# Forward to the Future 1
# *Trapped in Time!*

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I was just finishing up my shift at Hawkrose & Penking Heavy Engineering when I heard a faint whining noise. It seemed to be coming from the virtual reality simulation area. The place gets pretty dead late in the evening, and I was the only person around. I had little choice but to find out what it was — but I was nervous, I can tell you. It could have been a cyberspatial break-in. Physical security is unbeatable in the year 3001 — we have DNA-sensitive robot guards, for example — but electronic security is another thing altogether. There are just too many smart crooks with electronics training.

The room was full of an acrid smoke. It had to be a physical break-in, which was impossible. I started to sweat. The smoke began to clear.

There was a strange contraption in the middle of the room, a delicate framework of shiny metal, glass, and what appeared to be off-white plastic. It had an old-fashioned look. A man was sitting in the middle of it, hidden inside a black cloak. He moved.

"Security," I shouted. "This room is sealed. Come out with your hands raised. Do not touch any lasers, phasers, rocket-launchers, or other weaponry, or you will be instantly annihilated by our biocybernetic defence systems." I was bluffing, but maybe he wouldn't know that. He climbed out. "Identification?" I asked.

"Uh — you want to know my name, sir?"

He sounded polite, and rather old-fashioned. What was he trying to pull? "Identify yourself immediately," I said.

"You may call me the Time Traveller. I am a friend of a Mr. Herbert Wells."

Herbert — wait, did he mean Herbert *George* Wells? H.G.Wells, the famous science fiction writer? "Yeah, and singularities grow on trees." I spread him out against a wall and searched him. I found some very strange items, including a quill pen. I looked closely at the machine. It was made of steel, tin, glass, and crustal, with beautifully engineered brass fittings. Some parts were made of a white plastic material which I couldn't place.

I knew his story made no sense — but somehow it sounded convincing. There was a kind of *ancient* feel to the equipment, a genuine antique. You can't fool me when it comes to engineering.

"Suppose that on a whim I pretend to believe you," I said. "How did you get here and why?"

"I had no choice. I was on my way to the distant future when I smelt smoke. I turned off the machine, but too late. The temporal selection gear has stripped its teeth." He fiddled inside the machine for a moment and pulled out a very sad-looking disc of the plastic stuff, a wisp of smoke still rising from it. "Perhaps you could make me a new one."

"That depends," I said. "On what sort of plastic you need."

"Excuse me, but what is 'plastic'?"

He was either a very good actor or he was telling the truth. He didn't know what plastic was. I said "White stuff, like that."

"Oh, this? This is ivory."

At that moment I became convinced. *Nobody* in 3001 could get hold of ivory. For one thing, trade in the stuff had been prohibited for a thousand years. For another, the last epehant was killed by poachers nine hundred and fifty years ago. What ivory remained was in museums, priceless, and had aged to a dull yellow. This stuff was *fresh*.

"Not a hope," I said, explaining why. The Time Traveller looked close to tears. "Then I am trapped," he whispered.

"Maybe, maybe not," I said. "If there's a way, Hawkrose & Penking will find it. Now, tell me how this contraption works, and I'll see what we can come up with."

"You may recall that in the 1894-5 issue of *The New Review* my friend Mr. Wells published a story called 'The Time Machine'."

Asd it happened, I did. My hobby is ancient literary history. "Of course. I've always felt it was fitting that the magazine couldn't decide which year to be published in."

"It was based on a true invention. Mr. Wells himself explained the main idea, when he said that 'There is no difference between Time and any other of the three dimensions of Space except that our consciousness moves along it.' This machine moves in a different direction from our consciousness, that's all. When it works."

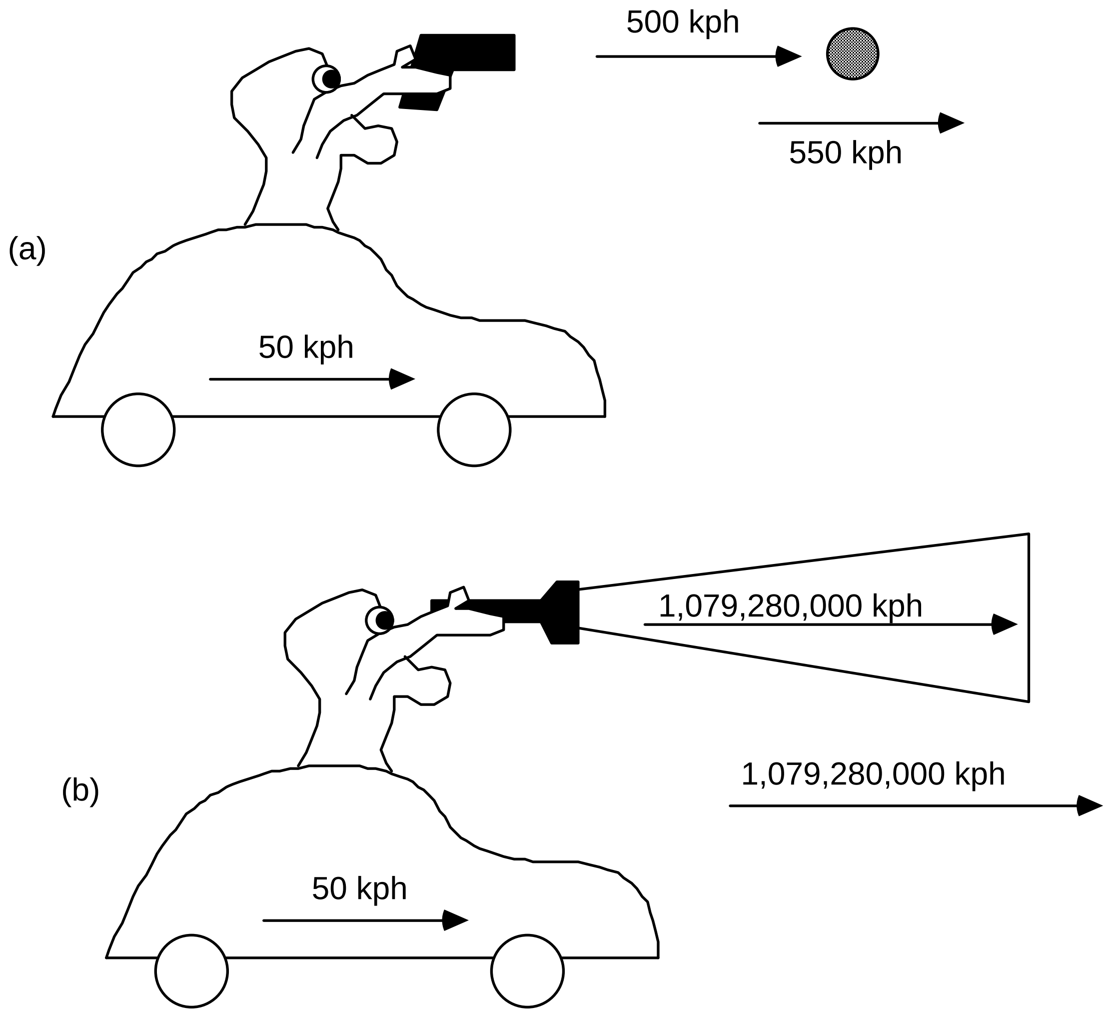
"Interesting," I said. "Not entirely true, but interesting."

"Not entirely true?" So I had to explain to him some basic relativity, the kind the kids get in third grade. Starting with Special Relativity.

"The main thing to remember," I said, "is that 'relativity' is a silly name."

"Then why use it?"

"Historical accident," I said. "We're stuck with it. Unless you can get your machine working, go back, and persuade Einstein to invent a better one." I explained that 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 kph and you fire a gun forwards, so that the bullet moves at 500 kph relative to the car, then it will hit a stationary target at a speed of 550 kph, adding the two components (**Fig.1a**). However, if instead of firing the gun you switch on a torch, which 'fires' light at a speed of 1,079,280,000 kph (2.998 x $10^5$ kps), then that light will not hit the stationary target at a speed of 1,079,280,050 kph. It will hit it at 1,079,280,000 kph, exactly the same speed that it would have had if the car had been stationary. (**Fig.1b**)




(a) In Newtonian mechanics, relative velocities combine by addition.

(b) In Relativistic mechanics, the speed of light is constant.

"You can prove this for yourself," I told him. "You need a cardboard box about the size of a shoebox, a torch, and a mirror."

"Cardboard? Torch?"

"Oh, heck — use a wooden box and a lantern. 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 1,079,280,000 KPH' on the bottom of the inside of the box. Stand still, close the flap, aim the lantern 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 1,079,280,000 kph both times..."

"That," said the Time Traveller haughtily, "is a silly experiment."

"True. 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. If Newtonian physics were correct, that motion would show up as a difference in the apparent speed of light when the Earth was at opposite points of its orbit, moving in opposite directions. But they couldn't find any difference in the speed at all, even with very sensitive equipment."

"Yes, I know about their work. It seemed to me that all it proved was that the Earth must carry the ether along with it when it moves in orbit."

That had never occurred to me. "It's a cute theory. But you'd expect to see funny effects in the light from distant stars if the ether was swirling around like that. Michelson and Mroley came to the conclusion that either there isn't an ether at all, or the Earth *isn't* moving relative to it — which is not very credible — or that there's something pretty weird about light."

"Oh."

"A physicist called Albert Einstein is generally credited with the theory — called Special Relativity, as I said — that there's something pretty weird about light. He published it in 1905. 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. 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 approach the speed of light, time slows down to a crawl, and mass becomes infinite."

"It is difficult to credit such a strange tale."

"You arrive in the middle of this building in what you claim is a Time Machine, and you say I'm telling an incredible story?"

"Well, when I started out this building didn't exist. Anyway, I'm here."

"Yes. And so is Special Relativity. Now, I admit 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.

"Precisely *because* relativity is about the non-relative behaviour of light, everything in it depends heavily upon which 'frame of reference' used by an observer. Moving and static observers see the same events in different ways."

"That I understand. The Time Machine works on just such a principle."

"Yeah, right. 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.2a**). The horizontal coordinate, *x*, determines a particle's position in space; the vertical coordinate, *t*, determines its position in time."

"But that is what I told you!" the Time Traveller said excitedly. "Time is just a fourth dimension!"

"Yes, but there's an extra wrinkle that you won't have realised. Let me continue. In full-blooded Minkowski spacetime *x* is three-dimensional; but for convenience let's pretend it's one-dimensional. Later on I'll have to represent space as being 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 constant, 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?"

"Um — light?"

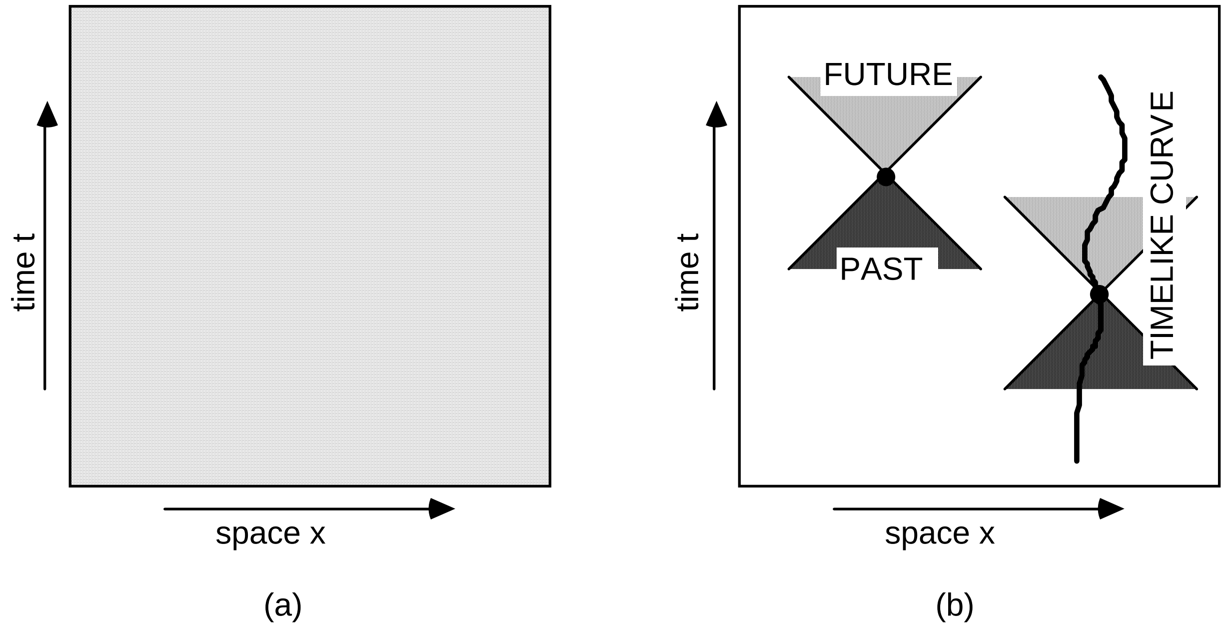
"Of course. So 45_ world-lines correspond to particles of light — light rays or photons — or anything else that can move at the same speed."

"Particles of light?"

"Look, just accept it as an image, OK? Think of light rays, if it makes you feel more comfortable."

"As you wish. My head is starting to ache."

"You ain't seen nuthin' yet. Now, relativity forbids bodies that move faster than light. The mathematical reason is that their lengths would become imaginary — involving the number i = œ-1 — as would masses 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.2b**).




Minkowski spacetime.

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.

"Now, 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

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

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

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

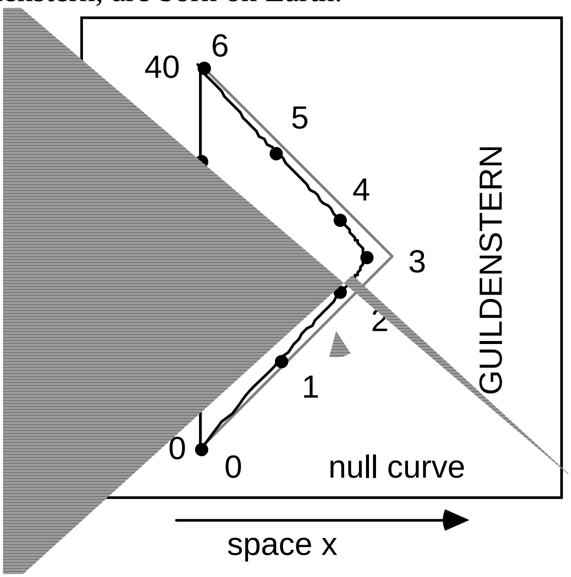
Note the minus sign: time is special. That's where H.G.Wells went wrong. Time is another dimension, but it's not like the spatial dimensions. Though it can get mixed up with them, to some extent, as I'll explain in a moment. At any rate, the main point to understand is that along the lines of 45_ slope where $(x-X)^2 = (t-T)^2$, the interval is *zero*. Those 45_ lines are called *null curves*."

"I see that. But what does this 'interval' represent?"

I told him that 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.

"It seems to me that time is somewhat mutable in this theory," said the Time Traveller thoughtfully.

"That's true. In fact, in 1911 Paul Langevin pointed out a curious feature of special relativity, known as the *twin paradox*. Suppose that (**Fig.3**) two twins, Rosencrantz and Guildenstern, are born on Earth.




The Twin Paradox.

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."

"But surely," said the Time traveller, "The situation is symmetric. In Guildenstern's frame, it is Rosencrantz who seems to travel at nearly the speed of light. So by the same argument, it is Rosencratz who ages less. And that is absurd."

"That's why people think it's a paradox. But it isn't It only seems paradoxical if you don't actually look at a spacetime diagram, because then you may think 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. Acceleration is *not* a relative quantity in Einstein's theory. Like I said, 'relativity' is a silly name."

The Time Traveller shook his head slowly — I couldn't decide whether he didn't believe what I was saying, or was overawed by its intellectual depth. "But it is only a theory, of course," he said, almost to himself. "Reality is not like that."

"Oh, but it is! The effect was tested back in the late twentieth century, by transporting atomic clocks around the Earth on jumbo jets. Of course, aircraft are so slow compared to light that the time difference observed (and predicted) is only the tiniest fraction of a second."

"Um," said the Time Traveller. "Jumbo jets? Atomic clocks?"

"Just take my word for it, my friend: *it happens*."

"So you are telling me that 'the time is out of joint', to continue your Shakespearean motif. *Hamlet*," he added as an afterthought.

"Precisely. So it ought to be possible to exploit the out-of-jointness to make a time machine."

"I did."

"Yes, but without that ivory gizmo we're going to have to use conventional physics, which means relativity. And to do that, we're going to have to understand Einstein's approach to gravity."

"What does gravity have to do with time travel?"

"Everything. Though I admit it's not obvious. You see, Einstein invented another theory, called General Relativity, which was a synthesis of Newtonian gravitation and Special Relativity. You know what Newton said about gravity?"

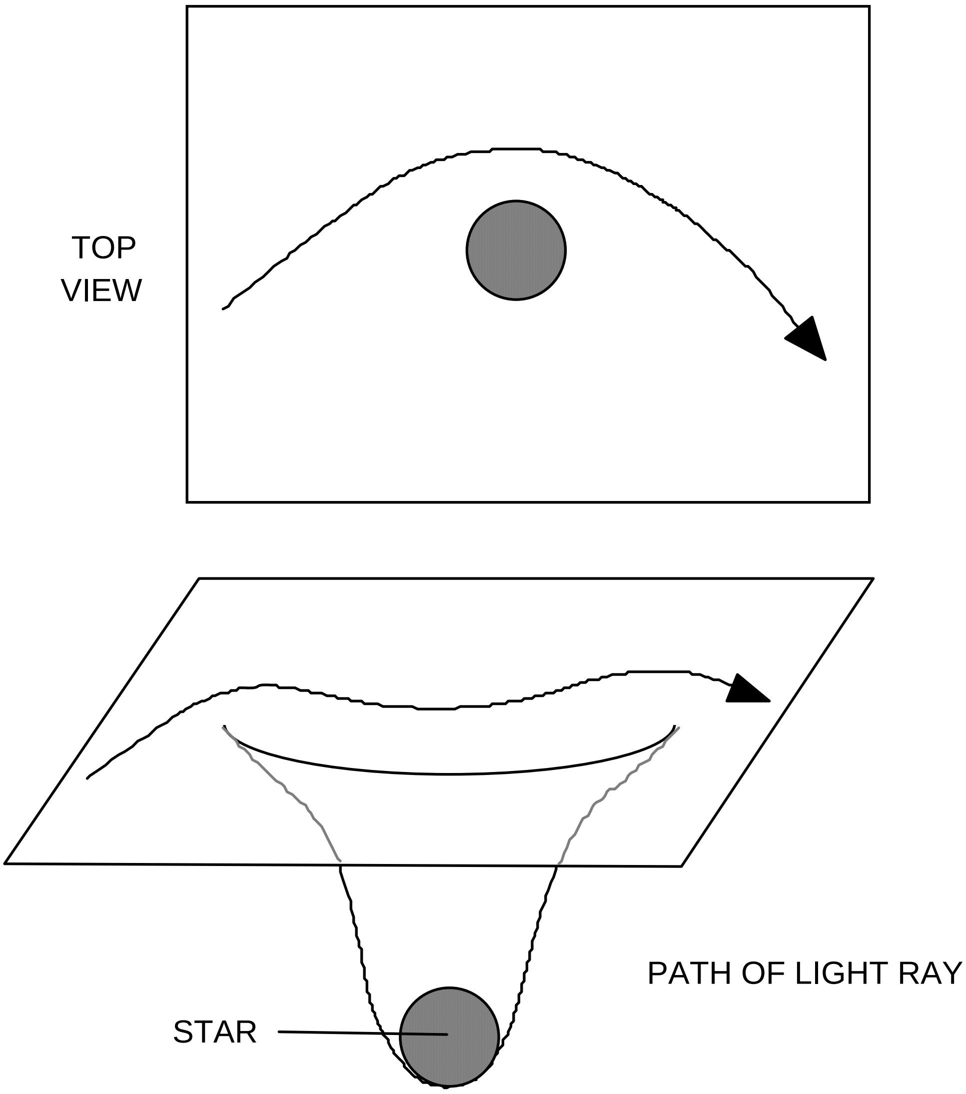
"Naturally. It is a force that moves particles away from the perfect straight line paths that they would otherwise follow. The force exerted by any particle of matter varies inversely as the square of the distance."

"OK. But let's think geometrically. The paths that particles follow, in the absence of any forces such as gravity, are *geodesics*. That is, they are shortest paths, they minimize the total distance between their end points. In flat Minkowski spacetime, the analogous relativistic paths minimize the interval instead. The problem is to add in effects of gravity consistently. Einstein incorporated gravity not as an extra force, but as a distortion of the structure of spacetime, which changes the value of the interval. This variable interval between nearby events is called the *metric* of spacetime. The usual image is to say that spacetime becomes 'curved'."

"Curved round what?"

"It's not curved round anything. It's just intrisically distorted compared to flat spacetime. You might as well ask 'flat along what?' about ordinary Euclidean space, it's just as sensible — or silly — a question. 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 — very powerful and very distant cosmological objects — produce multiple images in telescopes because their light is lensed by an intervening galaxy."

**Fig.4** illustrates this idea by showing a spacelike section of spacetime (that is, one taken at a 'fixed' instant of time) near a star.



Bending of light by gravity.

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.

"Far from the star," I told him, "this spacetime is very close indeed to Minkowski spacetime; that is, the gravitational effect falls off rapidly and soon becomes negligible. Spacetimes 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."

The Time Traveller digested this information. "So I can give spacetime any form I wish? That sounds implausibly flexible."

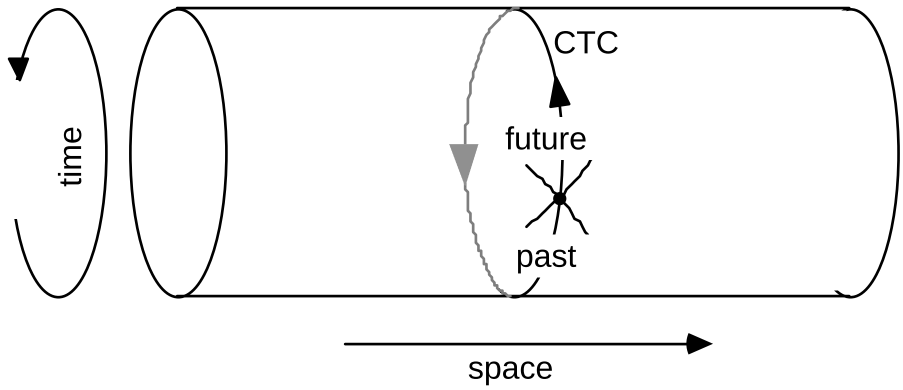
"No. When setting up a spacetime, you can't just bend things any way you like. The metric must obey the *Einstein equations*, which relate the motion of freely moving particles to the degree of distortion away from 'flat' Minkowski spacetime."

"I see. There is a connection between the distribution of masses within the spacetime, and the structure of the spacetime itself. As if matter creates and moulds its own space and time."

"Precisely. And now I can explain how twentieth century physicists interpreted the phrase 'time machine' within the framework of General Relativity." I could see his interest suddenly increase. He was no longer listening just out of politeness. "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?'."

The Time Traveller leaned forward nervously, and his eyes narrowed. "And can they?"

"Well, 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.5**).




A simple example of a spacetime with a CTC.

Then the time coordinate becomes cyclic."

"You mean history repeats, as in Hindu mythology?"

"Sort of. Spacetime repeats; what happens to history depends upon whether you think free will might be in operation. It's a tricky question and one that Einstein's equations don't really address. They just govern the overall coarse structure of spacetime.

"Although a cylindrical spacetime *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 isn't folded or wrinkled. A creature that was confined purely to the surface wouldn't notice that it had been bent, because distances *on* the surface wouldn't have 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*."

The Time Traveller sighed. "Another new word."

"Topology is a flexible kind of geometry — it studies the properties of shapes that persist when the shape is continuously deformed. Like the presence of holes, say, or knots."

"Ah. In my day this was called analysis situs. It was very new."

"Well, now it's very old and very respectable. Rolling up Minkowski spacetime is an example of a powerful topological 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."

"You are speaking metaphorically, of course."

"Well, until recently I'd have agreed with you. But when Hawkrose & Penking describes itself as a 'heavy engineering' company, it really does mean *heavy*. *Extremely* heavy. But I'm getting ahead of myself."

"Like me." I laughed politely: in his position I'd have had trouble producing any joke, however feeble.

"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 talking about intrinsic curvature, as experience by a creature that lives in the spacetime; not about apparent curvature as seen in some external representation. Apparent bending of this type is 'harmless' — it doesn't actually change the metric. Now, 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*."

"I see that. There is a very important distinction between what is mathematically possible and what is physically feasible."

He was quick, I'll hand it to him. "Yes. 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. Which is where the heavy engineering comes in. Unfortunately for you, there's no 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. 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.

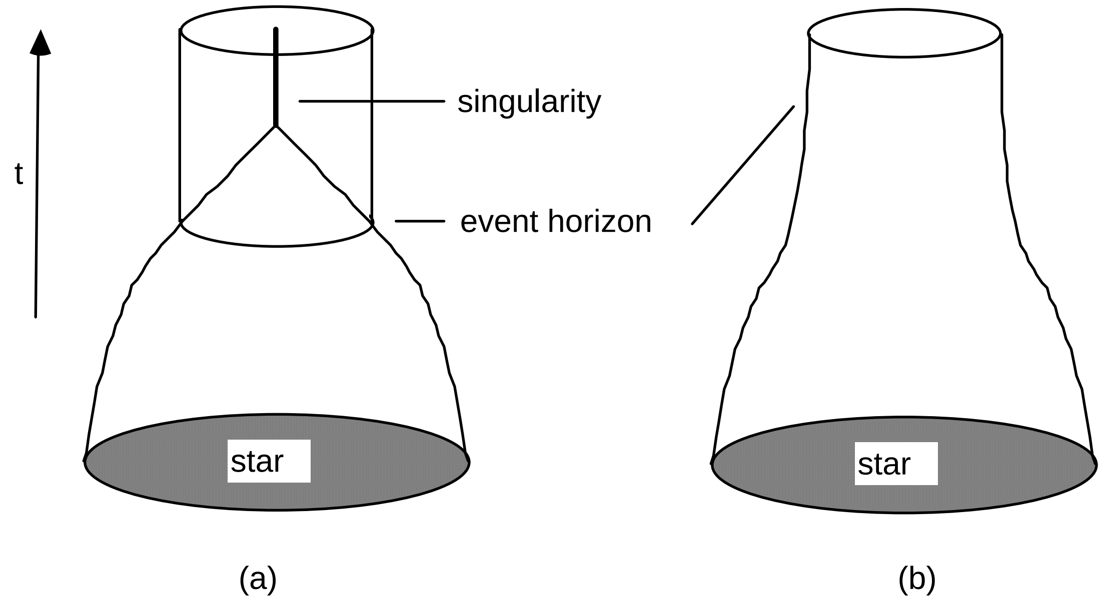
"However, you can get to some remarkably interesting ones. In classical Newtonian mechanics, there is no limit to the speed of a moving object. Particles can escape from an attracting mass, however strong its gravitational field, by moving faster than the appropriate escape velocity. In an article presented 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."

"That is a remarkable idea."

"You said it. They were both 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.

The development over time of a static — non-rotating — black hole is shown in **Fig.6**, in which space is represented as two-dimensional and time runs vertically from bottom to top.




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

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.6a** 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.6b**. 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.

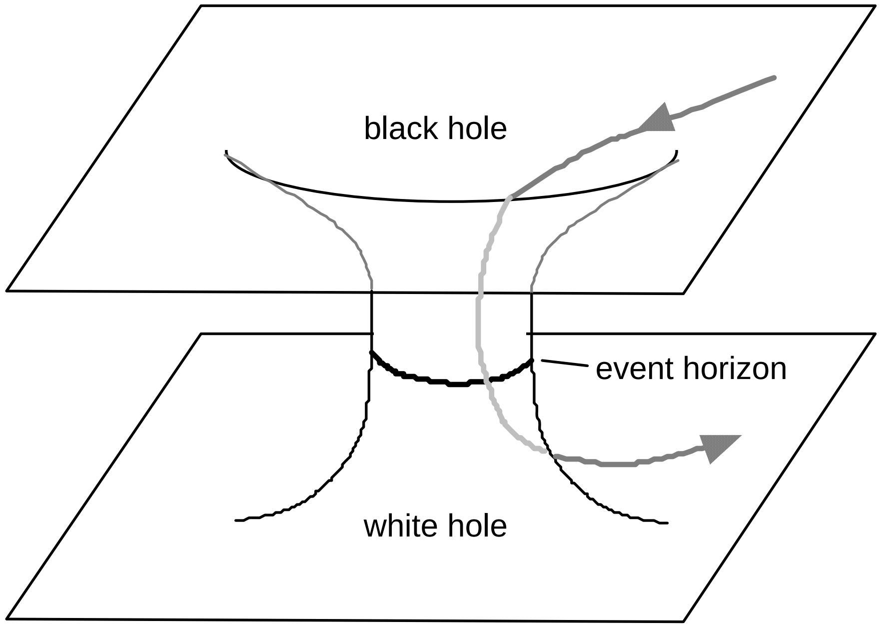
"That's where scope for engineering comes in," I said. "Hawkrose and Penking have developed a whole battery of techniques, from quantum foam enlargement to improbability calculus. Because the spacetime topology of a black hole is asymptotically flat — like Minkowski spacetime at large distances — it 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. That's what I mean by heavy engineering. The technology of 3001 can *build* black holes. We use matter-processors — modified neutron stars mostly, with gravitational traps and heavy-duty laser-compressors.

"However, a static black hole doesn't possess CTCs. The next step is to notice 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.6 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."

"Why should the singularity inside a white hole suddenly decide to spew forth a star, having remained unchanged since the dawn of time?" protested the Time Traveller.

"Good point. It makes sense for an initial concentration of matter to collapse, if it is dense enough, and thus to form a black hole; but the reverse seems to violate causality. It doesn't, of course — but the cause lies outside our own universe, so we don't see the result coming. 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. Hawkrose & Penking have just developed an effective method for doing that, based on the uncertainty principle. We use a Heisenberg amplifier to make the position of matter so uncertain that it may well be outside the normal universe altogether.

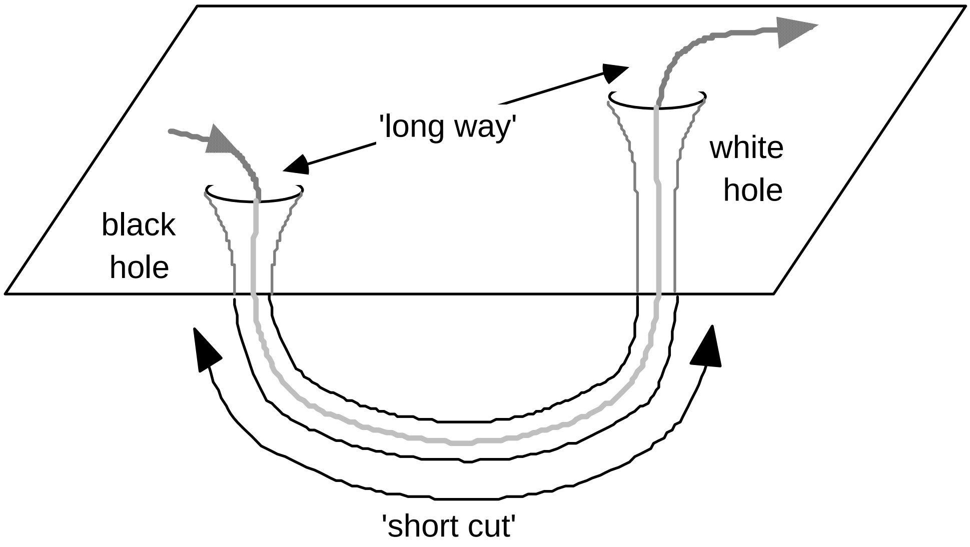
"Not only that: we can glue a black hole and a white hole together. We cut them along their event horizons with a cosmotome and sew the edges together with cold dark matter. The result (more accurately, a fixed spacelike section of it) is shown in **Fig.7**: a sort of tube.




A wormhole.

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.

"Because the topology of Fig.7 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*. Hawkrose and Penking make the best wormholes in the universe," I said with pride. "They're called wormholes because they look like the holes a maggot bores in an apple. Only here the apple is — well, not so much spacetime as everything that's *not* spacetime." A wormhole is shown schematically in **Fig.8**; 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.




Using a wormhole as a matter-transmitter. (The length of the wormhole is exaggerated in the picture because the picture is drawn in normal spacetime. It can actually be very short, even if the ends are far apart in 'normal' spacetime, because distance is intrinsic to the spacetime in the wormhole.)

"I see. A wormhole is a short cut through the universe."

"Right," I said. "But that's *matter-transmission*, not time travel."

"But is has some connection with time travel?" the time Traveller asked, his fingers shaking.

"Well," I said, "that'd be *telling*..."

(*To be continued*...)

**FURTHER READING**

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