to go back to earlier than that.

This is a form of religious shop-talk. Singularities are merely the acne of differentiable geometry. Mathematicians, like teenagers, have this compulsive need to moan about their pimples while they poke around a pimple's edge. Such pathologies are an artifact of a geometry that can't digest things like Heisenberg uncertainty, not a property of the real space-time that you and I live in. **Singularities cannot exist in a digital world which contains such things as the Planck length.** Mathematical space and real space are not isomorphic. Physics has no more to say about singularities than dividing by zero has an answer.

The first cracks in the deterministic monolith did not appear until the late nineteenth century, at just about the time H. G. Wells was writing his time machine story. The challenge came out of thermodynamics. Carnot, Clausius, Kelvin, Gibbs, Boltzmann had been laying the foundations of the second law of thermodynamics, which puts the kibosh on perpetual motion machines and the like. Their work raised to a science the building of steam engines, internal combustion engines, turbines, refrigerators, atomic reactors, rockets.

Thermodynamics is not naturally deterministic—that was the rub. **A time-symmetric deterministic system is mathematically equivalent to a system in which entropy is constant.** Entropy, which is a measure of disorder, is related to the concept of information. The mathematics of entropy is identical to the mathematics of information theory. If a system's entropy is increasing it is losing information. So if you can show me a way of creating information without destroying more information than you create, I can use your method to build a perpetual motion machine.

We cannot proceed from order to disorder without losing information, without forgetting—and a time-symmetric determinism cannot forget. The early entropists finagled this point by the ad hoc addition of a device which unnaturally destroyed information. They set up boxes in phase-space in which they collected samples. The statistical operations done on those samples made information disappear—and out popped entropy.

At the end of the last century Ludwig Boltzmann was doing marvelous work to establish the second law of thermodynamics on a firm theoretical foundation and became involved in an endless round of acrimonious assaults. Zermelo and Loschmidt, among others, scorned him for his efforts, claiming that you cannot derive a time asymmetric law from a set of time-symmetric laws. Boltzmann acquired formidable enemies, including such luminaries as Mach and Ostwald.

He was so shaken by these attacks that he spent much effort and thought on the conundrum outlined above, making a stunningly valiant attempt to derive entropy from first Newtonian principles. He tried to create a universe in which entropy increased when time was reversed but was ultimately not successful. It can't be done for *the same reason* you can't get entropy to increase in a Newtonian universe in which time runs *forward!* (Cheating with phase-space boxes not allowed.)

Only with the work of Heisenberg and Schroedinger (after Boltzmann's death) did physics acquire a non-deterministic mechanics in which information about the future and past is lost in a time-symmetric way that puts thermodynamics on a first principle foundation. Physics has still not fully assimilated the message. Physicists still talk of time's arrow. When the great Wheeler and his student Everett proposed the many-worlds interpretation of quantum mechanics as an alternative to the Copenhagen school, they threw away the advanced (backwards) solutions of Schroedinger's equation as "meaningless." Dozens of physicists have proposed "hidden" variable riders to quantum mechanics in an attempt to preserve a Newtonian-like determinism. Etcetera.

But the message is clear. Time travelers beware. God—or Laplace's computer if you prefer—has a very hazy vision of the future and just as hazy a vision of the past. God does not calculate with a mathematician's real numbers. Everything He does is subject to round-off error. Your time machine will have to do a lot of ad-libbing and Hollywood-like set building in the no-man's land between God's error bars.

TIME MACHINES

Model 1: We build a sphere. By means of Clarkean magic we reverse time inside at the rate of ten years per day. Our time traveler crawls into the machine on March 31, 2001, and spends ten subjective years inside before he climbs out. When he does, he is not ten years younger than when he went in. Entropy, again. He is ten years older. He buys a newspaper and finds out that the date is April 1, 2001. His time machine is the *equivalent* of a machine which ages a man at the rate of ten years per day.

Model 2: This is a new design. It is obvious from the results of Model 1 that we will have to use our Clarkean magic on the *exterior* of our sphere, thus rewinding the whole Universe for a new start. We try it. When we open the hatch there are no dinosaurs. It is a bit of a mess, though. Our reverse time field only expanded at the velocity of light. There were problems at the boundary where reversed time met normal time. Nothing that time won't heal. Just major tectonic collisions. What's a planet or two? Given a few billion years our expanding time-reversal field will have eaten the whole Universe and we'll be safely on our way to the Big Crunch.

Model 3: Disasters never stopped a dedicated science fiction writer. For our third attempt let's try a faster-than-light time machine. We all know the limerick, "There once was a lady named Bright/who traveled much faster than light. /She departed one day in a relative way/and came home the previous night."

To make it simple let us send Miss Bright off in her ftl yacht at 1.4 light speeds for a day of fun. By the Einsteinian equations this is just enough to reverse her time flow by one day per day. After a day of such fast living, is she a day younger? No. She is a day older because entropy *increases* whether you are going forwards or backwards in time. When she returns, does she come home for "the previous night"? No. In fact she finds that Earth's clocks have advanced by 24 hours. Why?

Here is what the physicists forgot to tell you about the mathematics of ftl though they learned it in the first course they took on relativity. *The clocks of the Universe are not linked synchronously*. Einstein called it the Principle of Non-simultaneity. The rate and direction of time flow are only *local* phenomena. Your starship clock may be running slow or even backwards, it may be doing the jig; nevertheless nothing requires Earth clocks to stay in lockstep. Your ftl ship may travel 30 million light years off into the galactic void, and then back to Earth, all at slightly above the velocity of light to keep ship's time both reversed and slow. The crew will hardly age during the journey, but when they get back to Earth they will not find dinosaurs, they will find an Earth 60 million years older than the one they left. The time-reversal was only local to the starship.

Remember the word "local." It is a time machine killer. There is no way to globally change the direction or pace of time. Recently there has been all sorts of talk about weird time machines that use rotating cylinders, massive rotating toruses, and zooming strings passing each other at near light speed. Mathematically we can follow a path through these weird worlds in which time is reversed. But all this is local to the inside of any time machine and it doesn't really matter what goes on *inside*—when the door of the time machine is flung open, we find neither baby grandfathers nor screeching dinosaurs. Time has been marching forward relentlessly for the rest of us. Relativity doesn't expect clocks to stay synchronized.

When I taught calculus to first year university students I loved to play dirty tricks on them like proving that 60 million B.C. was equal to 1994 A.D. Only about 1 in 40 students could catch the flaw in my reasoning—I very carefully neglected to remember an important "constant of integration." It is true that -60,000,000 = 1994 + C. Alas, physicists with Ph.Ds can forget their constants of integration, too. That's where some of their time machines come from.

In physics, when we deal with time, what is important is not the interval between dates, though that is what appears in our equations. More fundamental is a derivative of time, the rate at which time flows with respect to some standard reference frame. If we are moving at the velocity of light, that rate is zero. If we could move faster-than-light, that rate would have to be negative. If we move close to a massive body, the rate slows down. If we move away from a massive body, the rate speeds up. A clock is our mechanical integrator of time flow.

In Newton's time there was no need to notice the ***flow*** of time because it was thought to be constant regardless of the frame of reference. Two synchronized clocks stayed synchronized no matter what path they took through the Universe. Einstein showed us that it was not so easy. Time's flow varies with frame of reference. The date on a clock face is not independent of the path that the clock has traveled. We can speciously "create" all kinds of time machines by maneuvering our traveler through a complicated Einsteinian space-time warp and then**—only at the end of the journey—reverting to Newtonian mechanics by assuming that the clocks of the Universe have been synchronized all along. You can't have it both ways. Local time-reversal does not equal global time-reversal.**

Before you grin at the idea of having ftl travel liberated from time paradoxes, let me sober you up. If we travel at 1.4 lightspeeds the equations tell us that we age at the normal Earth rate. What if we build a machine that can traverse a thousand light-years every 3.65 days—that's a hundred thousand light-speeds. Then what? Let's send a ship to the Pleiades of Taurus, while we safely remain home. Our target is Pleione, a lovely B7 giant 400 light-years from Sol. Our ship comes back from its flyby after three Earth days—but the crew is 800 years older. They traveled 800 years backwards in time, the hard way, while we were moving forward in time at our usual leisurely pace. **For faster-than-light travel Einstein's equations give us the reverse of the "twin-paradox."**

This makes for interesting science-fiction stories. I used that theme in my story "Shipwright" which appeared in *Analog*, April 1978. The godship of *Courtship Rite*, *Analog* 1982, also operates under the same constraints. A faster-than-light starship will do some funny things with space-time. What it *won't* do is send you back into "the" past.

Model 4: Let's try something even more desperate than ftl. There has been talk of using wormholes as time machines—more as a stimulus to examining the boundaries of general relativity than as a serious proposition. The best description of such a machine is in Kip Thorne's book *Black Holes and Time Warps*. Again we'll use Clarkean magic to whump up such a wormhole.

Here is what Kip describes. The mouths of the wormhole are two spheres, each two meters in diameter. In normal space they can be as far apart as we care to move them, but through hyperspace they are connected by a tunnel that always remains thirty centimeters long. The tunnel is prevented from collapsing by the use of "exotic" matter which must have a negative energy density as experienced by a beam of light passing through it.

This is a great way to move across the light-years in the time it takes to crawl across thirty centimeters. Kip suggests that the device may also be a time machine and Robert Forward built his novel *Timemaster* around that concept. Kip operates the wormhole time machine like this:

One mouth of the worm is put in a spaceship with its pilot. The other mouth stays on Earth with an assistant. The pilot and her assistant hold hands through the wormhole. Our spaceship departs at nearly the speed of light for a twelve hour journey by ship time, a ten year journey by Earth time. After twelve hours the pilot releases the hand of her grounded assistant. The pilot is by then already back on Earth, but her assistant must wait another ten years for the spaceship to return. This suggests that the two mouths of the wormhole are now separated by a few meters of space but ten years of time. Messages from the newly returned pilot can now be sent back through time via the wormhole.

What is wrong here? In his comments Hawking suggested that a beam of vacuum fluctuations might shut down the wormhole before it became a time machine. I see a more fundamental flaw. A wormhole is clearly a general relativistic machine involving, as it does, some very curved space. Thus it must obey general relativity's prime law; the equivalence principle—which states that locally we cannot distinguish between inertial acceleration and gravity.

The pilot will be feeling acceleration as her starship accelerates. She is holding the hand of her assistant who, by remaining on Earth, is not accelerating but who must nevertheless feel the acceleration in his arm which will appear as gravity to him. General relativity demands that if one mouth of a wormhole is inertially accelerating then a gravitic field ***must*** be induced inside the wormhole tunnel. It won't collapse until the two wormholes are brought to rest.

When the ship stops accelerating, the Earthbound assistant will see through the wormhole tunnel a red-shifted pilot. (We won't mention his arm, which will be reaching through a humongous field, or the time variation across his arm.) The redshift is the consequence of looking down into a very deep gravity well. With this redshift is associated a substantial slowing of time. In fact the time slowdown will be so great that it will take the pilot ten years to let go of her assistant's hand back on Earth. She will think it only took her twelve hours. He will be exhausted. Even if Clarkean magic *can* keep a wormhole stable, there is no way that you can make a time machine out of it because of that redshift.

This is the "static" case. The fun comes when you try to move through the wormhole. Nobody has done adequate work on this. Don't expect your intuition about oil pipelines to work here. An essential element of wormhole construction is the lining of exotic negative energy-mass. Push on negative mass and it accelerates toward you, as if the force were operating backwards in time. And negative mass does not slow time, it speeds it up.

The physics looks a bit like *Alice Through The Looking Glass*. Expect weird phenomena. When you try to shove something through an end-accelerated wormhole you may find yourself generating a gravitic "back-EMF" that converts kinetic energy into negative mass. A wormhole between here and Pleione may be 30 centimeters long spacewise, but how long is it timewise—400 years? I may be able to crawl through and back again in ten Earth seconds by the clock at the Terran starbase, but will I be 800 years older by the time I get back?

I wait anxiously for some general relativity maestro to do the math for us! **Whatever the details, the equivalence principle will not allow a wormhole time machine.**

THE ONE AND ONLY NOW

One of my most vivid memories as a child was walking into a vast clock shop with thousands of timepieces from grandfather clocks to delicate watches, a cathedral resplendent with glass domes and torsion pendulums and crazy cuckoo clocks and every kind of ticking wonder. No two of them told the same time. I watched one grand mantle clock strike four, and later when I was marveling over another clock that was striking four, I glanced back at the first one to see if I could see myself at that earlier four P.M. It didn't happen. **There is only one now, no matter what the clocks say—because of that sneaky constant of integration.** I remember that I was indignant that the shopkeeper didn't keep his thousands of timepieces in lockstep. I reproached him. He had spectacles and a white beard. He only smiled down at me among his treasures and told me that he was an Einstein, not a Newton. I didn't know what he meant then, but I do now.