Faster-Than-Light Travel is Paradoxical

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Faster-Than-Light travel is a staple of many science fiction stories, right back to the classic age of “hard” science fiction in the 1950s and 1960s (stuff I read as a teenager), Dr Who (I remember the very first episode!) and going right through the era of Star Trek and Star Wars. Authors hypothesise various kinds of “FTL” drives some (like the Star Trek “warp drive”) moving the ship at multiples of the speed of light and others producing instantaneous jumps across light-years via an assumed “hyperspace” in which distance disappears.

As far as our current knowledge of physics is concerned they all suffer from the same problem: they potentially create “causal loops” (sometimes called “time-like” loops), which could, for example, give rise to the “grandfather paradox” where you prevent one of your ancestors marrying the person with whom they give rise to your line of descent. (What happens to you in that case? How did you prevent your birth when you never even came to exist?) Everything we currently know about physics says that one thing causing another requires something to pass between the two events - even if it is only a message transmitted by a flash of light. So, if A causes B, and B causes C everything we have ever seen suggests that A must happen *before* B and B *before* C, and that there is no possibility of C causing A because it happens *after* A.

Note that you do not have to physically travel in time to produce a causal paradox: it is enough to send a message back in time, such as “Don’t go out on that date!” It turns out we can do this with an FTL spaceship (and it is even easier if we have two at our disposal).

Time is not what you think!

We all have an intuitive understanding of time and space, and we certainly seem to experience time and space as separate things. If we think about it at all we tend to think that time would run at the same pace everywhere and Isaac Newton built his laws of motion on an assumption of “absolute time” - flowing, as he said, “evenly” everywhere. It does, indeed, seem like common sense and also very much in accord with the way we experience the World. Scientists were happy with this view for centuries and it certainly gives no scope for causal loops. We would also assume that if I say A and B occur at exactly the same time according to me, then everyone else would observe the same coincidence, so “simultaneous” means the same for everybody.[1]

But it just ain’t so! Admittedly no-one notices the discrepancies in everyday life: you and your friends may synchronise your watches and agree to meet for lunch at a certain time and place, and even if you do not actually turn up at the same time (someone is always late) you would still find that your watches appear to show the same time. If fact, *this is not true*, but you need to be able to measure time with an accuracy of fractions of a nano-second in order to find any differences. If you *could* do that, your watches *would* show slightly different times and the differences *would* depend on the speed at which you had moved, the different routes you had taken to the rendezvous (and particularly whether you had climbed any hills). This experiment has actually been done, using super-accurate atomic clocks some of which were flown round the World on commercial aircraft: they did indeed come back showing (slightly) different times.

In fact, the navigation system in your smart phone, which depends on atomic clocks carried in the GPS satellites, has to take account of the effect on clock rate both of the speed at which the satellites are travelling and of their high position in the Earth gravitational field. If the navigation calculations assumed that time ran at the same rate in orbit and on the ground, you would end up hundreds of meters from where you should be. Although the effects are indeed very small in our everyday circumstances (even if we cannot neglect them for GPS navigation) they become massive for objects travelling near the speed of light or very close to black holes. In the Large

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[1] Of course, light travels at a finite speed, so one observer in a certain orientation may perhaps *see* A happening before B, while the second observer in a different position may *see* B before A, but they would be able to correct for that and calculate that the events were simultaneous.

Hadron Collider at Cern, time gets stretch out by factors of thousands for the rapidly circulating particles, and the LHC simply would not work unless we compensated very accurately for the various effects predicted by Albert Einstein's *Theory of Relativity*.

Einstein, bye the way, did not invent the name "Theory of Relativity" and he did not like it because he was focussing on what was the *same* not what was *different*. Einstein later spent a lot of time talking about his "Principle of Equivalence" which captures the essence of the physics in a much better way - the laws of physics must be such that they are the *same* for all observers whatever their relative motions. His "Special" theory of 1905 is based on very simple reasoning (it requires no more than GCSE maths) but brilliant insight and applies to uniform relative motion; in contrast the "General Theory" of 1915, which extends the same Principle of Equivalence to object falling through gravitational fields (including into black holes) requires graduate level maths.

Einstein's insight of 1905 provided a different - and most people quickly agreed - the obviously correct way of looking at an issue that had 19th Century physicists very puzzled. They were educated in Newton's assumption of absolute space and time, and their studies of electromagnetism in this context seems to imply the necessary existence of a universal medium (which they called the "aether") permeating all of space and providing an absolute standard of rest. It would be vibrations of this aether that carried electromagnetic waves (such as light).

At the time it was a very reasonable point of view: every form of wave that was then known had to be carried by an underlying medium. There was nothing inherently implausible about a universal standard of rest - it seemed like common sense. Unfortunately, no matter how hard they tried, it was impossible to detect the aether. Experiments that should have produced positive results simply did not, and increasingly convoluted explanations were advanced to explain the null results. It was proposed, for example, that moving through the aether "squashed" all atoms along the direction of motion by an amount that nullified the experimental measurements. (This is not stupid: atoms are electrical objects so if you believed in an aether carrying electrical forces this was a plausible possibility.) In fact, something like this *does* happen, and we still call it the effect the Fitzgerald-Lorentz Contraction and physicists talk about "Lorentz Transformations" - they had all Einstein's equations before Einstein, but got the meaning wrong. Einstein showed that it was only part of the story and the real explanation was much more fundamental.

The Universal Speed Limit

In fact, it turned out that however you tried to measure the speed of light (even if you were sure you were moving at high speed relative to the underlying aether) you would always get the same answer. Einstein simply recognised that the constancy of the speed of light is a fundamental feature of the way space and time work: once you recognise that, and that the principle applies to all observers in uniform relative motion the rest of his theory (including length contraction, clock slowing down and $E = mc^2$) follows very quickly and simply, and a great deal of other stuff suddenly starts to make more sense. There is no absolute standard of rest, the laws of physics should only talk about *relative* motions[2].

But it is also fundamental that any idea of a universal absolute time and, consequently, any idea that different observers would agree on what things happen at the same time, has to be abandoned: time just does not work like that, and we have the experimental evidence to prove it. Nevertheless, *as long as nothing travels faster than light*, it turns out that every observer can

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[2] The is a very important difference between Einstein's interpretation and everything that went before. By claiming that every observer in uniform relative motion had to be treated the same, he also insisted that if I looked at <u>you</u>, moving past me at high velocity, and saw that your clocks were running slow and that your rulers had contracted, you would also look at <u>me</u> *and see exactly the same thing*. How can we *both* see the other one shrinking? This is where we need the maths, but here is an analogy with some element of truth: think about us both holding rulers, first of all parallel and then one of us *rotates* away from the other. We *both* see the other ruler as foreshortened by perspective. It turns out that we can think about Relativity as a sort of rotation in space-time giving this type of mutual perspective effect.

always agree on the order of events that are potentially causally related (that is any event sequence potentially connected by flashes of light).

In fact, Einstein very easily showed that the closer you pushed an object to the speed of light, the harder it became to accelerate even more. Most of the energy you pour into pushing harder goes into increasing the mass of the object not into making it go faster. (This is why $E=mc^2$.) The Large Hadron Collider has to be much bigger than the previous CERN accelerator, even though the actual speed of the protons and anti-protons is only a slight whisker closer to the speed of light - but they got more than ten times heavier. We just never get there. (Conversely, it turns out, a particle moving faster than light - if it existed (and we do not think that they do) - would apparently find it impossible to slow down to the speed of light. A particle travelling exactly at the speed of light, such as a photon - or in fact any massless particle -, cannot change its speed at all.)

So, as far as we know, the speed of light is a universal limit. This includes all the influences that one object can exert on another. For example, when you throw a ball, the force is actually transmitted by the electromagnetic interactions of the electrons in the atoms of your hand and atomic electrons in the ball. Therefore, as far as we know, no *causal influence* can move faster than the speed of light. You might say that the speed of light is really *the speed of causality*.

Paradox! A Most Ingenious Paradox!

So, let us now assume that we have an FTL spaceship - the *Stroud High* - that can instantaneously jump from one location to another. (The argument that follows would still work if the travel was not instantaneous, for example a spaceship moving at ten times the speed of light - but the detailed calculation we would have to do would obscure the essential point.) The real question now is, “Instantaneous according to who?”

In your frame of reference, where the *Stroud High* is stationary, it vanishes from *here* and instantly appears *there.* Of course, we do not see it appear until the light reach us a little later, but we know the distance so we know how long the light has to travel and we can work out that the jump was instantaneous.

Suppose, however that the whole experiment is being watched from another spaceship - the *Marling* - moving, at the moment, *away* from us, at, say, half the speed of light. With a little planning we could arrange that the *Marling* arrives at the time and place when and where the *Stroud High* pops out of hyperspace. The can be close enough together to quickly exchange messages - even if they are travelling at different speeds. The *Marling* could also look back to the departure point and light would eventually arrive that would show the *Stroud High* departing. In the frame of reference of *Marling*, however, our ship would not be observed to make an instantaneous jump: in fact *it would appear to arrive before it left*. (A little bit of relativity maths is required to work this out - but there is no doubt at all that this is what would be seen. If, in contrast, the *Marling* was moving *towards* us the jump would appear to take a finite positive time.)

Now suppose that the *Marling*, as soon as it receives *Stroud High*’s message, switches on *its* instantaneous FTL drive to go back to the original departure point. In its own frame of reference that instantaneous jump should take it back to a time *before the Stroud High has left.* The *Stroud High* will there see it arrive carrying a message from the future. In fact, the *Stroud High* itself could reach its distant destination accelerate away to a high velocity, and then FTL back to the starting point, arriving before it had left. (Why do we need to build the FTL ship in the first place, since it can just go round this loop indefinitely?)

Whenever physicists set up thought experiments of this type, and they seem to lead to a paradox, they conclude that one of the assumptions made must be a nonsense, and since the rest of the physics is well established, the problem must be the assumption of FTL travel. If you do believe FTL travel ought to be possible, you also ought to explain how such paradoxes could be avoided.

Some physicists do speculate about methods of FTL travel, but scientists like Stephen Hawking have proposed a *Chronology Protection Conjecture* which supposes that nature would devise *something* that would prevent the paradox occurring. Some physicists put their money on quantum physics being the key because there appear to be ways in which small quantum fluctuations would be amplified by time-like loops to a degree that would destroy any device that tried to create them. (This is quite plausible, because it is assumed that such loops would have to be grown from microscopically small beginnings where quantum effects dominate.)

This, of course, is all highly speculative - but fun to think about. It is sometimes very useful to do these “thought experiments” in order to put your finger on a particular problem in physics. Einstein himself was the acknowledged master of thought experiments, pinning down the crucial issue in such a precise way that the we did not need to do the experiment at all because the the outcome would be clear and the physics illuminated.

Now, you might be inclined to think that this type of thought experiment is so far from any current reality that it is never likely to be done. Remember, however, that we do not actually need to send FTL ships across the universe (though it makes a nice narrative). The paradox, however, can be created just by sending messages, which might be as basic as a single photon, whose polarisation going one way means one thing and going the other means a different thing. Furthermore, we know how to accelerate sub-atomic particles to velocities where “relativistic” effects become dominant. In addition, physicists are currently doing experiments with “quantum teleportation” which rely on “quantum entanglement” effects that tie together the outcomes of experiments carried out simultaneously at places so distantly separated that no communication could pass from one to the other during the duration of the experiment. In spite of all that, so far at least, everything confirms that no causal effect can move faster than the speed of light.

Are there any loopholes? How much do we really believe in this relativity stuff? It turns out that relativity is pretty fundamental to a lot of modern physics. Some advanced mathematics shows that there are only two ways in which you can build a consistent set of physics laws that *always* respect causality: one of them is Newton’s absolute space and time (and we now know quite certainly that that is wrong) the other is based on Einstein’s Principle of Equivalence. No third choice!

Everyday things, such as GPS, would not work if Relativity were not true to a very high degree of accuracy. We also now have observations of neutron star and black hole collisions which show that it still seems to work extraordinarily well in the strongest gravitational fields, and it also seems to explain a good deal about the large scale structure of the Universe.

We cannot easily get around this. Any loophole will have to be very ingenious, down in the tiniest of small print.

There are a few speculative possibilities. “Time-like loops”, surprisingly, do not actually seem to be forbidden by General Relativity. They may even exist around some rapidly rotating black holes. We do not, however, know of any way to use them. (Getting on or off the loop from outside may be impossible.) Other types of time-like “wormholes” are not ruled out, either, but we do not know how to create them (they seem to need “exotic matter” with negative energy density to hold them open and pushing normal matter through seems to make them explode). Nevertheless, there are, perhaps, ways to avoid paradoxes. (For example, travelling back in time to *introduce* your grandfather and grandmother - and ensure that you are born - is not necessarily paradoxical.) This may get physics off the hook, but it is where the philosophers start to worry. If the course of events in such a time-like loop is all predetermined what does it mean for free will? Could you ever choose *not* to do the introductions?

The truth here is that we cannot really do the proper physics of these speculations because they enter the area where both Einstein’s General Relativity *and* the other great theory of physics, Quantum Mechanics, need to be applied together - and we simply do not yet know how to do this. It is the great problem of modern physics. Stephen Hawking spent much of his later career working on this problem with limited success. A great many other physicists are working hard on the issue and so far the *simplest* ideas seem to involve 10, 11 or even 26-dimensional spaces. Meanwhile other physicists point out - with a good deal of justice - that these ideas actually create many more problems than they solve.