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# THE GEOMETRY OF TIME TRAVEL

A Lecture by

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*Gresham Lecture*

# The Geometry of Time Travel

Ian Stewart

*There is no difference between Time and any other of the three dimensions of Space except that our consciousness moves along it.*

H.G.Wells, *The Time Machine.*

Time travel used to be just science fiction. When H.G.Wells published 'The Time Machine' in the 1894-5 issue of *The New Review*, even the Time Traveller's friends didn't believe a word. But if you look through today's mainstream physics journals, things like *Annals of Physics* and *Physical Review Letters*, you will find occasional articles about time travel — taking it completely seriously, and applying state-of-the-art physics. There's been quite a spate of them in recent years. Some claim to prove that time travel is impossible, and some say that it's possible in principle but impossible in practice because of the huge energy overheads. Whatever the articles say, they're becoming a lot more frequent.

Most of The Real Physics of Time Travel is General Relativity; and the rest is Quantum Mechanics. The General Relativity is by far the most interesting, so I'll concentrate on that.

But first:

## Special Relativity

I'll try to get through this bit quickly, but we need some of the basics. The main one is that 'Relativity' is a silly name.

The whole point of Special Relativity is *not* that 'everything is relative', but that one particular thing — the speed of light — is unexpectedly *absolute*. If you're travelling in a car at 50 mph and you fire a gun forwards, so that the bullet moves at 500 mph relative to the car, then it will hit a stationary target at a speed of 550 mph, adding the two components. However, if instead of firing the gun you switch on a torch, which 'fires' light at a speed of 670,647,740 mph (186,000 mps), then that light will not hit the stationary target at a speed of 670,647,790 mph. It will hit it at 670,647,740 mph, exactly the same speed that it would have had if the car had been stationary.

You can prove this in your own home. You'll need a cardboard box about the size of a shoebox, a torch, and a mirror. Cut a small hole in the front of the box, to let the light in. Cut a flap in the top so that you can open the box and look inside; and write 'THE SPEED OF LIGHT IS 670,647,740 MPH' on the bottom of the inside of the box. Stand still, close the flap, aim the torch at the mirror so that the beam reflects back into the box through the hole, and open the flap to read off the speed of light. Then *run towards the mirror* and repeat the experiment. Funny, you get 670,647,740 mph both times...

You may think this is a silly experiment; but with more sophisticated equipment *you get the same answer* — as Albert Michelson and Edward Morley discovered between 1881 and 1894. They were trying to detect the motion of the Earth relative to the 'ether', all all-pervading fluid that was thought to transmit all electromagnetic radiation, light included. Their conclusion was that either there isn't an ether at all, or the Earth *isn't* moving relative to it — which is fishy given its orbit round the Sun, which points it in opposite directions every six months — or that there's something pretty weird about light.

Albert Einstein is generally credited with the theory — known as Special Relativity — that there's something pretty weird about light. He published it in 1905 along with the first serious evidence for quantum mechanics and a general theory of diffusion processes. But a lot of other people — among them Hendrik Lorentz and Henri Poincaré — were working on the same idea, because it was widely recognised that Maxwell's equations for electromagnetism didn't entirely gell with Newtonian mechanics. The problem was one of 'moving frames of reference'. How do the equations change when the observer is moving? There are formulas that answer this question, known as coordinate transformations. In Newtonian mechanics, for example, velocities measured by (or relative to) a moving observer change by subtracting the motion of the observer. But Newtonian transformations mess up Maxwell's equations something chronic. The answer is to use different formulas, called Lorentz transformations. They keep the speed of light constant, but have spin-off effects on space, time, and mass. Objects shrink as they apoproach the speed of light, time slows down to a crawl, and mass becomes infinite.

It's not easy to think about this kind of thing using just the formulas, and the idea didn't really take off until 1908 when the mathematician Hermann Minkowski provided a good geometric model for relativity — a simple way to *visualise* it — now called Minkowski (or *flat*) spacetime.

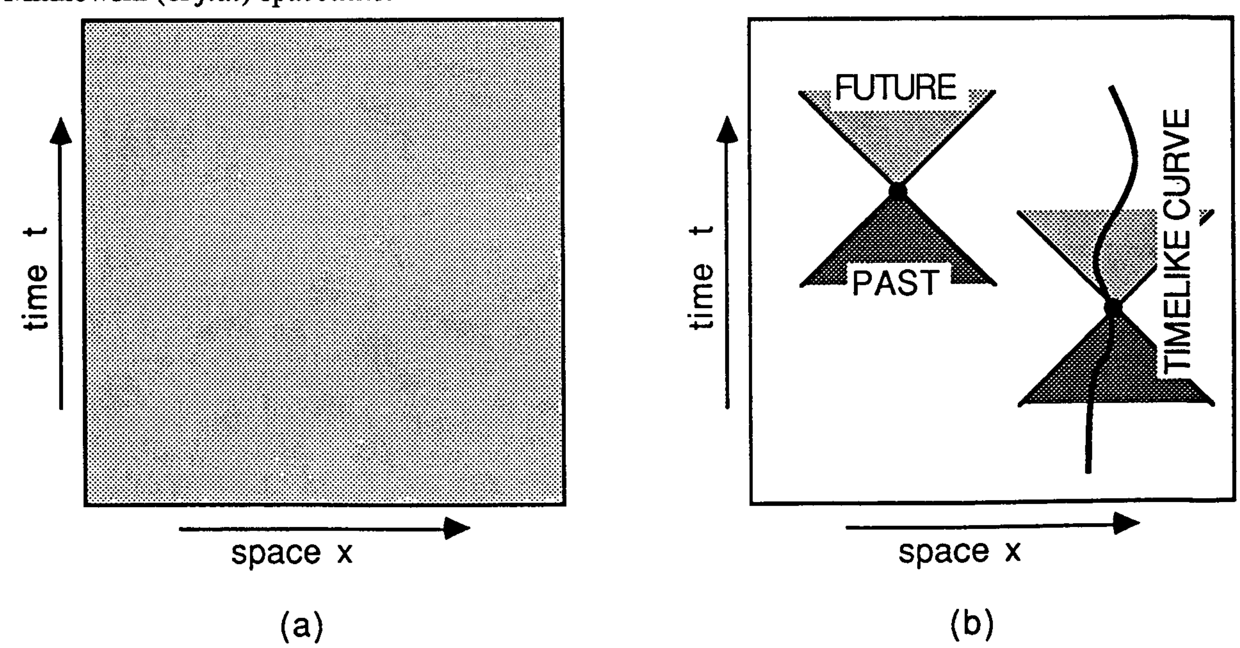


***Figure 1*** Minkowski spacetime.

*Because* relativity is about the non-relative behaviour of light, everything in it depends heavily upon which 'frame of reference' an observer is employing. Moving and static observers see the same events in different ways. Mathematically, a frame of reference is a coordinate system. Newtonian physics provides space with three fixed coordinates $(x,y,z)$. The structure of space was thought to be independent of time, and it was not traditional to represent time as a coordinate at all. Minkowski introduced time as an explicit extra coordinate. We can draw two-dimensional Minkowski spacetime as a plane (**Fig.1a**). The horizontal coordinate, $x$, determines a particle's position in space; the vertical coordinate, $t$, determines its position in time. In full-blooded Minkowski spacetime $x$ is three-dimensional; but for convenience it's shown here as being one-dimensional. Later I'll also represent space as being a two-dimensional. The problem is that four dimensions of spacetime don't fit conveniently on to two-dimensional paper, so a lot of the mathematics involves tricks for cutting down the number of dimensions of space. The simplest trick is to ignore a few dimensions.

As the particle moves, it traces out a curve in space-time called its *world-line*. If the velocity is consant, then the world-line is straight, and its slope depends on the speed. Particles that move very slowly cover a small amount of space in a lot of time, so their world-lines are close to the vertical; particles that move very fast cover a lot of space in very little time, so their world-lines are nearly horizontal. In between, at an angle of 45°, are the world-lines of particles that cover a given amount of space in the same amount of time — measured in the right units. Those units are chosen to correspond via the speed of light — say years for time and light-years for space. What covers one light-year of space in one year of time? Light, of course. So 45° world-lines correspond to particles of light — light rays or photons — or anything else that can move at the same speed.

You all know that Relativity forbids bodies that move faster than light. (The mathematical reason is that their lengths would become imaginary — involving the number $i = \sqrt{-1}$ — as would mases and the local passage of time.) So the world-line of a real particle can never slope more than 45° away from the vertical. Such a world-line is called a *timelike curve* (**Fig.1b**). Any event — point in space-time — has associated with it a *light cone*, formed by the two diagonal lines at 45° inclinations that pass through it. It's called a cone because when space has two dimensions, the corresponding surface really is a (double) cone. The forward region contains the *future* of the event, all the points in space-time that it could possibly influence; the backward region is its *past*, the events that could possibly influence *it*. Everything else is forbidden territory, elsewheres and elsewhens that have no possible causal connections with the chosen event.

Pythagoras's Theorem tells us that in ordinary space, the distance between two points with coordinates $(x,y,z)$ and $(X,Y,Z)$ is the square root of the quantity

$$(x-X)^2 + (y-Y)^2 + (z-Z)^2. \qquad (1)$$

In Special Relativity, there is an analogous quantity, called the *interval* between events $(x,t)$ and $(X,T)$; it is

$$(x-X)^2 - (t-T)^2. \qquad (2)$$

Note the minus sign: time is special. (And H.G.Wells turns out not to be quite correct!) Along the lines of 45° slope, the interval is *zero*.

The interval is related to the apparent rate of passage of time for a moving observer. The faster an object moves, the slower time on it appears to pass. This effect is called *time dilation*. As you approach a null curve — that is, travel closer and closer to the speed of light — the passage of time that you experience slows down towards zero. If you could travel *at* the speed of light, time would be frozen. No time passes on a photon.

The key to relativistic time travel is the hoary old *twin paradox*[1], pointed out by Paul Langevin in 1911. Suppose that (**Fig.2**) two twins, Rosencrantz and Guildenstern, are born on Earth. Rosencrantz stays there all his life, while Guildenstern travels away at nearly lightspeed, and then turns round and comes home again at the same speed. Because of time dilation, only six years (say) have passed in Guildenstern's frame of reference, whereas 40 years have passed in Rosencrantz's frame. Experiments carting atomic clocks around the Earth on jumbo jets have verified this scenario, but aircraft are so slow compared to light that the time difference observed (and predicted) is only the tiniest fraction of a second.

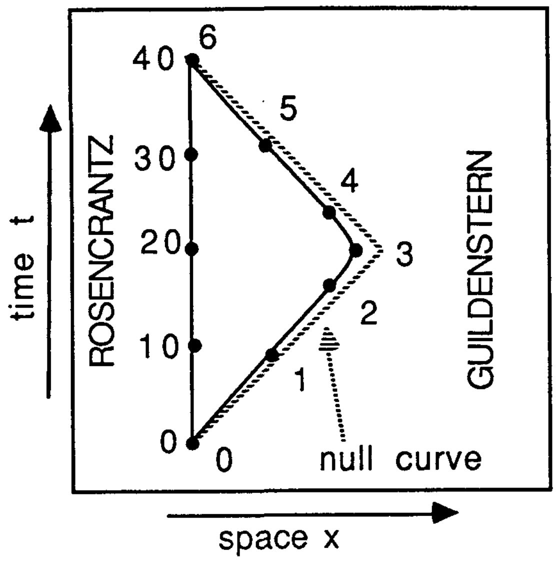


***Figure 2*** The Twin Paradox.

'The time is out of joint', as Shakespeare said in Hamlet. So it ought to be possible to exploit the out-of-jointness to make a time machine. But how? The missing ingredient turns out to be... gravity.

## General Relativity

Einstein invented General Relativity as a synthesis of Newtonian gravitation and Special Relativity. In Newton's view, gravity is a force that moves particles away from the perfect straight line paths that they would otherwise follow. These paths are *geodesics*: they minimize the total distance. In flat Minkowski spacetime, the analogous objects minimize the interval (formula (2) above) instead. Gravity is incorporated, not as an extra force, but as a distortion of the structure of spacetime, which changes the interval. This variable interval between nearby events is called the *metric* of spacetime. The usual image is to say that spacetime becomes 'curved', though this term is easily misinterpreted.

[1] Although this is called a paradox, it isn't! People think it's paradoxical because they don't actually look at a spacetime diagram, and they assume that it doesn't matter which twin is used as the 'fixed' frame. But Guildenstern's motion involves acceleration (positive and negative), while Rosencrantz's doesn't — and that destroys the apparent symmetry between the two twins.

In particular, it doesn't have to be curved *round* anything else. The curvature is interpreted physically as the force of gravity, and it causes light-cones to deform. One result is 'gravitational lensing', the bending of light by massive objects, which Einstein discovered in 1911 and published in 1915. The effect was first observed during an eclipse of the Sun. More recently it has been discovered that some distant quasars produce multiple images in telescopes because their light is lensed by an intervening galaxy.

**Fig.3** shows a spacelike section of spacetime (that is, one taken at a 'fixed' instant of time) near a star: it takes the form of a curved surface that bends downwards to create a circular valley in which the star sits. This spacetime structure is *static*: it remains exactly the same as time passes. Light follows geodesics across the surface, and is 'pulled down' into the hole, because that path provides a short cut. Particles moving in spacetime at sublight speeds behave in the same way. If you look down on this picture from above you see that the particles no longer follow straight lines, but are 'pulled towards' the star, whence the Newtonian picture of a gravitational force.

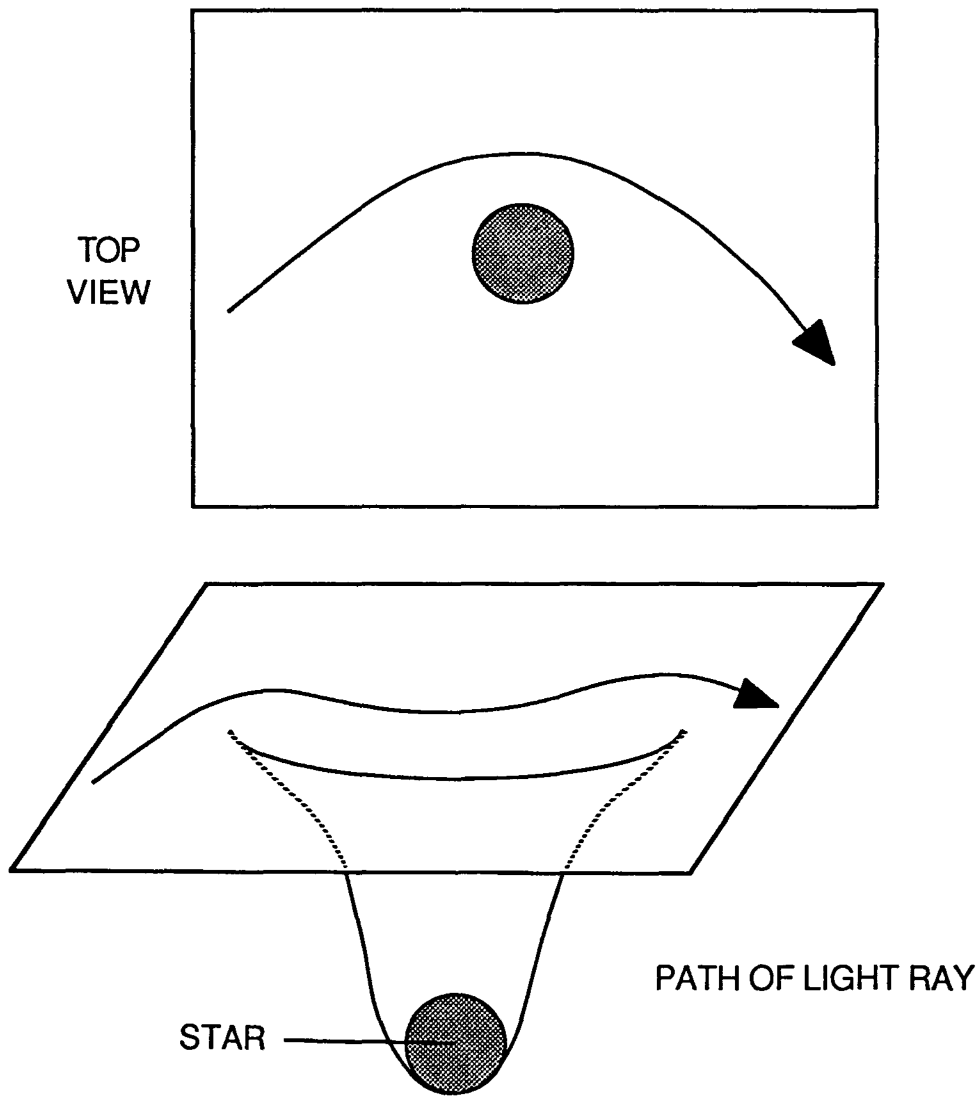


***Figure 3*** Bending of light by gravity.

Far from the star, this spacetime is very close indeed to Minkowski spacetime; that is, the gravitational effect falls off rapidly and soon becomes negligible. Spactimes that look like Minkowski spacetime at large distances are said to be *asymptotically flat.* Remember that term: it's important for making time machines. Most of our own universe is asymptotically flat, because massive bodies such as stars are scattered very thinly.

When setting up a spacetime, you can't just bend things any way you like. The metric must obey the *Einstein equations*, which relate the motion of freely moving particles to the degree of distortion away from 'flat' Minkowski spacetime.

I can now explain what a time machine looks like within the framework of General Relativity. A time machine lets a particle or object return to its own past, so its world-line, a timelike curve, must close into a loop. A time machine is just a *closed timelike curve*, abbreviated to CTC. Instead of asking 'is time travel possible?' we ask 'can CTCs exist?'.

In flat Minkowski spacetime, they can't. Forward and backward light cones — the future and past of an event — never intersect. But they can intersect in other types of spacetime. The simplest example takes Minkowksi spacetime and 'rolls it up' into a cylinder (**Fig.4**). Then the time coordinate becomes cyclic, as in Hindu mythology.

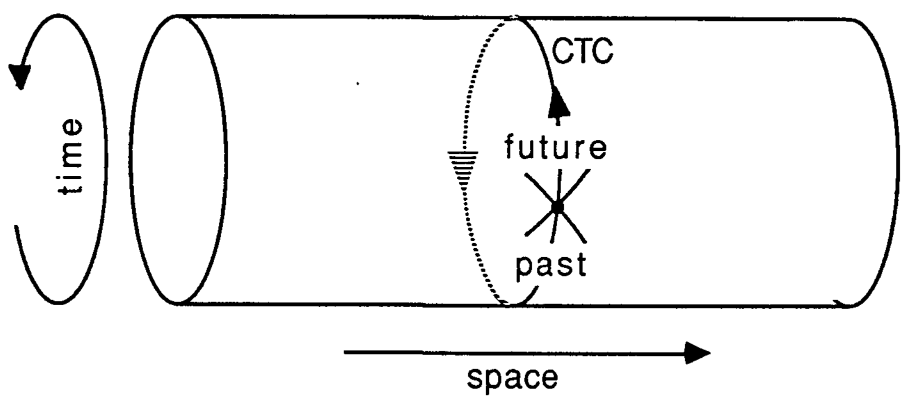


***Figure 4*** A simple example of a spacetime with a CTC.

Although this *picture* looks curved, actually the corresponding spacetime is *not* curved — not in the gravitational sense. When you roll up a sheet of paper into a cylinder, it doesn't *distort.* You can flatten it out again and the paper is not folded or wrinkled. An ant that is confined purely to the surface won't notice that it has been bent, because distances *on* the surface haven't changed. In short the metric — a local property of spacetime structure *near* a given event — doesn't change. What changes is the global geometry of spacetime, its overall *topology.*

Rolling up Minkowski spacetime is an example of a powerful mathematical trick for building new spacetimes out of old ones: cut-and-paste. If you can cut pieces out of known spacetimes, and glue them together without distorting their metrics, then the result is also a possible spacetime. I say 'distorting the metric' rather than 'bending', for exactly the reason that I say that rolled-up Mikowski spacetime is *not* curved. I'm taking about intrinsic curvature, as experience by a creature that lives in the spacetime; not about apparent curvature as seen in some external representation. In the rest of this article I'll say that apparent bending is 'harmless' if it doesn't actually change the metric. We'll see other examples of the cut-and-paste construction as we proceed.

The rolled up version of Minkowski spacetime is a very simple way to prove that spacetimes that obey the Einstein equations *can* possess CTCs — and thus that time travel is not inconsistent with currently known physics. But that doesn't imply that time-travel is *possible*. There is a very important distinction between what is mathematically possible and what is physically feasible.

A spacetime is mathematically possible if it obeys the Einstein equations. It is physically feasible if it can exist, or could be created, as part of our own universe. There's no very good reason to suppose that rolled-up Minkowski spacetime is physically feasible: certainly it would be hard to refashion the universe in that form if it wasn't already endowed with cyclic time, and right now very few people think that it is. The search for spacetimes that possess CTCs *and* have plausible physics is a search for more plausible topologies. There are many mathematically possible topologies, but — as with the Irishman giving directions — you can't get to all of them from here.

## Black Holes

But you can get to some remarkably interesting ones.

In classical Newtonian mechanics, there is no limit to the speed of a moving object. Particles can escape from an attracting mass, however strong its gravitational field, by moving faster than the appropriate escape velocity. In an article presented to the Royal Society in 1783, John Michell observed that this idea, combined with that of a finite velocity for light, implies that sufficiently massive objects cannot emit light at all — because the speed of light will be lower than the escape velocity. In 1796 Pierre Simon de Laplace repeated these observations in his *Exposition of the System of the World.* Both of them imagined that the universe might be littered with huge bodies, bigger than stars, but totally dark.

They were a century ahead of their time.

In 1915 Karl Schwarzschild took the first step towards answering the analogous question within the context of General Relativity, when he solved the Einstein equations for the gravitational field around a massive sphere in a vacuum. His solution behaved very strangely at a critical distance from the centre of the sphere, now called the *Schwarzschild radius*. It is equal to $2GM/c^2$ where $G$ is the gravitational constant, $M$ the mass of the sphere, and $c$ the speed of light. When it was discovered, its mathematical significance seemed to be that space and time lost their identity in Schwarzschild's solution, and became meaningless. However, the Schwarzschild radius for the Sun's mass is 2km, and for the Earth 1 cm — buried inaccessibly deep. What would happen to a star that was so dense that it lay inside its own Schwarzschild radius?

In 1939 Robert Oppenheimer and Hartland Snyder showed that it would collapse under its own gravitational attraction. Indeed a whole portion of spacetime would collapse to form a region from which no matter, not even light, could escape. This was the birth of an exciting new physical concept. In 1967 John Archibald Wheeler coined the term *black hole*, and the new concept was christened. A curious postscript is that in 1950 David Finkelstein resolved the mathematical question: the loss of spacetime identity in Schwarzschild's original solution is just an artefact of a poor choice of coordinates. But even using a good choice, there is still something very weird about the Schwarzschild radius, and Oppenheimer and Snyder's newborn concept remains valid.

The development over time of a static — non-rotating — black hole is shown in **Fig.5**, in which space is represented as two-dimensional and time runs vertically from bottom to top. An initial radially symmetric distribution of matter (the shaded circle) shrinks to the Schwarzschild radius, and then continues to shrink until, after a finite time, all the mass has collapsed to a single point, the singularity. From outside, all that can be detected is the *event horizon* at the Schwarzschild radius, which separates the region from which light can escape from the region that is forever unobservable from outside. Inside the event horizon lurks the black hole.

**Fig.5a** is the sequence of events seen by a hypothetical observer on the surface of the star, and the time coordinate $t$ is the one experienced by such an observer. If you were to watch the collapse from outside you would see the star shrinking, towards the Schwarzschild radius, but you'd never see it get there. As it shrinks, its speed of collapse as seen from outside approaches that of light, and relativistic time-dilation implies that the entire collapse takes infinitely long when seen by an outside observer, as in **Fig.5b**. However, you'd see the light emitted by the star shifting deeper and deeper into the red end of the spectrum. Inside a black hole, the roles of space and time are reversed. Just as time inexorably increases in the outside world, so space inexorably decreases inside a black hole.

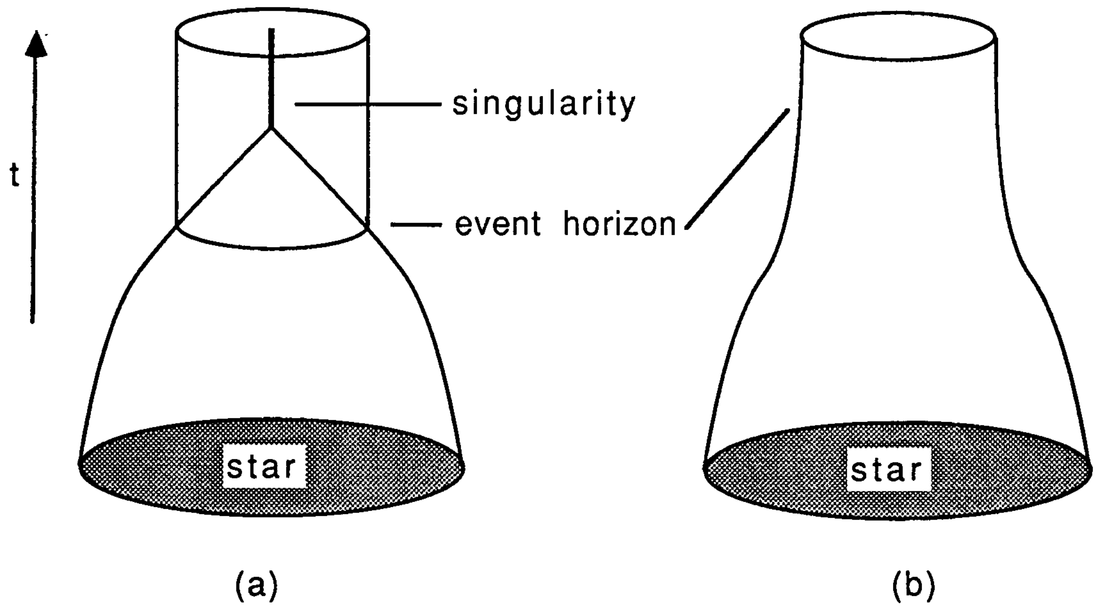


***Figure** 5.* Formation of a black hole as seen by (a) an observer at the surface of the collapsing mass and (b) an external observer.

Because the spacetime topology of a black hole is asymptotically flat — like Minkowski spacetime at large distances — it can be cut-and-pasted into the spacetime of any universe that has reasonably large asymptotically flat regions — such as our own. This makes black hole topology physically plausible in our universe. Indeed, the scenario of gravitational collapse makes it even more plausible: you just have to start with a big enough concentration of matter, such as a neutron star or the centre of a galaxy. A technologically advanced society could *build* black holes.

A static black hole doesn't possess CTCs, though, so we haven't achieved time travel yet. However, we're getting close. The key is the realisation that Einstein's equations are time-reversible: to every solution there corresponds another that is just the same, except that time runs backwards. The time-reversal of a black hole is a *white hole*, and it looks like Fig.5 turned upside down. An ordinary event horizon is a barrier from which no particle can escape; a time-reversed horizon is one into which no particle can fall, but from which particles may from time to time be emitted. So, seen from the outside, a white hole would appear as the sudden explosion of a star's worth of matter, coming from a time-reversed event horizon.

White holes may seem rather strange. It makes sense for an initial concentration of matter to collapse, if it is dense enough, and thus to form a black hole; but why should the singularity inside a white hole suddenly decide to spew forth a star, having remained unchanged since the dawn of time? Let's just agree that white holes are a mathematical possibility, and notice that they too are asymptotically flat. So if you knew how to make one, you could glue it neatly into your own universe.

Not only that: you can glue a black hole and a white hole together. Cut them along their event horizons, and paste along these two horizons. The result (more accurately, a fixed spacelike section of it) is shown in **Fig.6**: a sort of tube. Matter can pass through the tube in one direction only: into the black hole and out of the white. It's a kind of matter-valve. The passage through the valve is achieved by following a timelike curve, because material particles can indeed traverse it.

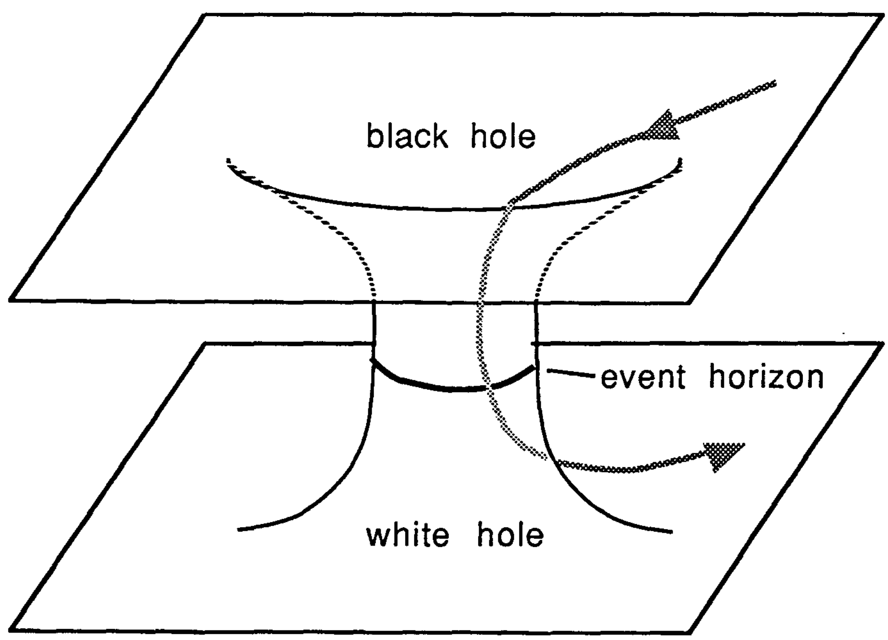


***Figure 6*** A wormhole.

Because the topology of Fig.6 is asymptotically flat at both ends of the tube, both ends can be glued into any asymptotically flat region of any spacetime. You could glue one end into our universe, and the other end into somebody else's; or you could glue both ends into ours — *anywhere you like* (except near a concentration of matter). Now you've got a *wormhole.* I've drawn one schematically in **Fig.7**; but you have to remember that the distance *through* the wormhole is very short, whereas that between the two openings, across normal spacetime, can be as big as you like.

A wormhole is a short cut through the universe. But that's *matter-transmission,* not time travel. Never mind: we're nearly there.

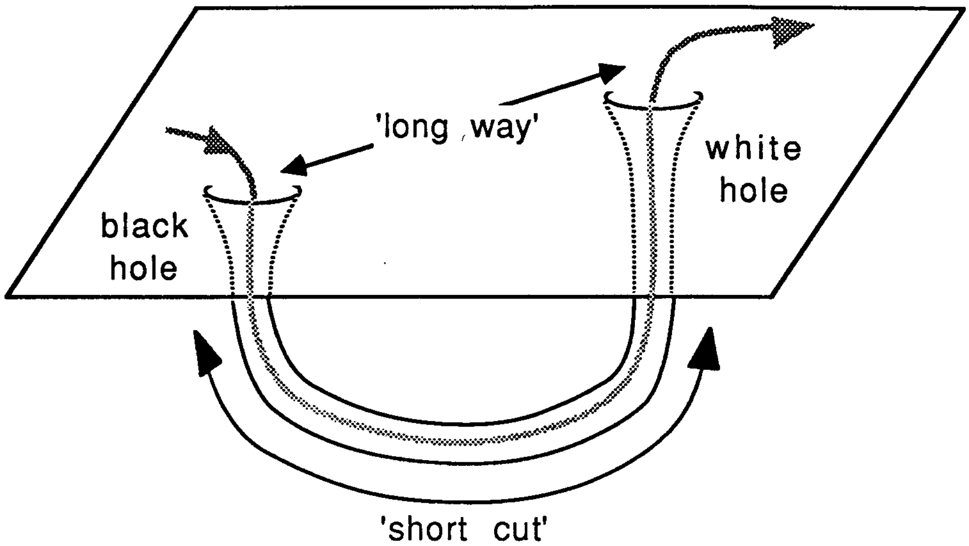


*Figure 7.* Using a wormhole as a matter-transmitter.

## Turning a Wormhole into a Time Machine

In 1988 Michael Morris, Kip Thorne, and Ulvi Yurtsever realised that by combining a wormhole with the twin paradox, they could get a CTC. The idea is to leave the white end of the wormhole fixed, and to tow the black one away (or zigzag it back and forth) at just below the speed of light.

**Fig.8** shows how this leads to time travel. The white end of the wormhole remains static, and time passes at its normal rate, shown by the numbers. The black end zig-zags to and fro at just less than the speed of light; so time-dilation comes into play, and time passes more slowly for an observer moving with that end. Think about world-lines that join the two wormholes through normal space, so that the time experienced by observers at each end are the same: lines joining dots with the same numbers. At first those lines slope less than 45°, so they are not timelike, and it is not possible for material particles to proceed along them. But at some instant, in this case time 3, the line achieves a 45° slope. After this 'time barrier' is crossed, you can travel from the white end of the wormhole to the black through normal space — following a timelike curve. An example of such a world-line runs from point 5 in the white end of the wormhole to point 4 in the black. Once there, you can return *through* the wormhole, again along a timelike curve; and because this is a short cut you can do so in a very short period of time, effectively travelling instantly from point 4 at the black end to the corresponding point 4 at the white. This is the same place as your starting point, but one year in the *past* ! You've travelled in time. By waiting one year, you can close the CTC and end up at the same place and time that you started from.

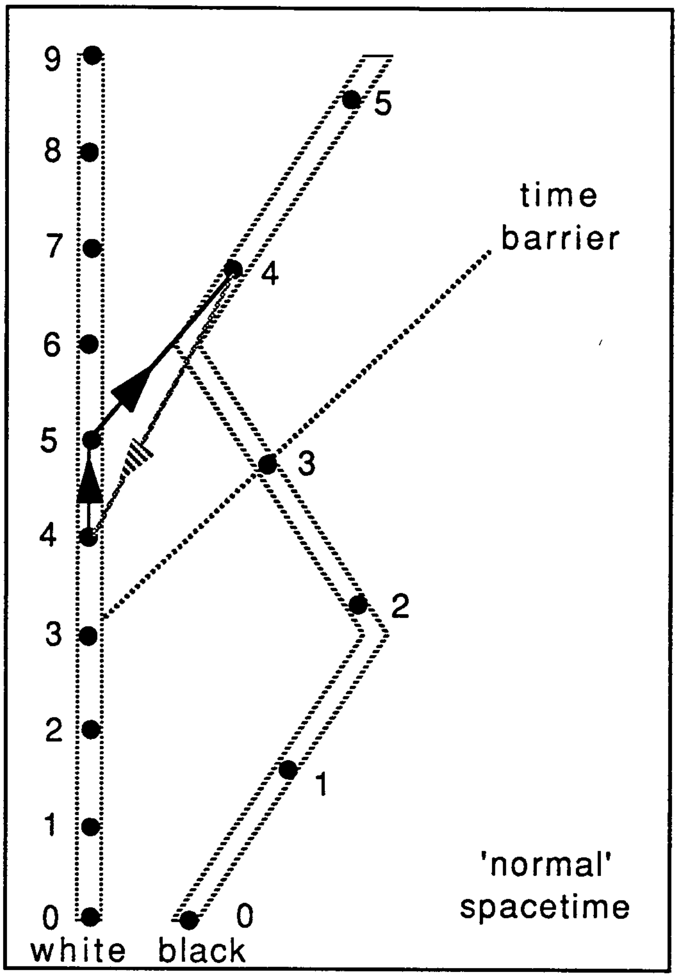


*Figure 8* Turning a wormhole into a Time Machine.

You can make your own wormhole in your own home. Take a plastic bin-liner and cut out the bottom. Fix one end, and imagine the other rushing to and fro at just below lightspeed, so that time inside it slows down. When the far end of the bag comes near, walk across to it, arriving at some time in your own past. Climb through it, and you'll travel back in time.

If your imagination is vivid enough, that is.

The actual distance you have to travel through ordinary space need not be huge: it depends on how far the right end of the wormhole has to move on each leg of its zigzag path. In space of more than one dimension it can spiral rather than zigzag, which corresponds to making the black end following a circular orbit at close to lightspeed. You could achieve this by setting up a binary pair of black holes, rotating rapidly round a common centre of gravity.

The further into the future your starting point is, the further back in time you can travel from that point. But there's one disadvantage of this method: you can never travel back past the time barrier, and that occurs some time after you build the wormholes. No hope of getting back to hunt dinosaurs.

## Yes But...

Could you really build one of these devices? Could you really get through the wormhole? A technologically advanced civilisation could build the holes, and move them around, by creating intense gravitational fields. But that's not the only obstacle.

Another is the 'catflap effect': when you move a mass through a wormhole it tends to shut on your tail. It turns out that in order to get through without getting your tail trapped you have to travel faster than light, so that's no good. It's easiest to see why if we represent the spacetime geometry using a *Penrose map*. When you draw a map of the Earth on a flat sheet of paper you have to distort the coordinates — for example, lines of longitude may become curved., The Penrose map of a spacetime also distorts the coordinates; but it is designed so that light cones don't change — they still run at 45° angles. **Fig.9** shows a Penrose map of a wormhole. Any timelike path that starts at the wormhole entrace, such as the wiggly line shown, must run into the future singularity. There's no way to get across to the exit without exceeding the speed of light.

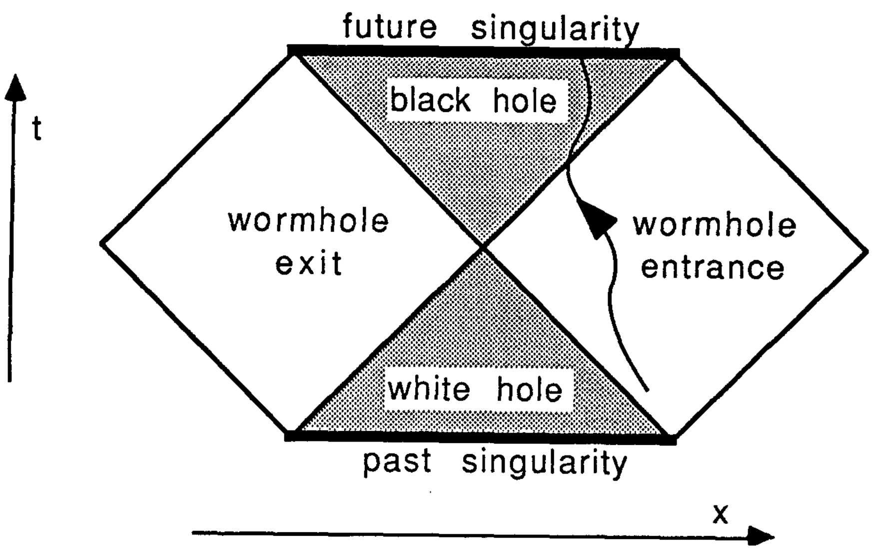


***Figure 9*** The Penrose map of a wormhole.

The traditional way round this difficulty is to thread the wormhole with *exotic matter*, exerting enormous negative pressure, like a stretched spring. Matt Visser has recently suggested an alternative geometry for a benign wormhole. Two identical cubes are cut in space, and their corresponding faces are pasted together; then the edges are reinforced with exotic matter.

## Rotating Black Holes

The classic answer, though, is to employ a rotating black hole.

The Schwarzschild solution of Einstein's equations corresponds to a *static* black hole, one formed by the collapse of a non-rotating sphere. In 1962 Roy Kerr solved the equations for a rotating black hole (**Fig.10**), now known as a *Kerr black hole*. (There are two other kinds of black hole: the Reissner-Nordstrøm black hole, which is static but has electric charge, and the Kerr-Newman black hole which rotates and has electric charge.) It is almost a miracle that an explicit solution exists — and definitely a miracle that Kerr was able to find it. It's extremely complicated and not *at all* obvious. But it has spectacular consequences.

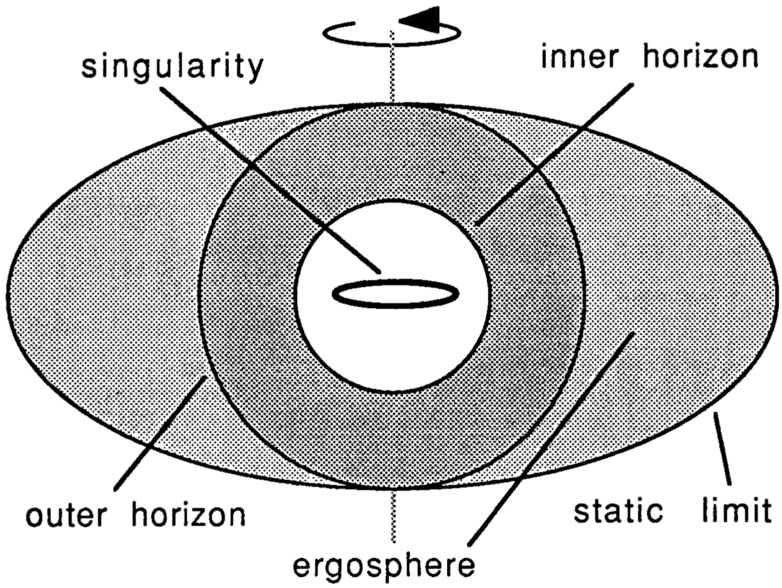


***Figure 10*** Structure of a rotating black hole.

One is that there is no longer a point singularity inside the black hole. Instead, there is a circular ring singularity, in the plane of rotation. In a static black hole, all matter must fall into the singularity; but in a rotating one, it need not. It can either travel above the equatorial plane, or pass through the ring. The event horizon also becomes more complex; indeed it splits into two. Signals or matter than penetrate the *outer horizon* cannot get back out again; signals or matter emitted by the singularity itself cannot travel past the *inner horizon*. Further out still, but tangent to the outer horizon at the poles, is the *static limit*. Outside this, particles can move at will. Inside it, they must rotate in the same direction as the black hole, although they can still escape by moving radially. Between the static limit and the outer horizon is the *ergosphere*. If you fire a projectile into the ergosphere, and split it into two pieces, one being captured by the black hole and one escaping, then you can extract some of the black hole's rotational energy.

The most spectacular consequence of all, however, is the Penrose map of a Kerr black hole, shown in **Fig.11**. The white diamonds represent asymptotically flat regions of spacetime — one in our universe, and several others that need not be. The singularity is shown as a system of broken lines, indicating that it is possible to pass through it (going through the ring). Beyond the singularities lie antigravity universes in which distances are negative and matter repels other matter. Any body in this region will be flung away from the singularity to infinite distances. Several legal (that is, not exceeding the speed of light) trajectories are shown as curved paths. They lead through the wormhole to any of its alternative exits. The most spectacular feature of all, however, is that this is only part of the full diagram. This repeats indefinitely in the vertical direction, and provides an *infinite number* of possible entrances and exits.

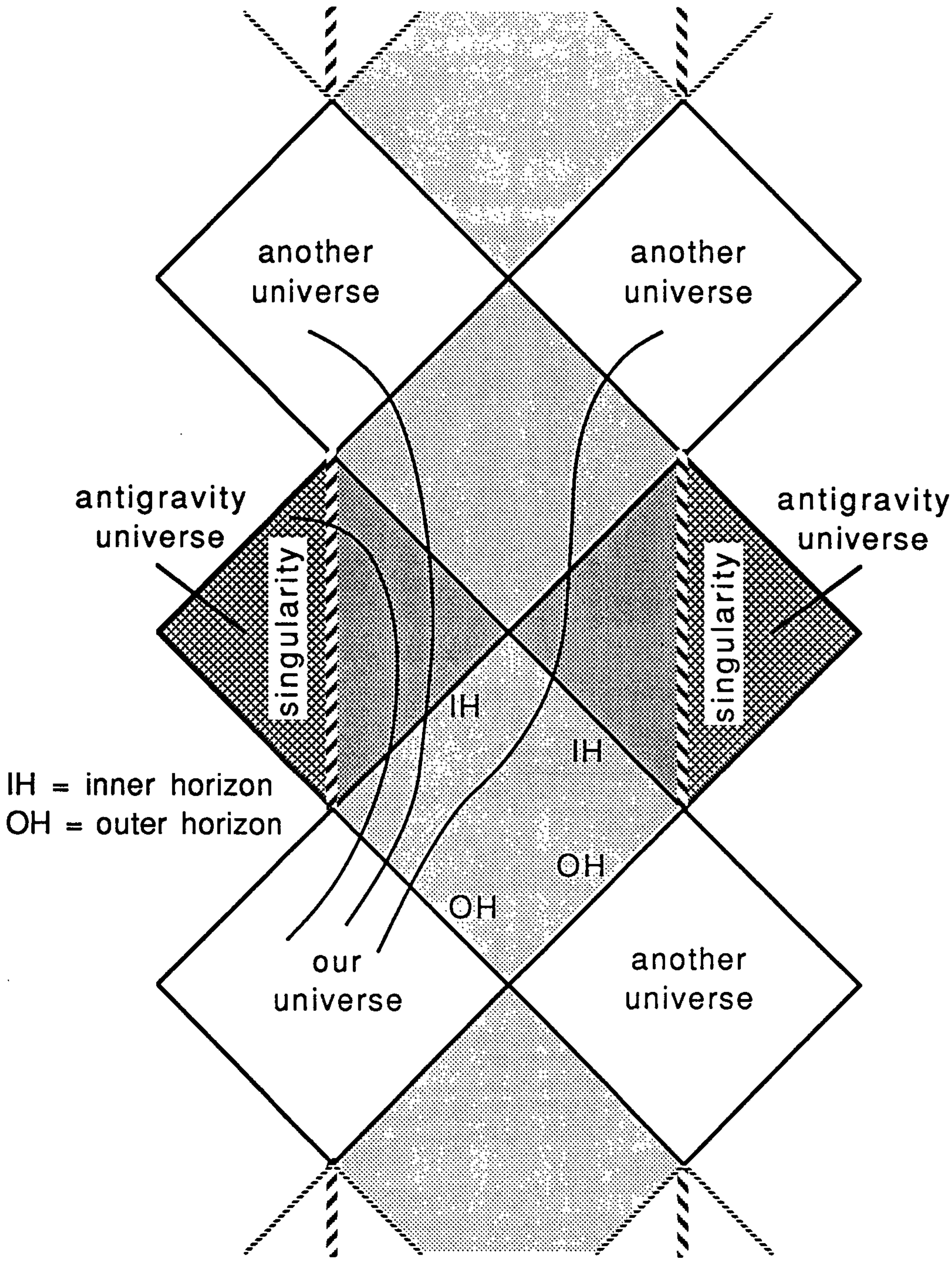


***Figure 11*** Penrose map of a rotating black hole.

If you use a rotating black hole instead of a wormhole, and if you can find a way to tow its entrances and exits around at nearly lightspeed, you'll get a much more practical time machine — one that you can get through without running into the singularity.

**Cosmic String**

If you don't fancy trying to control Kerr black holes, you can settle for a much simpler kind of singularity that has only recently come into fashion: *cosmic string*. This is a static spacetime, so that spacelike sections remain unchanged as time passes. It is best visualised by taking two dimensions of space. Cut out a wedge-shaped sector and paste the edges together. If you do this with paper you end up with a pointed cone; but mathematically you can just identify the corresponding edges without doing any bending. The time coordinate works just as it does in Minkowski spacetime (and to get the right shape for light cones you should identify the edges without making actual cones). If you throw in a third space coordinate and repeat the same construction on every perpendicular cross-section, you get a *line* mass. This is the fully-fledged cosmic string.

To make a model of one, thread lots of identical cones on a length of — well, string. Remember, each cone is a constant-time section of the actual spacetime.

The physical interpretation of this spacetime is that the cosmic string has a mass, proportional to the angle cut out. However, it doesn't behave like an ordinary mass. Everywhere except the cone point, spacetime is locally flat — just like Minkowski spacetime. The apparent curvature of a real cone is 'harmless'. But the cosmic string creates global changes in the spacetime topology, affecting the large-scale structure of geodesics. For instance, matter that goes past a cosmic string is gravitationally lensed, as we'll see in more detail in a moment.

Recent surveys of the distribution of galaxies in or universe has revealed that they clump on vast scales, forming structures hundreds of millions of light years long. This clumpiness is too great to have been caused by gravitational attraction among the known matter. One theory is that the clumps were 'seeded' by real cosmic strings.

A cosmic string is much like a wormhole, because the mathematical glue lets you 'jump across' the sector of Minkowski spacetime that is cut out. In 1991 J.R.Gott exploited this analogy to construct a time machine: more precisely, he showed that the spacetime formed by two cosmic strings that whizz past each other at nearly lightspeed contains CTCs. The starting-point is two static strings, symmetrically placed, as in **Fig.12**, which as usual is a constant-time spacelike section. The time coordinate is suppressed; but if it were added, it would run perpendicular to the page.

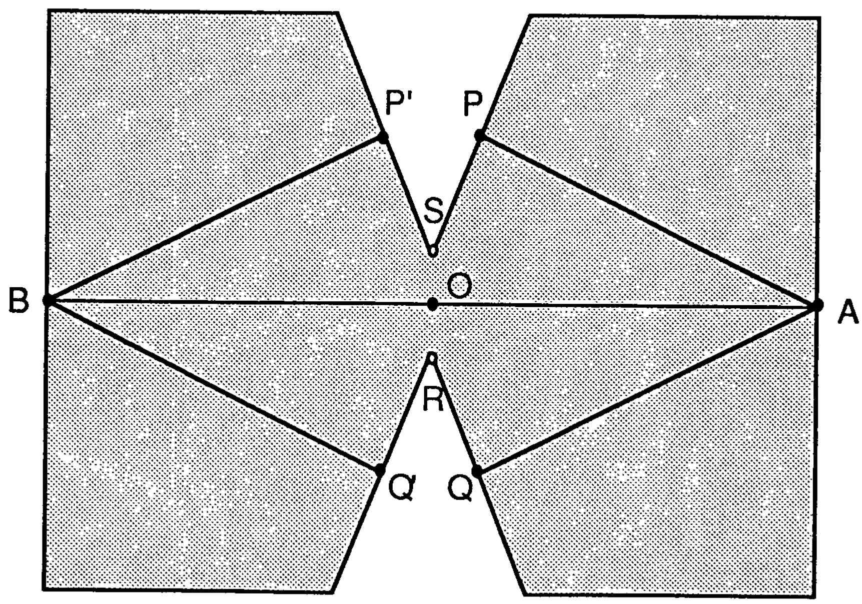


***Figure 12*** Two cosmic strings.

Because of the 'gluing', points P and P' are identical, and so are Q and Q'. The figure shows three geodesics joining two points A and B: the horizontal line AB, the line APP'B, and the symmetrically placed line AQQ'B. This demonstrates gravitational lensing by the cosmic strings: an observer at B would see three copies of A, one along each of these three directions.

Gott calculated that if the two cosmic strings are close enough together, then it takes light longer to traverse the path AB than to traverse the other two. This has an important consequence. If a particle starts from position A but at time T in the past, it can get to B at time T into the future. Call these events A(past) and B(future). If the strings R and S are now made to move, so that S moves rapidly to the right and R rapidly to the left, then A(past) and B(future) become simultaneous in the frame of a stationary observer (thanks to time-dilation).

To construct the required CTC, we make the particle move from A(past) to B(future) passing via PP'; then by symnmetry we make it return from B(future) to A(past) via QQ'. Gott's calculations show that provided the cosmic strings travel at close to lightspeed, this CTC really does exist — mathematically.

Again the question is: can such a scenario be realised physically by a technologically advanced civilisation? The answer would seem to be yes, provided of course that they have the ability to create cosmic strings, or to harness naturally occurring ones. If any natural ones exist, of course, which is moot. But in January 1992 Sean Carroll, Edward Farhi, and Alan Guth found a snag. There isn't enough available energy in the universe to build a Gott time machine. More precisely the universe never contains enough matter to provide such energy from the decay products of stationary particles. So the advanced civilization would need to develop a powerful new energy source.

The clumsy and energy-wasteful devices of relativistic physics are thus still a pale shadow of the elegant machine of Wells's Time Traveller, 'a glittering metallic framework, scarcely larger than a small clock. very delicately made. There was ivory in it, and some transparent crystalline substance.' (Actually this is the description of a miniaturized prototype, but Wells tells us that the actual machine was much the same.)

There's still a bit of R&D to be done.



## FURTHER READING

Andreas Albrecht, Robert Brandenberger, and Neil Turok, Cosmic strings and cosmic structure, *New Scientist* 16 April 1987, 40-44.

Sean M. Carroll, Edward Farhi, and Alan H. Guth, An obstacle to building a time machine, *Physical Review Letters* **68** (1992) 263-269.

Marcus Chown, Time travel without the paradoxes, *New Scientist* 28 March 1992, 23.

John R. Cramer, Neutrinos, ripples, and time loops, *Analog*, February 1993, 107-111.

David Deutsch, *Physical Review D*, October 1991.

Robert Geroch and Gary T. Horowitz, Global structure of spacetimes, in *General Relativity: an Einstein Centenary Survey* (editors S.W.Hawking and W.Israel), Cambridge University Press, Cambridge 1979, 212-293.

J. Richard Gott, III, Closed timelike curves produced by pairs of moving cosmic strings: exact solutions, *Physical Review Letters* **66** (1991) 1126-1129.

John Gribbin, *In Search of the Edge of Time*, Bantam Press, New York 1992.

Jean-Pierre Luminet, *Black Holes*, Cambridge University Press, Cambridge 1992.

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever, Wormholes, time machines, and the weak energy condition, *Physical Review Letters* **61** (1988) 1446-1449.

R.Penrose, Singularities and time-asymmetry, in *General Relativity: an Einstein Centenary Survey* (editors S.W.Hawking and W.Israel), Cambridge University Press, Cambridge 1979, 581-638

Ian Redmount, Wormholes, time travel, and quantum gravity, *New Scientist* 28 April 1990, 57-61.

Frank J. Tipler, Singularities and causality violation, *Annals of Physics* **108** (1977) 1-36.