Time. On. Essay. An.

An Argument That Wormhole Time-Machines Do Not Exist

Julian Moore; Budapest, November 2008

Author's Apology

Throughout the ages – immediately begging the question to be discussed – time has been a subject of peculiar fascination. Many great minds have considered the vexed question of time and made acute observations, but the nature of time remains obscure.

Yet, if great philosophers, physicists and poets have been unable to penetrate the heart of the mystery, what hope is there for one without a license to practise in any of their domains? Precious little I fear. However, in good quantum fashion I shall borrow a licence *pro tem* and accept that I must settle the debt later – unless, by some improbable good fortune, it should be cancelled as the corresponding un-license falls forever beyond the horizon of the slowly evaporating black hole of ignorance. All of which is to say that I knowingly blunder along a well travelled path, no doubt much to the amusement of those who have travelled this way before, but I do so in hope.

Perhaps I shall never truly understand time: I am immersed in it, swept along in the flow and unable to climb out to inspect it from the banks. But, if an understanding of time is to be my eternally attended Godot, I can at least consider some perspectives on the past, present and future while I wait. So, while *Waiting for Godot* I shall tell a tale or two of the fourth dimension. As Vladimir says, "It'll pass the time."[1]

But first I must acknowledge my debts. Such ideas as I have been able to attribute to previous travellers of note I gladly acknowledge, but I am no less indebted to the many whose ideas have diffused into my awareness only to be re-presented here unjustly shorn of proper attribution; to them my apologies. The errors are entirely my own; I risk them out of principled objection to Wittgenstein's proposition that "Whereof one cannot speak, thereof one must be silent,"[2] preferring the opposing dictum that "Whereof one has not spoken, thereof one shall remain ignorant."

In that which is original, assertions should be considered suppositions, suppositions suggestions, suggestions speculations, and every speculation merely another round of pin the tail on the (theoretical) donkey – unless of course the novelties are found to have unexpected value.

The Enigma of Time

That time passes, that time flows inexorably like a great river from the inaccessible source of the far future, down through the roaring present to the vast and placid expanse of the past seems unarguable; the evidence is everywhere – in mile-deep formations of stratified rock, in the slow creep of the equinoxes, in memories of what was and ignorance of what is yet to be. But whilst it may seem unarguable that time flows, as soon as we pose such questions as "But what is it to flow?" and "What is it that is flowing?" what seemed previously indisputable becomes doubtful. As St Augustine said by way of introduction to his own consideration of the nature of time in his *Confessions*,

> *What then is time? If no one asks me, I know; if I want to explain it to a questioner, I do not know.*[3]

Time remains a mystery, and one that encompasses far more than mere vagaries of perception; our idea of time is inextricably bound to common-sense notions of cause and effect, of existence – and, for the most part, it is formulated and communicated in common-sense language.

The Constraints of Language

Unfortunately, by preferentially supporting concepts of ready applicability to everyday life, language constrains our discussions – of time or anything else. As Benjamin Whorf put it:

> *We cut nature up, organize it into concepts, and ascribe significances as we do, largely because we are parties to an agreement to organize it this way – an agreement that holds throughout our speech community and is codified in the patterns of our language. … we cannot talk at all except by subscribing to the organization and classification of data which the agreement decrees.*[4]

Whorf's "Standard Average European" typically considers time as linear, moving steadily, whether the passage of time is envisioned as a straight line, as is usually the case for a succession of years whose numbers do not repeat, or as a circle for the days of the week, whose names come round again and again. But this conceptualisation is far from obligatory. Other peoples conceptualise and discuss time differently.

The Quechua language of South America has at least one feature that would seem to suit it admirably to discussions of Einstein's theories of relativity (or of quantum mechanics).

> *[The] Huarochirí people called the world and time together* pacha*, an untranslatable word that simultaneously denotes a moment or interval in time and a locus or extension in space—and does so, moreover, at any scale.*[5]

Moving only slightly further north, arising perhaps in part from the simultaneous use of a number of different calendar systems, the Aztec may have had a concept of time as spiral, for them

> *Moments did not simply line up like beads on a rope. Instead they arranged themselves more like the rope itself, in which various fibers of differing lengths are spun together, now some overlapping and others not, now others overlapping that had not meshed before. Time spirals and spins around and around, like the rope turning back or doubling over on itself, its fibers now meshing, now not.* [6]

Do the Huarochirí really consider the world as four dimensional spacetime? Do they subscribe to Heisenberg's Uncertainty Principle? Did the Aztec have a concept of time as multiple sets of causally connected events? I doubt it. The point is that the mere existence of the Quechua word *pacha* – a word in principle as equally capable of being applied to the very infinitesimalness of the instant as to the infinitude of eternity – and the spiralling of Aztec time nonetheless demonstrate that there are other ways of speaking about and implicitly conceptualising time.

What language shall we use? The language of mathematics has proven "unreasonably effective"[7] but there are cautions: there is always the danger of the accidental Humpty-Dumptyism, of using a word to mean "many different things."[8] The more specific we can be, the fewer the dangers of ambiguity. Time flies like an arrow; fruit flies like a banana.

The question then is what language-independent, universal features of time might provide us with productive lines of enquiry in the most specific terms? There are two: the definiteness of the past and the indefiniteness of the future, and it is here at last that the issue of time intersects with the considerations of modern physics, specifically Einstein's Theories of Relativity.

Relativity bears directly on both the definiteness of the past and the indefiniteness of the future, most obviously via the possibility of *time travel* – movement not from place to place but from one point in time to another – a possibility that seems intrinsic to General Relativity and which calls into question both the fixity of the past (may we not change it?) and the indefiniteness of the future ("where" can we go if not to somewhere that already exists?).

Time Travel

It is from relativity that we obtain our concept of four-dimensional spacetime – the single composite entity which replaced the hitherto disparate domains of three-dimensional space and one-dimensional time.

Henri Poincaré had considered the possibility of translating physics into four dimensional geometry, but thought it would "entail great pain for limited profit,"[9] thus it was left to Hermann Minkowski to take Raum (space) and Zeit (time) to give us Raum-zeit (spacetime), which he did in almost oracular words:

> *From henceforth space in itself and time in itself sink to mere shadows, and only a kind of union of the two preserves an independent existence*[10]

However, it should be noted that despite making this statement in 1908 – three years after Einstein published the Special theory – Minkowski was not endorsing a perspective due to Einstein, he was speaking for himself. Combining space and time into a single entity was then considered a shocking conceptual shift, Max Wien noting in a letter to Arnold Sommerfeld that it induced "a slight brain-shiver, now space and time appear conglomerated together in a gray, miserable chaos",[11] but the idea subsequently proved far less painful and vastly more profitable than Poincaré had anticipated: it provided a framework for the re-expression of Einstein's Special Theory of Relativity and a sound basis for the formulation of the General Theory.

In relativity, spacetime is treated as a *manifold* – a mathematical object that can be loosely described as the formal specification of space that is continuous and smooth, and locally (in some sufficiently small region around any point) "flat," but which may nonetheless be globally curved. Flatness can be determined from the interior angles of a triangle: if they sum to 180º the space in which the triangle is drawn is flat, it has no *intrinsic* curvature; if they do not, the space is curved.

Ten years after Special Relativity, General Relativity took simple, flat, Minkowskian spacetime and allowed it to bend. Having unified matter and energy with Special Relativity ($E=mc^2$), Einstein gave matter-energy the role of the sculptor of spacetime, and just as the sculptor may press his fingers into his clay or run his hand over its surface, matter both shapes spacetime and responds to it.

The whole of General Relativity can summed up in the simple equation

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

which says that $G_{\mu\nu}$, the Einstein tensor (which describes the curvature of spacetime), is proportional to $T_{\mu\nu,}$ the Stress-Energy Tensor (which describes the characteristics of matter-energy in that spacetime).

From this equation, whose elegance conceals great complexity, arise many significant and experimentally established consequences such as the bending of light, the precession of the orbit of Mercury, the dilation of time for speeding objects and for objects in a gravitational field. But of all the consequences of General Relativity, black holes, wormholes and time machines are perhaps the most exotic and challenging for our understanding of time.

The existence of "closed time-like curves" (CTCs), or in everyday language, *time travel*, seems intrinsic to the theory of General Relativity. In 1949, Kurt Gödel solved Einstein's equations for a rotating universe[12] and discovered it contained CTCs. His was not the first solution to contain CTCs, merely the first in which their existence was noted: in 1924, Kornél Lánczos solved Einstein's equations for a rotating cylinder of dust[13], and in 1937 Willem Jacob van Stockum independently solved the same problem,[14] but it was not until 1973 that Frank Tipler recognised their solution permitted closed time-like curves. [15]

However, the issue of time travel was generally neglected despite the discovery of other ways of creating CTCs on the basis that all such contrived solutions were physically unrealistic.

But, whilst the practical impossibility of time travel precluded us from reaping speculative benefits, it also saved physicists from having to confront more disquieting consequences. The existence of time travel would immediately negate a large number, if not all, of our hitherto invaluable conservation laws: the conservation of energy, momentum, baryon number, etc. are implicitly temporal conservation laws, they state that given a quantifiable property *P*, the value of *P* as a function of time is fixed. Without conserved quantities, physics would be in a mess.

Yet there is worse to come. As if the prospect of the non-conservation of energy etc. is not bad enough, what would time travel do to entropy? Entropy is not conserved, entropy increases – things become more disordered and their capacity to do thermodynamic work diminishes – with the passage of time. If time travel existed, what would prevent low entropy from being sent into the future and high entropy being returned without apparently doing any thermodynamic work, in complete contradiction of the Second Law of Thermodynamics? That alone should give us pause, for as Eddington said,

> *…experimentalists do bungle things sometimes. But if your theory is to found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation*[16]

And then a way to make a time machine not nearly unrealistic enough to be ignored was found – from a wormhole.

Wormholes

Once space and time had become spacetime, and spacetime had admitted curvature, it was not long before the idea occurred that spacetime might be topologically non-trivial, i.e. that it might have holes like those of the doughnut and tea-cup handle.

The traditional illustration of a wormhole is shown in Fig. 1. In such illustrations one dimension of space is suppressed, a slice is taken "through the equatorial plane" of the wormhole mouth, and then the slice is folded over and "embedded in a fictitious higher-dimensional space"[17] to better convey the essential features.

In 1935 Einstein himself, in collaboration with Nathan Rosen, first considered wormholes (which they called "bridges") as a way of creating particles directly from the fabric of spacetime,[18] but Einstein-Rosen bridges were considered mere curiosities and largely neglected, only to be completely ignored once it was proved that they were so unstable not even light could pass through before they pinched off.[19]

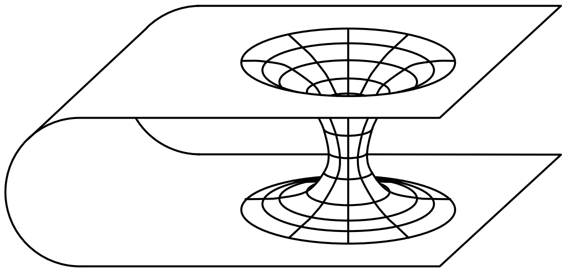

Figure 1 – an equatorial slice through a wormhole, "fictitiously embedded"[1]

Then in 1988 Misner, Thorne and Yurtsever demonstrated that wormholes could in fact be stabilised,[20] and although the technological hurdles to be leapt included the manufacture and manipulation of "exotic matter" (i.e. matter that had negative energy) thanks to quantum mechanics the existence of such matter was no longer *impossible*, and so the accumulation of enough to sustain a wormhole became "merely" a matter of practicability; the consequences had to be taken seriously.

In fact, they did more than create a stable wormhole. At Carl Sagan's request (in support of scientific plausibility for his novel *Contact*), they created a *traversable* wormhole, one suitable for interstellar travel. A traversable wormhole is stable, does not contain excessive tidal forces (and so will not rip the traveller apart) and has no horizons – the familiar but intangible boundary of a black hole beyond whose bourne no traveller returns.

Once a wormhole has been obtained, suitably enlarged and stabilised, interstellar travel is either permitted naturally, because the two mouths of the wormhole just happen to be light-years apart, or one end of the wormhole needs to be positioned. We may aim to do this quickly as possible, at a speed only fractionally less than that of light, and note the effects of Special Relativity – according to which time passes more slowly for an object in motion relative to an inertial observer.

Thus if one wormhole mouth was sent on a round trip at sufficiently high speed a significant time difference would accumulate between the two mouths and a time machine would form when the returning wormhole mouth came sufficiently close to the stationary mouth.

Notwithstanding the difficulties it causes for physics the idea of time travel is appealing, so it is with some regret I say there are several reasons to doubt this conclusion. The three difficulties are: practical, theoretical and logico-philosophical.

Firstly, to create a wormhole for interstellar travel one must be able to transport one mouth independently of the other. The various mechanisms proposed for transporting a wormhole seem implausible, requiring as they do that its mouths should possess properties – such as mass or charge – with which we can interact, for which the arguments seem unsustainable.

Secondly, even if a wormhole mouth could be moved, the motion is generally treated within the framework of Special Relativity; however, the smoothness and continuity constraints on spacetime are to be expected to result in General Relativistic effects quite different to those of Special Relativity and the Lorentz transformations.

Thirdly – and here I stand upon the battlefield with all the trepidation of a sling-less David, blindfolded, armed with nothing more dangerous than a faux donkey tail, uncertain whether I am even facing the right way, to confront a veritable host of physics' Goliaths – the creation of a time machine arises directly from the application of Lorentz transformations to the motion of wormhole mouths. But they are not objects *in* spacetime, they are regions *of* spacetime and it is a category error to apply the Lorentz transformations to them.

[1] Whilst the embedding may be fictitious in one sense, it is difficult to see how real space (as opposed to mathematical space) could *not* be embedded in a real higher dimension: if it is smooth and continuous it is difficult to see how topological structure could be supported without self-intersections otherwise.

De Oris Foraminis Vermis

Concerning the mouth of the hole of a worm, what properties does it have? How does one grasp it so as to be able to exert a force on it and cause it to move? Being not so much a thing in spacetime, but a feature of spacetime itself, this is a non-trivial task.

Matt Visser explains that a wormhole mouth can have mass or charge.[21] Beginning with the principle of the conservation of the (ADM) mass of an entire a universe, he argues that the mouths of a traversable wormhole between *two* universes acquire or lose mass as an object passes through the wormhole so that mass is conserved in each universe. This argument, it is said, can also be applied to an intra-universe wormhole; following which a similar argument leads to the conclusion that a wormhole mouth can become charged.

The first question raised is: where would charge reside? In the case of a black hole there is a horizon[2] on which charge can reside;[22] a traversable wormhole mouth is not so distinguished. The second and third questions are: why do two joined universe still conserve mass separately if there are no horizons, and how is the two-universe argument extensible to a single universe?

After careful consideration I conclude that the answers are: 'nowhere', 'they don't', and 'it isn't'. A traversable wormhole mouth cannot carry mass or charge.

However the ADM mass is defined, with respect to the "imprint at infinity" or to the boundary conditions of the manifold, as soon as a traversable wormhole exists between two universes there is in fact only one universe, one manifold. Even if this were not the case, the extension from an inter-universe wormhole to an intra-universe wormhole is surely illegitimate. This seems clearest from consideration of charge: the divergence theorem relates the charge within a closed surface to the flux passing through that surface, implicitly assuming that the surface divides space into two regions – inside and out. In the case of an intra-universe wormhole, a closed surface enclosing a wormhole mouth does not divide space into two distinct regions: one can reach the "interior" without crossing the surface by going the long way round. This viewpoint is supported by Misner, Thorne & Wheeler who say, re lines of force trapped by a wormhole:

> *One of the wormhole mouths... appears to be the seat of an electric charge. Out of this region of 3-space [the observer] finds lines of force emerging…He may construct a boundary around this charge, determine the flux though this boundary and incorrectly apply the theorem of Gauss and "prove" that there is a charge "inside the boundary". It isn't a boundary.*[23]

If this is true for charge and the resulting electric field, and considering that the divergence theorem is equally applicable to mass and the gravitational field, it seems improbable that a traversable, intra-universe wormhole mouth can sustain mass or charge.

In fact, in the absence of a horizon – which by definition a traversable wormhole does not have – it seems difficult for a wormhole mouth to have any properties other than those of spacetime. However, this does not mean that a wormhole mouth cannot move, merely that it would have to move in more mysterious ways.

Bending the Rules

The Special Theory of Relativity has unfortunate consequences for the exploration of space: since no material object can be accelerated to or beyond the speed of light, it places the stars effectively beyond our reach forever. The traversable wormhole provided one alternative way of reaching the stars; Miguel Alcubierre's "warp drive" provided another.

Alcubierre's approach to evading the constraints of Special Relativity was to engage in some metric engineering – the manipulation of spacetime so as to alter the separations between points – in order to move faster than light globally whilst moving slower than light locally. Alcubierre created a metric in which a moving region of space could contain a spaceship at rest. In this way the diktats of Special

[2] Usually. Black holes with extreme charge or extreme angular momentum may lose their horizons, introducing another physical anathema – a naked singularity, a point at which our current theories break down (General Relativity predicting infinite energy density and spacetime curvature at this point, for example) that is not hidden from view; it is hoped that "quantum gravity" will avoid such singularities. Although string theory's lack of background independence remains an issue, if one is willing to accept the existence of compactified spatial dimensions, it would seem logical that the arbitrarily large energy density available at the end of gravitational collapse should be sufficient to re-inflate compactified dimensions. A black hole that had shed its horizon to reveal such a decompactified region would be a very revealing astrophysical (or particle physics) object, unfortunately this footnote is too shallow to contain a discussion of the observational possibilities.

Relativity are obeyed while the "warp bubble" is free to move at superluminal velocity. The "heuristic" of the Alcubierre metric is that:

> *By a purely local expansion of spacetime behind the spaceship and an opposite contraction in front of it, motion faster than the speed of light as seen by observers outside the disturbed region is possible.* [24]

The effect mirrors the Hubble expansion of the universe in which the expansion of adjacent regions of space accumulates; if the far edge of a region one megaparsec across is receding at ~75km/s, the far edge of the second identically sized region just beyond it is receding at ~150km/s and so on. Substitute contraction for expansion and the region ahead of a "warp bubble" can shrink as quickly as one might wish.

Though the metric Alcubierre described was said to have "one important drawback"[25] – violating all three of Hawking and Ellis's[26] energy conditions (weak, dominant and strong) – it was surely only a matter of time before human ingenuity managed to find a more acceptable way of propelling a "warp bubble" along. And then one day I thought I perceived a problem: if the speed of gravity, i.e. the speed at which changes to the metric propagate (at least in the weak field regime) is also the speed of light, how could changes to the metric propagate superluminally in order to move the bubble forward?

Of course, they can't; and I doubt that licensed practitioners gave it a second thought – they had other objections. D. H. Coule summed it up thus:

> *The warp drive spacetime of Alcubierre is impossible to set up without first being able to distribute matter at tachyonic speed, put roughly, you need one to make one!* [27]

S. V. Krasnikov proposed a modification,[28] now known as a Krasnikov Tube, that addressed a number of issues in the original Alcubierre approach, although not without introducing other difficulties.

However, the point here does not concern any particular warp drive mechanism; the point is that a region of spacetime can move, at almost arbitrary velocity, and transport an object that remains locally at rest within it if the space around it is allowed to distort.

Consider the application of this idea to the movement of a wormhole mouth. The standard embedding of a wormhole suggests that if it is to move at all either space contracts at the leading edge(s) and expands at the trailing edge(s) – or, most speculatively – that space flows *through* the wormhole, in which case one could not move the mouths independently. In either case most peculiar matter distributions would be required unless (and now I am not sure whether I am even holding the donkey's tail the right way up) the wormhole moved as some kind of "strong field" wave or soliton.

What the observable effects of a wormhole mouth within a warp bubble travelling superluminally or subluminally, or through a Krasnikov tube, or as a wave might be I do not know, but they would surely not be what one would expect from the simple application of Lorentz transformations to the wormhole mouth as an object in spacetime.

Which point brings me to the third and most significant objection to the creation of a wormhole time-machine, that a wormhole mouth is not an object in spacetime at all.

Not Waving But Drowning

Let us revisit the creation of the wormhole time-machine as described by Misner, Thorne and Yurtsever.

Figure 2 shows how sending one mouth of a wormhole on a relativistic round-trip is said to create a time machine; the right-hand mouth accelerates away from the left-hand mouth then turns around and comes back. Applying Special Relativity to its motion, the elapsed proper time for the right-hand mouth is less than that for the left-hand mouth – a fact assured by the non-inertial nature of the motion.

The time machine comes into existence as soon as the returning mouth comes within the Cauchy horizon; the dashed lines at 45º (as is customary on such spacetime diagrams) represent light rays, which define simultaneity in relativity. Consequently, just after $t_L = 8$ a photon could fall into the right-hand mouth, travel back in time and emerge from the left-hand mouth in time to travel to the right-hand mouth and fall in… ad infinitum. A Closed, Time-Like Curve.

The problem with this is that the background of the diagram is Minkowskian spacetime, essentially fixed and flat. Now, whilst one can introduce further diagrammatic features, such as light-cones, to illustrate aspects of curved spacetime, in this particular case very simple effects of Special Relativity are being illustrated, primarily that of time-dilation. The movement of objects in spacetime should be against a static background.

However, a wormhole is a structure *of* spacetime and not an object *in* spacetime, its mouths cannot move against the background – they are part of it. If one were to attempt to construct this diagram with pen and paper, the pen drawing the world-line of the right-hand mouth would be stuck to the paper and the paper would rip; spacetime would be more flexible and the movement in the Z-direction would correspond to a stretching and then a relaxation of the intervening space. During the outward leg of the journey a photon emitted from the right-hand mouth would be red-shifted to the left-hand mouth, and on the return such a photon would be blue-shifted; but, once the right-hand mouth had returned to its original Z-coordinate there would be no observable difference between the situations before and after (neglecting the likely emission of gravitational waves en route).

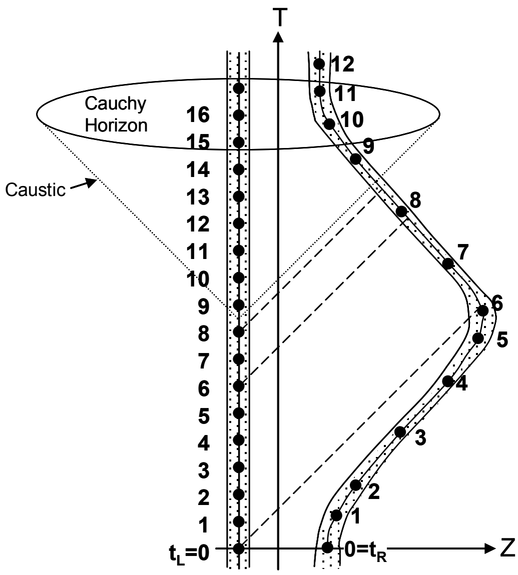

Fig. 2 – Spacetime diagram for conversion of a wormhole into a time machine (after *Misner, Thorne, Yurtsever 1988)*

To apply the Lorentz transformations to the wormhole mouth is to make a category error, an error made explicit in Matt Visser's re-description:

> *a short throat wormhole embedded in flat Minkowski space… and take the radius of the wormhole throat to zero… the wormhole is now mathematically modelled by Minkowski space with two timelike worldliness identified.* [29]

A moment's consideration of an analogy will clarify the point. Consider the point where a pair of scissor-blades cross as the scissors are closed; identify the edge of one blade with a Cartesian axis. As the blades are closed the point of contact "moves" along that axis towards the tip of the blades; given sufficiently long and rigid blades the "speed" of the contact point can be made arbitrarily large, certainly exceeding the speed of light. This does not violate relativity because nothing is actually moving. If we were to say instead of "the point of contact *moves*", "the coordinate of the point of contact increases in value" and instead of "the speed of the point of contact can exceed the speed of light", "the *coordinate speed*…" the confusion would be minimised.

How is this picture of a moving wormhole mouth to be reconciled with the observations of the thought experiment in which the moving wormhole mouth accompanies a traveller in a spaceship?

If the spaceship and wormhole mouth both sit in a region of flat spacetime inside a "warp bubble" travelling through flat space, then the elapsed time for the traveller will be the same as for the observer at the other end of the wormhole; if the spaceship is outside the "warp bubble", but travelling alongside it subluminally, I would expect the "warp bubble" boundary to exactly compensate for the absence of relative motion, and for the traveller's clock to be seen through the wormhole as running at the same rate as when observed directly.

If space – somehow – flowed through the wormhole, and the left-hand mouth could be kept in a "fixed" location by, say by moving in a small circle, I would also expect the necessary distortions of spacetime to produce a suitably compensatory effect.

Conclusion

It has been argued that wormholes cannot be turned into time machines because the justification for the creation of a time machine relies upon a misapplication of Special Relativity – even if wormhole mouths could be moved, which does not seem feasible other than by metric engineering around the wormhole mouth, which would produce other compensatory effects. A similar argument is expected to frustrate the creation of a time machine from a wormhole by placing one wormhole mouth in a deep gravitational well.

The non-existence of wormhole time machines would seem to lend further support to Hawking's Chronology Protection Conjecture.

VLADIMIR: *That passed the time.*
ESTRAGON: *It would have passed in any case.*
VLADIMIR: *Yes, but not so rapidly.*[30]

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