features

Einstein's equations of relativity do not rule out "closed time-like curves", bizarre trajectories in space-time that might allow us to travel backwards in time. What are the physical constraints on such "time machines" and what are the possible repercussions?

The physics of time travel

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The Queen bawled out, "He's murdering the time! Off with his head!"
Lewis Carroll

TIME travel has traditionally been the domain of science fiction, not physics. Fortunately, however, at least within Einstein's theories of relativity, discussions of time travel are open to physicists as well. Special relativity unifies the concepts of time and space. General relativity goes beyond unification and allows time and space to warp together in the presence of matter. General relativity even permits sufficient warping to allow "closed time-like curves". These seemingly perverse trajectories describe paths through space-time that always move forward in local time (i.e. an observer's watch always runs forward), but eventually end up back where and *when* they started. A space-time that contains closed time-like curves, localized in one region, can be said to have a "time machine".

Closed time-like curves appear in explicit analytical solutions to the Einstein equation of general relativity. Previously such solutions were deemed "unphysical", simply because they contained closed time-like curves. Nevertheless, since these solutions obey the field equations, they should not be rejected out of hand. Indeed, interest in closed time-like curves has increased in the past decade. The reasons for this are varied, ranging from the practical (if time machines can be built, they would have a lot of potential uses), to the theoretical (perhaps quantum gravity can say something about the existence of closed time-like curves, or vice versa) to the philosophical (do the laws of physics allow or prohibit closed time-like curves?).

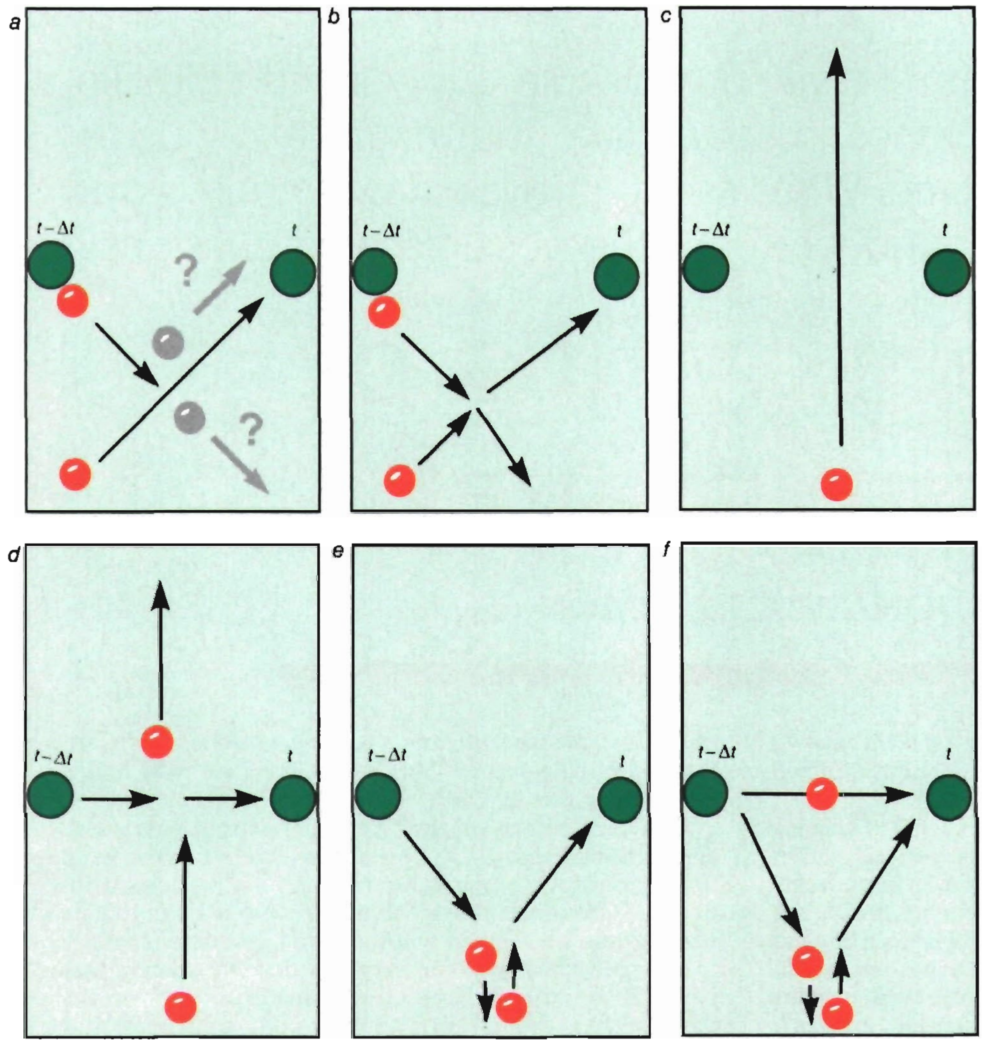
Travelling forward in time is easy and does not require much new physics. In Newtonian physics with its absolute background time we all travel forward in time at the rate of one second per second. Special relativity allows us to travel forward in time at faster rates. The so-called twin paradox is an excellent example. While one twin remains at home in an inertial frame, the other zooms off into the Universe, and then back home, at relativistic speeds with time dilated by a factor of $1/(1-v^2/c^2)^{\frac{1}{2}}$ each way, where v is the travelling twin's speed and c is the speed of light. On returning home the travelling twin, having experienced much less passage of time than the stationary twin, has "gone into the future" relative to the first twin and all other occupants of Earth.

This form of forward time travel happens quite naturally all the time. High-energy particle showers formed in the upper atmosphere by cosmic rays contain particles whose lifetimes are much shorter than the time it takes them to reach ground level, but whose speeds are extremely close to the speed of light. The very fact that we observe these particles at ground level means that their rate of time passage has dilated or, equivalently, that they have travelled into their future.

Although going into the future is straightforward, we also need to go into the past – which is difficult – to make a closed time-like curve. This is where general relativity – or, more precisely, the possibility of non-trivial space-times – is required. Conversely, if closed time-like curves exist, then a traveller can go back into the past. (Note that there is a distinction between going back into the past, discussed here, and going "backwards in time", that is having one's watch tick backwards, which is a separate issue with its own physics). There is currently no evidence that closed time-like curves exist. For instance, we do not see future tourists coming back to visit the present. However, it is not in the tradition of physics to turn the argument around and use this lack of evidence to argue that they cannot exist.

What about the paradoxes of time travel? Can they be used as evidence against the existence of closed time-like curves? The most serious of these is the "grandparent" paradox. In this scenario a time traveller goes back in time and kills his or her grandparent before he or she has any children. This would be a true paradox. One resolution to this paradox is to postulate that only self-consistent histories are allowed. With this postulate the rules of the game are turned around. We can ask whether a particular physical theory allows self-consistent evolution that is also consistent with its equation of motion.

We should also be aware that many physical theories with different equivalent formulations (such as the Schrödinger and Feynman formulations of quantum mechanics) can give different results in the presence of



1 (*a*) A billiard table time machine. When a ball enters the right-hand pocket at time *t* an earlier version of the same ball is released from the left-hand pocket with the same speed at an earlier time $t-\Delta t$. The direction of the earlier version is the reflection of the incident direction about a line connecting the point of entry into the pocket with the centre of the pocket. Although there is only one ball, two or more versions of the same ball can be on the table at certain times. The trajectory shown here is not self-consistent because the ball collides with the earlier version of itself at such an angle that it cannot enter the right-hand pocket. (*b*) A self-consistent trajectory for the initial conditions shown in (*a*). The ball sets off in the same direction as before but collides with the earlier version at an angle which does not prevent it from entering the right-hand pocket. (*c–f*) Four (of an infinite number of) self-consistent trajectories with the same initial conditions. The number of passages through the time machine varies from solution to solution

closed time-like curves. Therefore when determining the effect of closed time-like curves on a particular theory, we have to define the theory very carefully.

Classical behaviour

In avoiding the grandparent paradox, the self-consistency postulate at first seems to violate our concept of free will. It is difficult to imagine oneself as a time traveller when one is not allowed to make choices which might cause a paradox. But this is a bit of a red herring – this same lack of free will already exists in ordinary Newtonian mechanics, or in any deterministic theory: once the initial values of the fields and derivatives are specified, there is no room for free will. In this sense free will is not usually addressed in physics. Still, what might happen if a time traveller did actually meet a grandparent, having decided to kill him or her beforehand? There are many possible outcomes: the time traveller could feel remorse and decide against it; the grandparent could convince the traveller not to; or the time machine might break in anticipation of the event. The problem here seems to be that human beings have too many degrees of freedom to keep track of. Fortunately the fundamental physical issues are still present for a much simpler system – the billiard ball.

As a simple example of a time machine, due to Joseph Polchinski while he was at the University of Texas, we use a specialized billiard table with two pockets. Any object that falls into the right-hand pocket at time t is shot out of the left-hand pocket at an earlier time, $t-\Delta t$, with the same speed but a new direction (figure 1*a*). This time machine could be implemented using a space-time "wormhole" – a shortcut in space-time (of non-trivial topology) which connects two distant points by a shorter path. The points connected may be separated in time as well as space (see figure 2). Wormholes have not been observed yet but are allowed by the Einstein equations.

However, the trajectory in figure 1*a* is not self-consistent – if the ball enters the right-hand pocket at time t, it exits the left-hand pocket at an earlier time, $t-\Delta t$, and this earlier version of the ball collides with the current version, preventing it from reaching the right-hand pocket in the first place. This captures the bare essence of the grandparent paradox. This system has been analysed in great detail by Fernando Echeverria, Gunnar Klinkhammer and Kip Thorne at Caltech who have found answers to these questions, but have raised new, even more interesting, questions in the process. Their analysis is completely classical and non-relativistic (with the obvious exception of the time machine linking the pockets).

The resolution of the paradox in figure 1*a* is straightforward – if the ball moves off at the same angle, but only receives a glancing blow from the earlier version of itself, it will enter the right-hand pocket at a slightly different angle to that in figure 1*a*. The direction of the ball leaving the left-hand pocket will also be slightly different – hence the collision will be glancing, rather than head on as before. This self-consistent trajectory is shown in figure 1*b*. It should be emphasized that, although the initial conditions in figures 1*a* and *b* are exactly the same, the evolution of the latter is self-consistent whilst that of the former is not.

It turns out that every initial condition for this model has a self-consistent solution. In fact, for many initial conditions there is more than one self-consistent solution, and often an infinite number, which all obey Newton's laws of classical mechanics. The initial condition shown in figure 1 has an infinite number of self-consistent solutions; most are similar to 1*e* and 1*f*, where the final velocity of the ball is opposite to the initial velocity, but the number of passages through the time machine varies from solution to solution.

There are also systems of time machines and particles which have no self-consistent solutions for given initial data, but these are difficult to construct using Newtonian models with simply interacting particles. In any event the question of what happens to an initial configuration near a time machine is not answered by Newtonian mechanics, because we lose one of the most cherished simplifications of ordinary physics – that initial conditions plus the equations of motion should *uniquely* determine the solution. Also note that, although non-interacting particles have no such richness (or dearth) of solutions, they do not suffer from the grandparent paradox because they cannot affect their surroundings or each other.

Fields have properties similar to particles. Non-interacting fields, such as electromagnetism in the absence of charges, are free from multiple solutions (and paradoxes). However, fields can also destabilize a time machine by propagating through it an infinite number of times, and adding their field strengths in each passage. If the time machine has a focusing effect, this infinite build-up of field energy would back-react on the time machine. The billiard-table time machine, however, has a defocusing effect: incoming spherical waves entering the right-hand pocket become outgoing spherical waves from the left-hand pocket. Although some of these waves enter the right-hand pocket again and again, the sum converges and the field strength remains finite everywhere.

Quantum behaviour

The classical behaviour of particles and fields is sufficiently rich and confusing that one naturally turns to quantum mechanics to (possibly) answer the question of what happens when something passes through a time machine. It turns out that quantum mechanics gives a more definite answer than classical mechanics. However, one must first pick a definite formulation of quantum mechanics to get a definite answer, and there are several distinct formulations of quantum mechanics which are equivalent without closed time-like curves, but which are not equivalent in their presence.

The most basic formulations of non-relativistic quantum mechanics are due to Schrödinger and Heisenberg. In non-relativistic theories there is a universal time function which all observers agree on. In the Schrödinger formulation, an initial wave function is evolved forward in (Newtonian) time by the Schrödinger equation, and measurements correspond to insertions of time-independent operators. The Heisenberg formulation is equivalent, but all the time dependence is delegated to the operators.

For theories formulated in the four-dimensional (Minkowski) space-time of special relativity, there are many "times" to choose from (corresponding to the different proper times of different boosted inertial observers) and any one time function is as good as any other. For each time function, at every moment there is a three-dimensional spatial "hypersurface" orthogonal to the time axis. Evolution along a time axis can be specified either by its time function, or by the progression of these space-like "slices". However, the results of all the different formulations agree irrespective of the way time is defined or evolved.

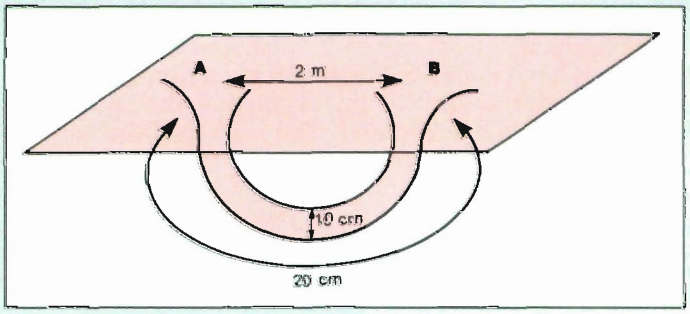
In general relativity there is generally no preferred time at all, but space-time, which is now curved or warped, can still be sliced into space-like slices. This enables the wave function to be defined on each slice and the evolution of the wave function from one slice to the next to be described by Schrödinger's equation. Two events on the same slice can be said to take place at the same time in some generalized notion of labelling, but they are not necessarily simultaneous in any physical sense.

However, in the presence of closed time-like curves we generally lose even our notion of space-like slicing, because nearby points in a space-like slice can be reached by time-like paths as well as space-like paths (figure 3). This means that the value of the field at one point is causally related to the value of the field at a neighbouring point, which destroys all initial-data formulations of quantum mechanics, including the Schrödinger and Heisenberg formulations.

A natural alternative to consider is the Feynman path integral formulation of quantum mechanics. In this, quantum amplitudes are constructed by summing over all possible paths of a particle (or histories of a field configuration), with a complex weighting given by e^{iS}, where S is the action of that path (or history). The

2 (*a*) A wormhole connecting the two points **A** and **B** at the same time. Distances are as shown and not as one would naively expect: the distance through the wormhole (20 cm) is much less than "directly" across via the rest of space (2 m). (*b*) Wormholes can also connect two points at different times. If these are separated far enough in external time, the wormhole would permit closed time-like curves. In this case a particle travelling through the wormhole from **B** to **A** arrives at **A** at an earlier external time. (Local time always advances forward for particles, whether moving from **A** to **B** or **B** to **A**.) Wormholes are not necessary to form closed time-like curves, but they can be useful for visualizing their effects

a



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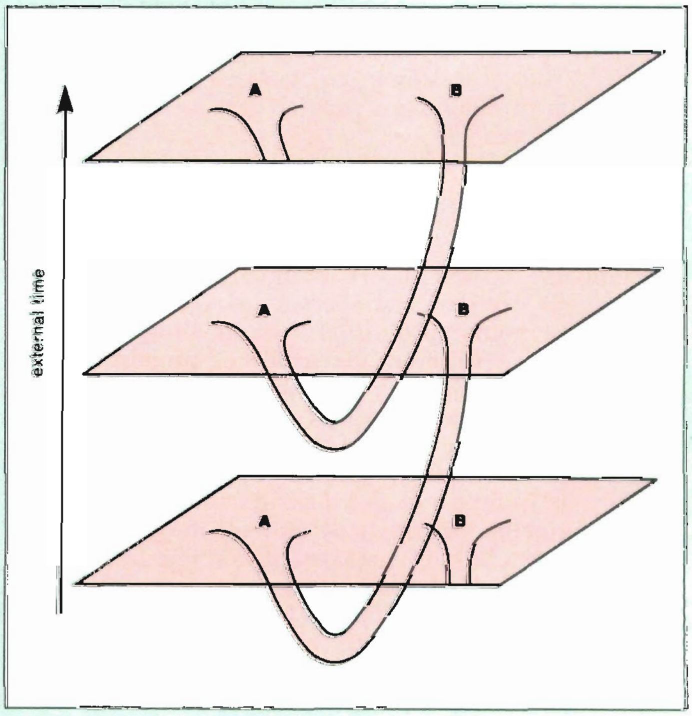


Feynman formulation is relatively insensitive to the existence of closed time-like curves in the region of integration, and in ordinary space-time it is completely equivalent to the Schrödinger/Heisenberg formulation for most theories. A reasonable supposition is that the histories summed over should be self-consistent (like figures 1*b*–*f*). This summation produces an amplitude to go from an initial state to a final state. The initial and final states must be on space-like slices free from any closed time-like regions, so any closed time-like curves that are created must be destroyed eventually.

But even restricting quantum mechanics to path-integral formulations is not enough to determine the effects of closed time-like curves, because the "propagator" (which connects the initial and final states) does not converge and various methods must be used to ensure convergence. These methods – which involve the addition of a small imaginary mass, or time, which is set to zero at the end of the calculation – are all equivalent in the absence of closed time-like curves. (The addition of an imaginary time component, known as Wick rotation, moves the contour of integration slightly off the real axis in the complex plane).

The imaginary mass technique allows a straightforward quantization of non-interacting particles and fields. However, the spectre of the grandparent paradox does rear its head for interacting fields. It has been shown by John Friedman, Nicholas Papastamatiou and myself at the University of Wisconsin-Milwaukee that the scattering amplitude becomes non-unitary. Unitarity in a quantum theory determines how probabilities are calculated from quantum amplitudes (normally by calculating the modulus squared of the amplitude). The mathematical definition of probability ensures that the sum of the probabilities always equals one, but the sum of the squared amplitudes depends on the physics of the theory.

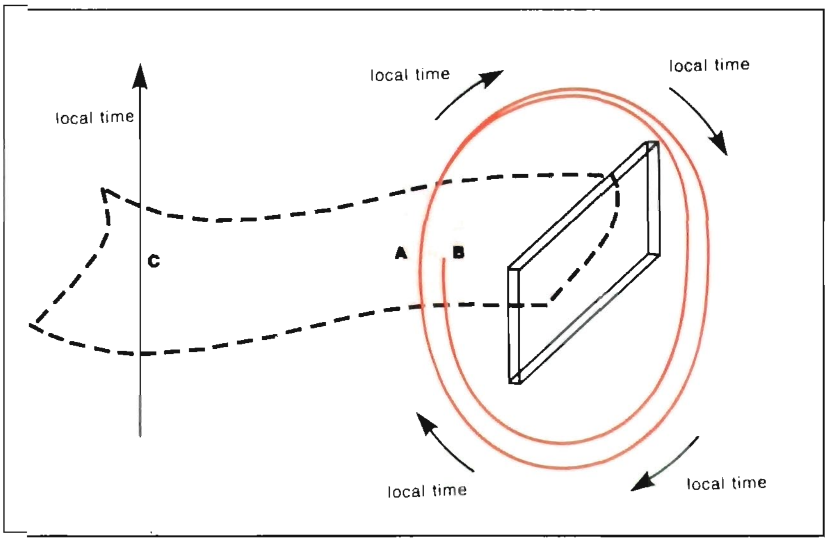
The usual cause of non-unitarity is that some information has been ignored. For example, transition amplitudes for the scattering of free electrons and protons into free electrons and protons will not be unitary unless bound states, that is hydrogen atoms, are also included. In the case of closed time-like curves, however, unitarity is violated in an unusual way: the sum of amplitudes squared (the norm) of the states genuinely changes.

James Hartle of the University of California at Santa Barbara has developed a framework in which genuine non-unitary evolution is possible with the probability still always proportional to the square of the quantum amplitude. If the theory is unitary, the proportionality factor is constant (and equal to one). Non-unitarity requires some additional rule of how to compute probability. However, the factor of proportionality will no longer be universal. The simplest way to "reconnect" the probability to the squared amplitude is to divide the amplitude by the norm of the initial state evolved in time (i.e. to "renormalize" the amplitude). This norm is not constant in time and also depends on the initial state.

This method uniquely determines the probability from the amplitude, but has two disturbing features. First, quantum mechanics is no longer linear, so the cherished principle of superposition is lost. Secondly, because the probabilities depend on the future value of the norm of the initial state, probabilities of events that take place before the formation of closed time-like curves depend on what happens once the closed time-like curves form. This gives an extra form of causality violation *before* the closed time-like curves form, independent of any causality violations occurring after they form.

A different renormalization technique, proposed by Arlen Anderson while at Imperial College, London, effectively sets all the non-unitary sectors of the evolution to zero, eliminating the disturbing features of Hartle's simpler method. This is clearly desirable, but it is not yet known if this method also wipes out important features in the process.

There is also a recent claim by Stephen Hawking of Cambridge University that Wick rotation leads to a loss of quantum coherence (and hence a loss of unitarity different from that just discussed). For quantum fields in equilibrium with a thermal bath (in ordinary flat space-time), the Feynman propagator is periodic in imaginary time (purely imaginary time corresponds to a Wick rotation of 90°), with the period inversely proportional to the temperature. Propagation through such a thermal bath results in a loss of quantum coherence due to the interaction of pure quantum states with the mixed states of the bath. In space-times with closed time-like curves some trajectories are periodic in real time. Wick rotation picks this up as an interaction with a thermal bath at an imaginary temperature. When the Wick rotation is inverted at the end of the calculation, there is still some remnant of the thermal nature of the interaction, which should result in a loss of quantum coherence.



3 A space-like slice (with one spatial dimension suppressed). There are no closed time-like curves on the left side of the slice, so an observer (or object with a time-like trajectory) intersecting the slice at point **C** never crosses this slice again. There are closed time-like curves passing through the slice on the right, including one passing through point **A**. An observer moving along this curve always moves forward locally in time but nevertheless re-intersects the space-like slice at **A**. By distorting the trajectory slightly, one may start at **A** and end at **B**. This means that point **B** is in the (causal) future with respect to **A** even though they are on the same space-like slice. Most initial data defined on this slice would be inconsistent with the time evolution of the system, destroying the usual initial-data formulation of quantum (and classical) mechanics

There is at least one more version of quantum mechanics with yet another set of odd behaviours in the presence of closed time-like curves. An information theoretic formulation of quantum mechanics due to David Deutsch of Oxford University, like the Wick-rotated path-integral formulation, routinely destroys quantum coherence, but in a novel way. The elements of the density matrix get mixed up in such a way that, in the language of the Everett–Wheeler "many worlds" interpretation of quantum mechanics, macroscopic observers can move and communicate from one "branch" to another by interacting with the closed time-like curve region (see Deutsch and Lockwood in Further reading).

Classical structure

So how difficult would it be to build a time machine? Probably very difficult, though it is not possible to rule them out completely. The time machines that are most difficult to rule out are microscopic time machines at the Planck scale ($l_{Pl} = \sqrt{(\hbar G/c^3)} = 2 \times 10^{-33}$ cm, $t_{Pl} = \sqrt{(\hbar G/c^5)} = 5 \times 10^{-44}$ s, where $\hbar$ is Planck's constant divided by 2π, G is the gravitational constant and c is the speed of light). At this scale, quantum gravitational effects completely dominate classical notions of space-time. However, until we have a firm understanding of quantum gravity, nothing certain can be said (superstring theory, a possible candidate for a quantum theory of gravity, is not even close to answering such questions). The loss of the classical notion of a background space-time results in what John Wheeler of Princeton University calls "space-time foam". In this model, space-time, which is smooth at scales much larger than the Planck scale, breaks up into a foam-like structure at smaller scales, possibly allowing topology change, causality violation and other unusual features.

What about at larger scales, whether subatomic or galactic? It is very easy to write down a solution to the Einstein equation of general relativity with closed time-like curves. First, for any space-time with closed time-like curves, compute the Einstein curvature tensor on the left-hand (geometric) side of the Einstein equation, $G_{\mu\nu} = 8\pi G T_{\mu\nu}$. Then find matter that satisfies the right-hand (stress–energy) side of the equation. However, according to Frank Tipler of Tulane University in New Orleans, Stephen Hawking and others, the most interesting space-times that allow closed time-like curves require conditions that are highly unlikely – "naked" curvature singularities, non-trivial large distance behaviour, or matter with negative mass/energy density. Here negative mass/energy does not mean antimatter, but matter that will gravitationally repel other matter, and thus excludes all known types of classical matter. ("Naked" singularities are points of infinite density and stress that are not hidden behind a black hole – it is thought that the general theory of relativity does not allow for naked singularities, with the possible exception of the Big Bang).

There are still a few open loopholes in these proofs, but space-times with closed time-like curves that are otherwise well behaved are quite constrained if they must satisfy the Einstein equation with reasonable matter and curvatures. Although difficult to find, such solutions are not impossible. As long ago as 1937 van Stockum of Edinburgh found a solution to the Einstein equation involving an infinitely long spinning cylinder (similar to recent solutions containing infinitely long cosmic strings) that contained closed time-like curves. One might scoff at a solution requiring an infinitely long cylinder, but that alone should not be enough to rule out the solution as unphysical. Indeed infinite cylinders are used routinely in elementary electromagnetism and mechanics because they are good approximations to non-infinite cylinders (and easy to solve). Moreover, general relativity is not just a local theory but also a cosmological theory. One cannot discard a solution merely because it is of infinite extent. As it turns out, von Stockum's theory needs structure at infinity to overcome the problem of constructing closed time-like curves theorems without negative mass/energy densities. This means that the solutions are not good approximations to local solutions, and that closed time-like curves do not appear for long (but finite) rotating cylinders.

In 1949 Kurt Gödel found a cosmological solution with closed time-like curves where the Universe is filled with rotating matter. If an observer goes far enough out (at high enough accelerations), he or she can traverse a closed time-like curve. More recently in 1991 Richard Gott of Princeton University found another solution to the Einstein equation with closed time-like curves, this time generated by two (non-spinning) cosmic strings passing each other at high speed. This solution has the interesting property that the closed time-like curves do not exist at early and late times, only at intermediate times near the moment of closest approach. The major problems with this solution are that the strings must be very massive (their mass and kinetic energy must dominate all of the mass/energy in the Universe), and that the region containing the closed time-like curves must be infinitely large. All these solutions have closed time-like curves threading though the entire Universe, all the way out to infinity. Although solutions to the Einstein equation, such closed time-like curves could not be created in a finite-sized laboratory, be it the solar system or the galaxy.

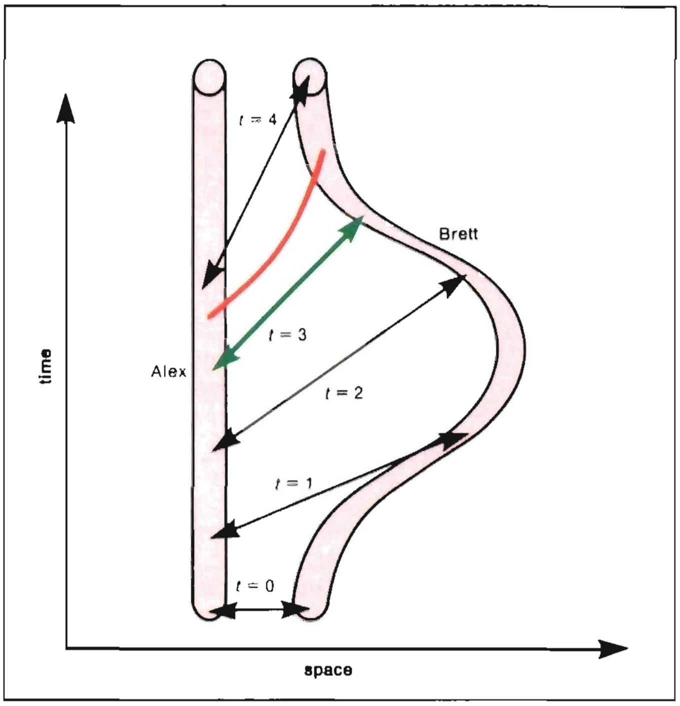
Time travel and black holes

The best known solution to general relativity containing closed time-like curves in a bounded region of space is the rotating black hole. A black hole is a region of space-time where the gravitational field is sufficiently strong, and space-time is sufficiently warped, that even light cannot escape. The location of the last beams of light, struggling to get away from the black hole but never able to break free, is called the event horizon. (For a non-rotating black hole this is given by the Schwarzschild radius.)

Inside the black hole the space-time curvature and gravitational forces become so strong that they are infinite at zero radius (at least according to classical general relativity). Anything falling inside the event horizon must reach this "curvature singularity" in a finite amount of (local observer) time. Once inside the event horizon, the observer inexorably proceeds from larger to smaller radius and finally to zero radius. Because the radius exhibits this time-like, unstoppable, "count-down" behaviour, it behaves as a time coordinate, not a spatial coordinate. The curvature singularity at zero radius is thus a moment in time, not a position in space, and it is as unavoidable for the observer trapped inside the black hole as next Tuesday is for those of us outside the black hole.

Similarly, inside an (ideal) rotating black hole, there is a region near the curvature singularity where the warping and rotation is so violent that the rotation angle, ϕ, becomes a time-like coordinate. Because ϕ is both time-like and periodic (with a period of 2π) there are closed time-like curves in this region of the space-time.

The closed time-like curve region of the rotating black hole solution, however, is not considered physical for reasons unrelated to the closed time-like curves. First, the curvature singularity lies to the past of the closed time-like curve region. For observers in that region the singularity is visible and boundary conditions for what comes out of the singularity must be imposed by some (unknown) additional physics. In principle anything at all could come out of the singularity and ruin the closed time-like curves. Secondly, and perhaps more importantly, there is an unstable region to the past of the closed time-like curves. It is widely thought that the end-point of this instability is a



4 The twin paradox acting on a wormhole can produce a time machine. The arrows connect moments of the same local time. Closed time-like curves can form after $t = 3$. The closed time-like curve chosen in red is closed by a wormhole – the difficult part of this experiment

curvature singularity which any observer would meet before any closed time-like curves could form.

Solutions with negative mass/energy can also be used to support closed time-like curves and evade the theorems proposed by Hawking, Tipler and others. While there is no known classical matter with negative mass, it can be produced from quantum effects without too much effort. The simplest example of this is the Casimir force between two uncharged conducting plates (or molecules). This force, which is distinct from and weaker than the van der Waals force, was predicted in 1948 and confirmed in 1958, and is caused by vacuum fluctuations of the electromagnetic field due to the Uncertainty Principle. The fluctuations are smaller in the presence of the conducting plates than they are in free space, which leads to an attractive force. Furthermore, the energy density between the plates is negative compared to that in free space. In flat space-time, this negative energy is not enough to maintain closed time-like curves, but in space-time with gravitational curvature (as in our Universe) there are currently no known obstacles, in principle, to creating enough negative energy to gravitationally support closed time-like curves.

Mike Morris and Kip Thorne at Caltech and others use this negative energy to create closed time-like curves using wormholes to connect one region in space-time to another directly. Without negative energy to support a wormhole, general relativity predicts that it will collapse in even less time than it would take light to cross the wormhole. The repulsive nature of the gravitational field arising from negative energy matter is what supports the wormhole. The two regions connecting the wormhole need not be widely separated in space; indeed if one can arrange for the two ends to be separated narrowly in space, but distantly in time, this is precisely what we need for a time machine.

Conceptually, the easiest way to make a time machine out of a wormhole is via the twin paradox of special relativity (figure 4). In this example one twin (Alex) stays at home whilst the other (Brett) zips off at high speed, rejoining Alex at a later time. Due to time dilation, much less proper time passes for Brett than for Alex by the time of their reunion (the arrows in figure 4 connect moments of the same local time for each twin). If Alex and Brett are clever enough to hold on to the ends of a very short wormhole while they are travelling, they can stay in near instantaneous contact for the whole of Brett's journey by communicating through the wormhole instead of though normal space. In figure 4, $t = 3$ represents the occurrence of the first closed light-like curve. Starting at that time, Alex can send a message to Brett at the speed of light though normal space, and then Brett can send the same message back to Alex via the wormhole (almost instantaneously if the wormhole is very short), where it arrives at the same moment it was sent. After that time there are closed time-like curves, as demonstrated by the red path, which close via the wormhole. The worst difficulties in creating a time machine of this type are finding a wormhole, stabilizing it with enough negative energy matter and keeping the ends of the wormhole near the twins.

Amos Ori at the Technion in Israel has recently found a new solution to the Einstein equation with several interesting properties. The closed time-like curves evolve from a causally well-behaved past, and the solution is trivially flat and causal at infinity and topologically trivial everywhere (unlike the wormhole time machine). Furthermore, the solution does not require negative energy when the closed time-like curves first form, but it does have negative energy after their formation. However, it is not yet known what would happen if the region where negative energy is used has positive energy matter put in its place. It is also not yet known whether this solution is stable against the classical field (infinite) build-up described earlier.

The future of closed time-like curves?

Aside from the classical difficulties described above, quantum field theory adds new difficulties to the creation of closed time-like curves. In his "chronology protection conjecture" Stephen Hawking argues that physics as a whole conspires to prevent the formation of closed time-like curves. The conjecture is bolstered, but not proven, by a two-tiered support system: the classical properties of general relativity and the quantum properties of fields in curved space-times. However, the classical theorems (of Hawking, Tipler and others) are not enough to support the conjecture on their own, especially concerning cosmological solutions with closed time-like curves or solutions that use negative energy matter.

The second attack is based on the properties of quantum fields in space-times which contain, or are about to generate, closed time-like curves. Sung-Won Kim and Kip Thorne at Caltech have shown that the energy density of quantum field states grows without bound as the moment of creation of the first closed time-like curves approaches. While this does not rule out closed time-like curves, it does mean that the approximation of having quantum fields evolve in a background space-time without gravitationally affecting the space-time itself breaks down as the moment of creation approaches. Unfortunately the correct treatment of this strong field back-reaction would require a full theory of quantum gravity, which we do not have. The reason for the divergence of the energy density is that the vacuum modes propagate around the closed time-like curves and cause quantum instability, even when the space-time is stable against classical field build-up.

One possible exception to this general behaviour might occur if the divergence of the energy density is so slow that it does not reach the Planck scale ($E_{Pl} = \sqrt{(\hbar c^5/G)} = 1 \times 10^{19}$ GeV) until one Planck time (~10^{43} s) before the epoch of closed time-like curves. Since this type of fluctuation is expected even for ordinary flat space when gravity is quantized (particularly in John Wheeler's picture of space-time foam), it is not at all obvious that this would spell doom for the closed time-like curves. Matt Visser of Washington University in St Louis has found examples of space-times with closed time-like curves formed by two wormholes with this very slow divergence, although admittedly only for very extreme parameters. If the two wormholes are separated by 1 astronomical unit (about eight light-minutes) the wormholes themselves can only be up to 10^{-18} cm large, meaning that only subatomic particles of energies greater than 20 TeV could pass through, and even then they could only travel eight minutes into the past.

Future thoughts

The physics of closed time-like curves is a diverse and fascinating subject, and its discussion should not be monopolized by science fiction aficionados at the expense of physicists. Moreover, the mere existence of a single closed time-like curve anywhere (and at any time) in the Universe forces us to choose between different versions of quantum mechanics that, in other circumstances, would be equivalent.

The question of whether closed time-like curves are forbidden in principle by the laws of physics is still very open, though, between general relativity and the general behaviour of quantum fields in curved space-times, the deck is certainly stacked against macroscopic closed time-like curves. The question of microscopic (Planck-scale) closed time-like curves remains open, however, and is likely to remain so until a full theory of quantum gravity has been found.

It is all one to me where I begin, for I shall come back there again in time. Parmenides

Further reading

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