Forward to the Future 2
Back to the Past, with Interest...

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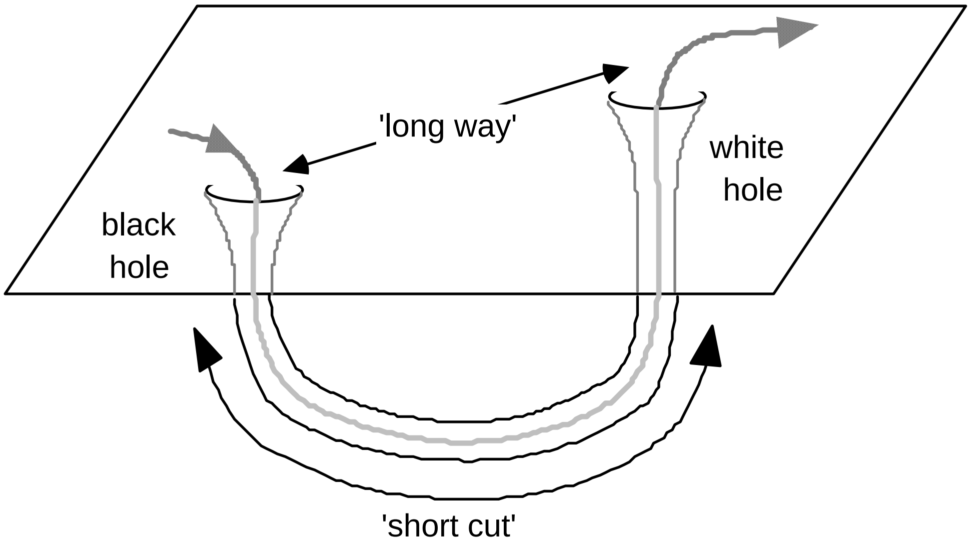
The story so far...

The year is 3001. H.G.Wells's Time Traveller has unexpectedly found himself at the offices of Hawkrose & Penking Heavy Engineering. Very *heavy: they build black holes. His time machine is irreparably damaged, but Hawkrose & Penking may be able to help.. The Time Traveller has been told about Special Relativity, in which the speed of light is constant, and General Relativity, in which gravity is produced by the curvature of space. He knows that in relativity, 'time machine' means closed timelike curve' or CTC, a world-line whose future encounters its own past. An attractive prospect is the twin paradox, in which Rosencrantz stays on earth all his life while Guildenstern travels away at close to the speed of light, and comes back much younger than his twin. 'The time is out of joint' — but is it unjointed enough to make a CTC? Hawkrose & Penking can make a matter-transmitter by connecting a black hole to a white hole to form a wormhole — but matter-transmission isn't time travel. Is it?*

Now read on...

We stared at my picture of a wormhole (**Fig.1**), hoping for inspiration.



Using a wormhole as a matter-transmitter.

"You do realise," I said to the Time Traveller, that people used to think time travel was a theoretical impossibility, a contradiction in terms."

"You are referring to the hoary old 'grandfather paradox'?"

"How *dare* you call my grandfather 'hoary' — oh, sorry, I misconstrued what you said. Yes, the idea goes back to René Barjavel's story *Le Voyageur Imprudent*. You go back in time and kill your grandfather, but because your father isn't born, neither are you, so you *can't* go back to kill him..."

"So you don't so you *are* born, so you do, so..."

"Quite."

"I only thought of that after I made my machine," said the Time Traveller. "I wonder... no, I quite liked the old codger anyway..."

"Don't even think about it," I said. If you think about the problem using Quantum Mechanics, you can easily see it doesn't exist."

"What kind of mechanics?"

"Quantum. New since your day. Quantum Mechanics, the underlying physics of matter, is indeterminate. Many events, such as the decay of a radioactive atom , are random. One way to make this indeterminacy mathematically respectable is the 'many worlds' interpretation invented by H.Everett. This view of the universe is very familiar to readers of science fiction: our world is just one of an infinite family of 'parallel worlds' in which every combination of possibilities occurs. In 1991 David Deutsch noted that, thanks to the many worlds interpretation, quantum mechanics involves no obstacles to 'free will'. Moreover — another standard science fiction trope — the grandfather paradox ceases to be paradoxical, because grandfather will be (or will have been) killed in a parallel world, not in the original one."

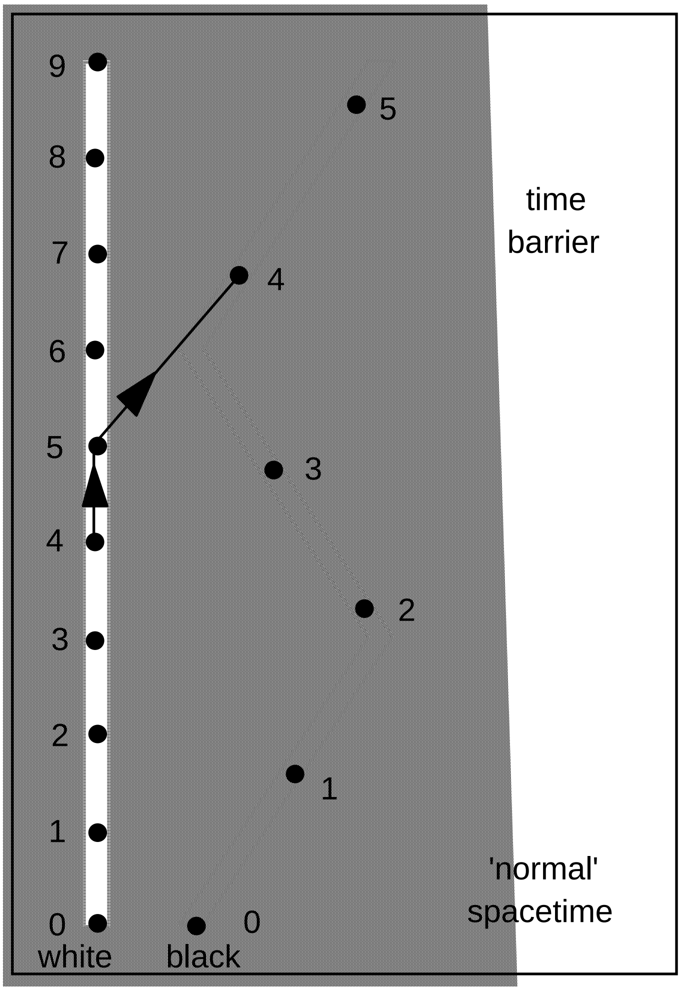
The Time Traveller digested this for a moment. 'That's getting me really worried," he said. "If I do get back to my home time, how can I tell whether I've moved to a parallel universe?"

"Don't worry," I said. "According to the many worlds interpretation, that's what you're doing every time your constituent atoms choose whether or not to change their quantum state. You're switching from this universe to a parallel universe — one for each possible choice of state." An idea of some sort was brewing in my brain; I could feel my subconscious trying to tell me something. But the Time Traveller was so eager to find a way home that I couldn't get enough peace and quiet for it to pop into conscious thought...

"I think we should forget this Quantum Mechanics business," he said, "and return to a simpler question. Is there a connection between wormholes and time machines?"

Of course! Was *that* what my subconscious was trying to tell me? No, I had a strange feeling it involved money... "Sure," I said. "It was noticed way back in 1988, when Michael Morris, Kip Thorne, and Ulvi Yurtsever realised that they could combine a wormhole with the twin paradox to get a CTC. I'd forgotten it until you asked. 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.2 shows how this leads to time travel.



Turning a wormhole into a Time Machine.

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. Notice that the corresponding 'ends' of the wormhole are *not* those with the same *t*-coordinate in Minkowski space, but those with the same 'elapsed time' for an observer that moves with them, as marked by the figures.

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," I told the Time Traveller.

"Wonderful! I can wait several years if necessary."

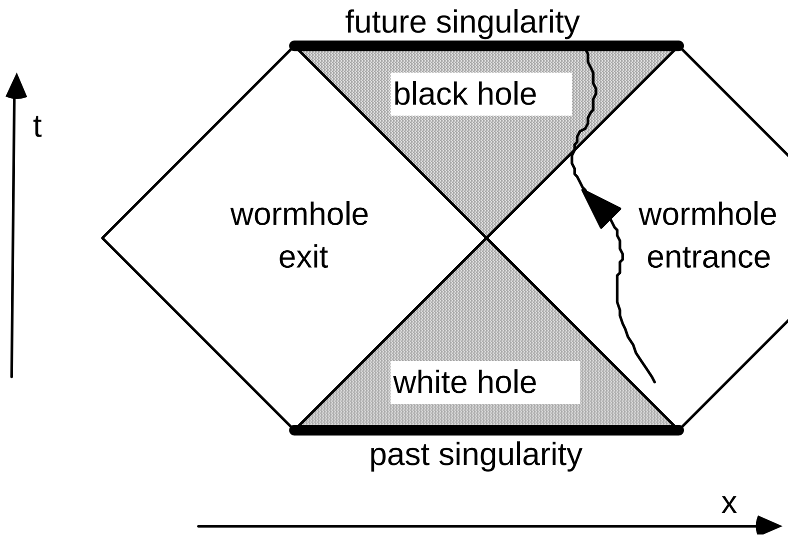
"Ah," I said. "There's a nasty snag. You can never travel back past the time barrier, and that occurs some time *after* you build the wormholes. There's no hope of getting back to your home time." His face fell. So did mine. I'd finally figured out what my subconscious was trying to tell me. It did involve money. But it suffered the same fault.

"There's another problem, too," I said. "Hawkrose & Penking's R&D department is working on it, but all we've got is a laboratory prototype. The question is: can you really *build* one of these devices? Can you really get through the wormhole? We can build the wormhole all right, and move its ends around around. That's just a matter of creating intense gravitational fields, our stock-in-trade.

"But the problem that bothers me most is what I call the 'catflap effect'. When you move a mass through a wormhole, the hole 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."

"Why?"

"The easiest way to see that is to represent the spacetime geometry using a *Penrose map,* invented by the twentieth century mathematical physicist Roger Penrose. 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.3** shows a Penrose map of a wormhole.



The 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."

"Which, you have told me, is impossible," said the Time Traveller.

"Well, maybe not. We're hoping to get round round the difficulty by threading the wormhole with *exotic matter*, exerting enormous negative pressure, like a stretched spring. But in 1991 Matt Visser suggested an alternative geometry for a benign wormhole, and we're going to test it out just as soon as we've located a good source of exotic matter. The idea is to cut two identical cubes in space, and paste their corresponding faces together. Then we'll reinforce the edges of the cube with exotic matter."

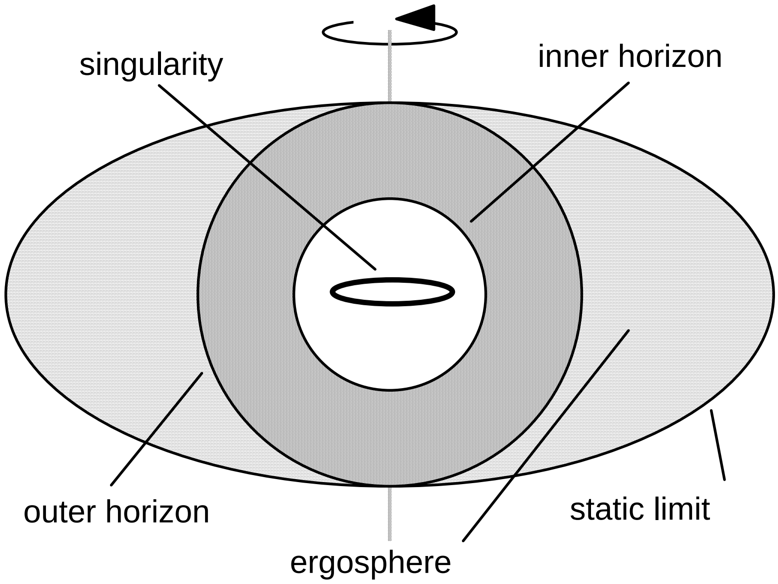
"It sounds complicated," said the time Traveller.

"Sure is. That's what engineers do. Make complicated things work. However, there's a more old-fashioned method that cuts out the need for exotic matter. And because it doesn't involve *building* a wormhole, there's no time-barrier effect. You can go back to any time you want. Depending on what nature has up her sleeve." Lots of money, if we struck lucky...

"I don't follow you," said the Time Traveller, interrupting my beautiful daydreams.

"I'm talking about using a naturally occurring time machine. A *rotating* black hole. Formed when a rotating star collapses gravitationally. The Schwarzschild solution of Einstein's equations corresponds to a *static* black hole, formed by the collapse of a non-rotating star. In 1962 Roy Kerr solved the equations for a rotating black hole, now known as a *Kerr black hole*. (There are two other kinds of black hole: the Reissner-Nordstro÷m 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.

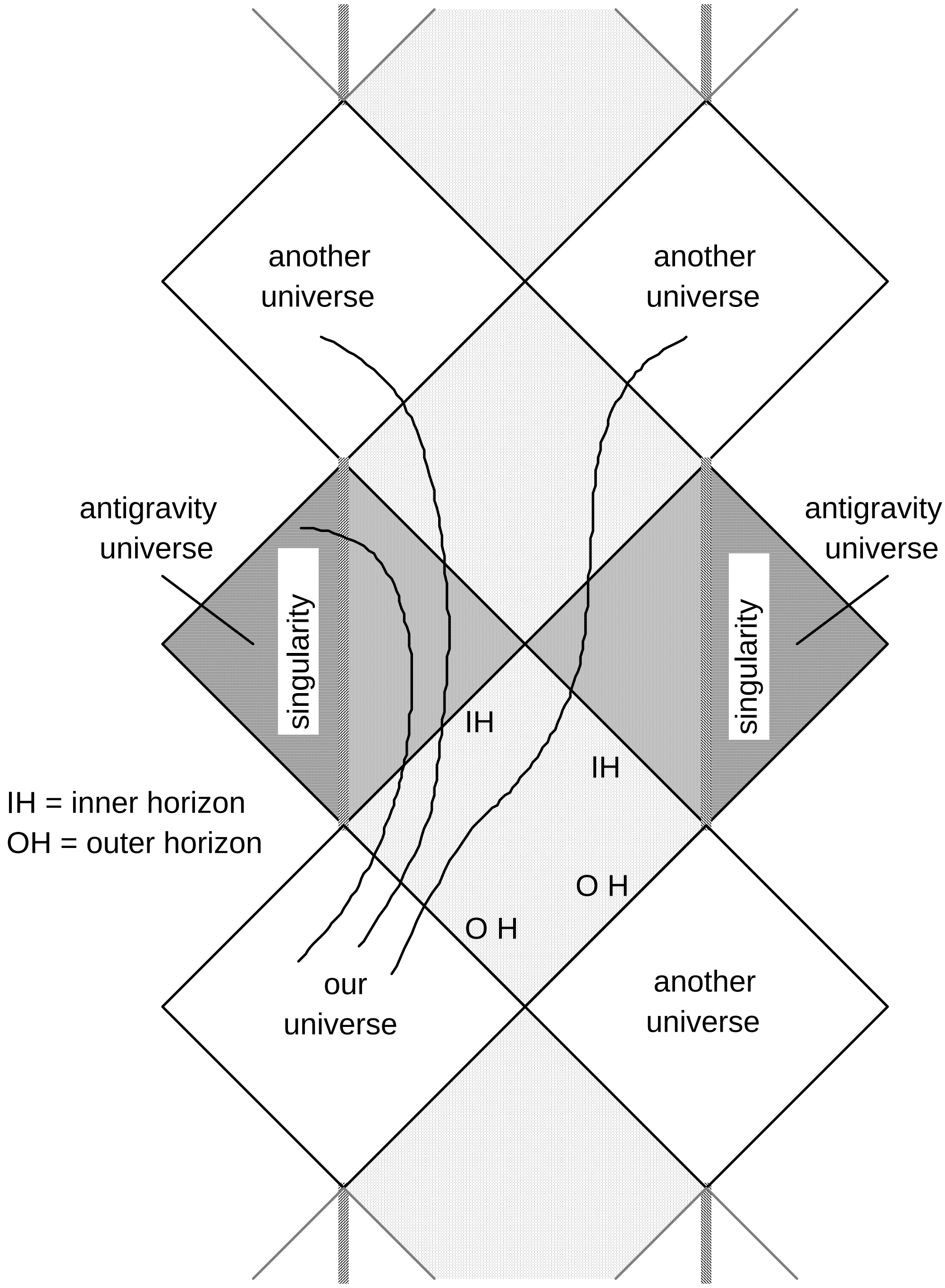
"One is that there is no longer a point singularity inside the black hole. Instead, there is a circular ring singularity, in the plane of rotation (**Fig.4**).



Cross-sectional structure of a rotating black hole.

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; in fact 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.5**.



Penrose map of a rotating black hole.

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.

"If we used a rotating black hole instead of a wormhole, and towed its entrances and exits around at nearly lightspeed with H&P matter-processing equipment, we'd get a much more practical time machine — one that you could get through without running into the singularity."

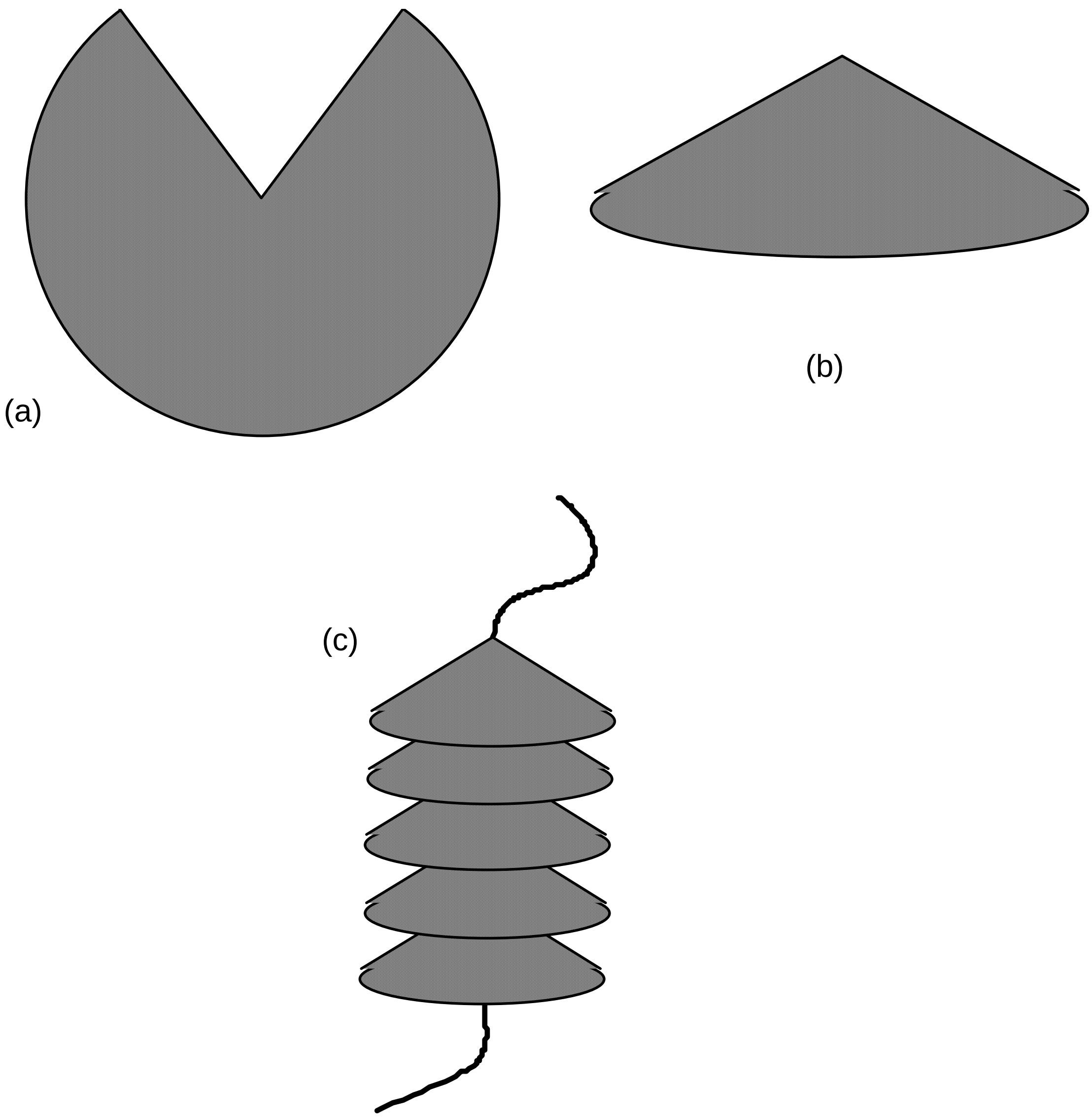
The Time Traveller rubbed his hands together happily. "Then I shall soon be back in my own time. Come, let us prepare the remains of my machine, to accompany me on the return voyage."

"Not so fast," I said. "Let me check with the computer. Oh, bother. There are no rotating black holes within reach."

"But I thought you said wormholes could be used as short cuts through spacetime?"

"Provided they've been built. There's one under construction to the nearest rotating black hole, but the union's on strike and it's not been finished yet." He looked extremely disappointed. Me too. Wait, what had I been watching on the virtual reality hypermedia system the other night? The Comic Thing? No, but something like that. Got it! "I've had an idea, hot off the press. If you don't fancy trying to control Kerr black holes, you can settle for a much simpler kind of singularity: *cosmic string*. This is a static spacetime, so that spacelike sections remain unchanged as time passes."

The best way to visualise cosmic string is to use two dimensions of space. Cut out a wedge-shaped sector and paste the edges together (**Fig.6a**). If you do this with paper you end up with a pointed cone (**Fig.6b**); 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 (**Fig.6c**). Remember, each cone is a constant-time section of the actual spacetime.



(a) Spatial structure of cosmic string (flattened). (b) Identifying the edges of the missing sector to get a cone. (c) Adding an extra dimension of space.

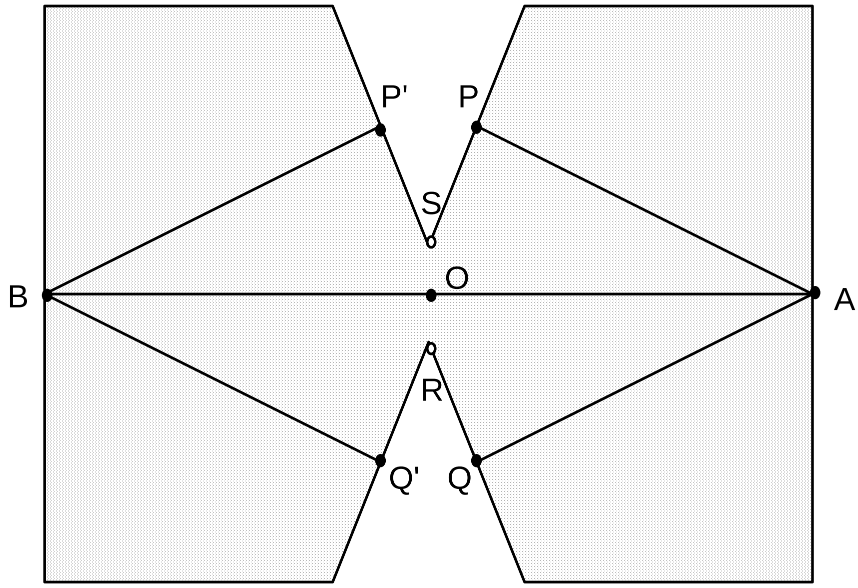
"I'm not sure I fully understand the physical interpretation of a cosmic string as a spacetime," said the Time Traveller.

"Well, basically it's that the cosmic string has a mass, proportional to the angle of the sector that gets cut out. But 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 — particle paths. For instance, matter or light that goes past a cosmic string is 'gravitationally lensed'."

"Pardon?"

"Bent, like light through a conventional lens. I'll explain that in more detail in a moment.

"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. Way back 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.7**, which as usual is a constant-time spacelike section."



Two cosmic strings, opened flat for clarity.

The time coordinate is suppressed; but if it were added, it would run perpendicular to the page.

"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).

"So, to construct the required CTC, we make the particle move from A(past) to B(future) passing via PP'; then by symmetry 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."

The Time Traveller scratched his head and grimaced. "By now I have learned to ask: can such a scenario be realised physically?"

"Well... in 1992 Sean Carroll, Edward Farhi, and Alan Guth proved that 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."

"It seems yet again that I am trapped forever in my own future."

"Not clear. If we could develop a sufficiently powerful new energy source... but I'm afraid that's not in the works yet. However, I recall that 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."

"So?"

"One theory is that the clumps were 'seeded' by naturally occurring cosmic strings. Provided Hawkrose and Penking's data-banks contain the coordinates of a naturally occurring cosmic string remnant — *and* provided there's a wormhole available to transport you there — we may yet be able to send you home." And make me a fortune...

"If so, mother Nature has outdone all of the engineering skills of Hawkrose and Penking."

"Except that you'll need our wormholes to get you to the cosmic string," I pointed out, as I asked the computer to search for a suitable cosmic string with a nearby wormhole link. A few second spassed, and then it chirped at me. "You're in luck," I said. "Catch the 3.25 from Lunar Central on the Betelgeuse line, change at epsilon Aurigae to the Ophiuchi hotline, then grab a local commuter to Aldebaran. I'll call a hovercab, pick up your machine, and buy you a ticket."

"But won't that be expensive?"

"Yes, I said. "Very. A year's salary. However, there's a way you can repay me." As I said this I gave the computer new instructions.

"How?" asked the Time Traveller. "I'd do anything to get back to the end of the nineteenth century."

The printout whirred into motion. I handed him a sheaf of papers. "Here is a complete listing of the stockmarket prices for major stocks over the entire period 1895-2999. I want you to start a trust fund in my name. Invest one franc in an account with the Bank of France — it's still in existence today and it was in your time too — and use that printout to make sure that the investment grows *very* fast. Understand?"

"Of course. If you can predict the future of the market, your fortune is guaranteed."

"Exactly. Well, provided we don't get switched to a parallel world. But then, in the past parallel world whose future will become this one, parallel versions of us are probably doing the same thing. There's a lot of convergence to history. I'm willing to risk it. Now, set up a board of trustees to make sure the system keeps working. Take 50% of the profits as an operating fee. Set the trust fund to mature on 27 January 3001 — tomorrow — on presentation of my signature. Here's a specimen signature to put on record."

"But what if I cheat and keep all the money?" he asked.

"I may just have to come back to the nineteenth century and convince you not to," I said.

"Oh. Right. Don't worry, I'll do what you ask." The hovercab arrived, and he left.

I have a gambling streak to my nature. I'd invested a year's salary getting him back to his own time. But if the gamble pays off... well, let's say I've got an important date tomorrow at the Bank of France.

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