# Groundhogs, Gravity and Loops through Time

**by Jeff Williams**

*One reason that time travel is so fascinating is that we have such a great desire to do it.*
-- J. Richard Gott

*...the best evidence we have that time travel is not possible, and never will be, is that we have not been invaded by hordes of tourists from the future*. -- Stephen Hawking

In the movie *Groundhog Day*, cynical weatherman Phil Connors (played by Bill Murray) is trapped in a time loop, doomed to relive the same day, day after day, in Punxsutawney, Pennsylvania. He uses this unremitting sequence of February 2$^{nd}$'s to turn himself into the kind of person that love-interest Rita (played by Andie MacDowell) can fall in love with.

Part of the movie's appeal, and the interest in time travel, stems from our wish to do things over again, to have a second chance. The extent to which this is possible, the extent to which the science fiction of time travel can be separated from science fact, is an active arena for research on the part of cosmologists and general relativists who specialize in the mathematical physics of *spacetime*. Many are wary. Robert Ehrlich, author of *Nine Crazy Ideas in Science*, gives a skeptical "two cuckoos" to the idea that time travel is practicable.

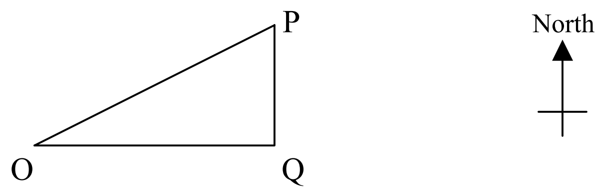
Yet in a sense, we are all time travellers. No matter what we do -- whether sitting in an armchair, eating dinner or exercising the dog -- each of us advances into the future at the rate of one second per second, one year per year, one century per century. This trivial kind of time travel is uninteresting. What would be interesting would be the possibility of time travel to the past or, alternatively, time travel to the future at a rate which is slower or faster than usually occurs. In fact the latter situation is not only theoretically possible, but has been repeatedly verified by experiment. Before pursuing this further, consider the nature of time.

Attempts to formulate a basic definition of time are often circular and are invariably fraught with difficulties because time is, itself, so basic. Fifth century theologian and philosopher, St. Augustine of Hippo, once commented, "What is time? If no one asks me, I know. But if I were required to explain it to one who asks me... I cannot." Although some scientists have tried to explain time in terms of something more elementary or have even denied its existence (see *The End of Time* by Julian Barbour), the overwhelming majority of physicists and mathematicians accept time as a given, fundamental entity, and then expend their efforts on trying to understand its properties and on incorporating it into their equations. This was true for Sir Isaac Newton. His ideas on how time behaved can be found in his *Principia* (1686):

*...equable progress of absolute time is liable to no change. The duration or perseverance of the existence of things remains the same, whether the motions are swift or slow, or none at all.*

Newton had some misgivings about this view of the properties of time, but at least it provided him with a clear-cut jumping off point for his brilliant development of classical mechanics. It was left to Albert Einstein to show (1905) that the view of Newton (which was essentially the same as that of Aristotle) was wrong. Time is not absolute. Time is affected by motion.

To understand Einstein's view of time, let us examine the Pythagorean view of space. Consider measuring the distance between a point O and a point P in a flat field.




Suppose the horizontal side of the above triangle is aligned West-to-East and distances in that direction are to be measured by a coordinate x. The vertical side is then aligned South-to-North, and distances in that direction will be measured by a coordinate y. Suppose a person walks from O to P, indirectly, by first walking East to point Q thereby changing their x-coordinate by an amount we shall denote by $\Delta x$, and then walking North to P thereby changing their y-coordinate by an amount we shall denote by $\Delta y$. The symbol $\Delta$ can be read as "change in." Had the person walked directly from O to P (along the hypotenuse of the triangle), they would have covered a distance equal to the square root of

$$(\Delta x)^2 + (\Delta y)^2.$$

This result is the well known theorem of Pythagoras. It is convenient to consider the above quantity, exactly as written, without including the square root. Such a quantity is called a *metric*. Thus we shall consider the metric (which is equal to the square of the distance) rather than the distance itself. [*Technical aside: In this present article, the use of the word "metric" conforms to its use in Differential Geometry and differs from its use in Real Analysis*].

If we consider ordinary 3-dimensional space, then a vertical direction -- call it "z" -- needs to be included, and the metric becomes

$$(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2.$$

For over two thousand years, this remained the standard metric for the physical world. It was not until the early 1900s that scientists such as Poincaré, Lorentz and especially

Albert Einstein challenged the view of Newton and Galileo. In 1905, Einstein created a new mechanics: the *Theory of Special Relativity*. However, it was left to a Russian-born geometer named Hermann Minkowski to recognize how Einstein's theory implied that reality embodied a natural 4-dimensional symmetry with *time* representing the extra dimension.

Minkowski had been one of Einstein's professors in 1900, when the latter had enrolled in *Section VIA: Physics & Mathematics* at Zürich Polytechnic. On one occasion, Minkowski remarked that Einstein was a "lazy dog," because of his reluctance to study mathematics (he preferred physics) and his tendency to skip lectures. Happily, a more mathematically inclined classmate named Marcel Grossmann never skipped lectures and took excellent notes which he allowed Einstein to borrow. Another classmate who also never skipped lectures was a Hungarian woman named Mileva Maric, whom Einstein would eventually marry.

When Einstein published his 1905 paper he had already left the Polytechnic and, failing to find a job in academia, had taken a position as a clerk at the Patent Office in Berne. Minkowski had also left, and had taken a position at the University of Göttingen, the home of German mathematics, especially geometry. It was there, during the 19$^{th}$ century, that the great Gauss and his student Riemann had developed the theory of curved surfaces. After reading Einstein's paper and recovering from his surprise that the "lazy dog" had produced something of merit, Minkowski threw himself into the task of creating a better language, a more geometric language, to describe Einstein's new physics.

Minkowski realized that it was not only the space variables that could mix and share each other's roles (as would happen if a rotation of axes caused the x-direction to point partly in the y-direction, and vice-versa), but that *time* should be included as an equal partner, and that doing this would provide a geometric explanation of the weird results that sprang from Einstein's relativity and the earlier prototype theories of Poincaré and Lorentz. According to Minkowski, *space* -- the 3-dimensional stage on which people, particles and the heavenly bodies of astronomy move hither and thither and interact according to the laws of Nature -- should be replaced by a 4-dimensional stage called *spacetime*. In September 1908, Minkowski spoke at the Congress of Natural Scientists in Cologne, the 80$^{th}$ *Naturforscheversammlung*. He began his lecture as follows:

> *...The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. Their tendency is radical. From now on, space by itself and time by itself are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.*

Revolutionary as the idea might have seemed to Minkowski's listeners, it had been voiced some years earlier by science fiction writer, H.G. Wells, who in his novel *The Time Machine* (1895), has the protagonist explain to his guests:

*...The geometry, for instance, they taught you at school is founded on a misconception...There are really four dimensions, three of which we call the three planes of Space, and a fourth, Time.*

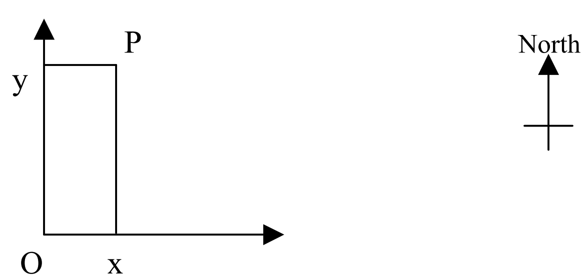
Time, which we will henceforth denote by "t", measures progress in a "temporal dimension" and, according to Minkowski and Einstein (and HGW!) shares many similarities with a variable such as x, which measures progress in one of the spatial dimensions. But time and space are not exactly the same. They differ physically. This difference is flagged mathematically by placing a negative sign in front of terms involving (the square of) t and a positive sign in front of terms involving (the squares of) x, y and z. Thus if time is to be included, then the metric should be modified to read as follows:

$$-\ (\Delta t)^2 + (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2.$$

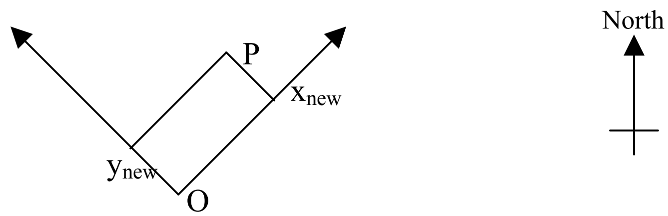
This is the famous Minkowski metric. It is the metric which is used in much of modern physics, most notably in Special Relativity. Three months after the congress in Cologne, Minkowski died of acute appendicitis, saddened by the knowledge that he would not live to see relativity develop to its full potential.

The moment has now arrived to analyze the possibility that was raised earlier: *time travel to the future at a rate which is faster than usually occurs.* To understand this concept better, consider an elderly man -- call him "George" -- who is ninety years old and living in a seniors residence when he receives a long-distance phone call from his daughter to say that she has just given birth to a baby girl, Teresa. George fantasizes about watching his grand daughter, Teresa, grow to womanhood and eventually marry. George would dearly love to go to the wedding, but he realizes that the wedding would take place some 20 years in the future, long after he himself is dead. To be present at the wedding, George would need to travel 20 years into the future more quickly than usual -- perhaps taking only a year or two instead of taking the full 20 years. Such a surprising accomplishment is theoretically possible, according to Einstein's Theory of Special Relativity.

To explain how, return to the Pythagorean view of space and the point P in a field:



In relation to the point O, point P is a distance x to the East and a distance y to the North. However, the convention of having an x-axis aligned West-to-East and a y-axis aligned South-to-North is arbitrary. One could equally well choose new distance coordinates, $x_{new}$ , $y_{new}$ , measured respectively in relation to a new axis that points towards the NorthEast and a new axis that points towards the NorthWest:




The location of the point P is unchanged. However, the new distances are different from the old ones since they lie along new directions that are inclined at 45° to the old directions. With a little geometry, it is easy to prove that $x_{new}$ and $y_{new}$ are related to x and y by:

$$x_{new} = x \cos 45° + y \sin 45°,$$

$$y_{new} = -x \sin 45° + y \cos 45°.$$

Two features are worth noting. First: the above formula for $x_{new}$ (and similarly for $y_{new}$) shows that $x_{new}$ is a mixture of both x and y. Second: since the point P is the same in both diagrams, the distance from O to P is unchanged and hence the Pythagorean metric is unchanged:

$$(\Delta x)^2 + (\Delta y)^2 = (\Delta x_{new})^2 + (\Delta y_{new})^2.$$

The fact that changing from the old coordinates x, y to new coordinates $x_{new}$ , $y_{new}$ leaves the metric unchanged is an important principle that carries into Special Relativity.

In Special Relativity, the appropriate metric is the Minkowski metric:

$$-(\Delta t)^2 + (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2.$$

The changes, or transformations, that produce $t_{new}$ , $x_{new}$ , $y_{new}$ , $z_{new}$ and leave the Minkowski metric unchanged are called Lorentz transformations, in honour of the Dutch physicist Hendrik Antoon Lorentz. In the Pythagorean setting, $x_{new}$ was expressed in terms of x and y. Likewise, in the special relativistic setting, $t_{new}$ (say) can be expected to depend upon t and x (and possibly on y and z, too). In fact the simplest kind of Lorentz transformation shows that $t_{new}$ depends upon t and x in a way that is reminiscent of the Pythagorean case where the axes were rotated through 45°, except that the sines and cosines of the Pythagorean case must be replaced by what mathematicians call *hyperbolic* sines and cosines. Furthermore, it is not a rotation that results in the introduction of the new time coordinate, $t_{new}$ , but a *velocity*. This fact lies at the heart of Einstein's theory: that the time t being recorded by some original observer will differ from the time $t_{new}$ recorded by a new observer who is travelling at some velocity (call its magnitude "$v$") relative to the first observer. Rather than considering the Lorentz transformation that relates $t_{new}$ to t (and x), it will be more useful to consider the formula that relates the two changes in time, $\Delta t_{new}$ and $\Delta t$, as measured by the two different observers:

$$\Delta t_{new} \;=\; \Delta t \, \frac{1 - v/c}{\sqrt{1 - v^2/c^2}} \,.$$

Deriving this formula from the Lorentz transformations requires some algebra and the details can be found in undergraduate physics texts. It was derived by Lorentz (1892) and later by Einstein in the framework of his new theory. What does it mean? What does the symbol "c" stand for?

The symbol c stands for the speed of light, which is approximately 300,000 kilometres per second, or 108,000,000 kilometres per hour. That c is constant, unaffected by the motion of the object transmitting the light or the observer receiving it, was a novel and central feature of Special Relativity. So, too, is the fact that nothing can travel faster than light. The symbol $v$ denotes the magnitude of the velocity (i.e. the speed) of one observer relative to the other. For everyday speeds, the ratio $v/c$ is miniscule. For example, for an observer in a jet plane travelling at 500 kilometres per hour relative to an earth-bound observer, $v/c = 500/108{,}000{,}000 = 0.0000046$. This is extremely close to zero, so that the factor

$$\frac{1 - v/c}{\sqrt{1 - v^2/c^2}}$$

is extremely close to 1, and hence $\Delta t_{new}$ becomes, for most practical purposes, indistinguishable from $\Delta t$. One can now understand Newton's erroneous conclusion that "duration... remains the same, whether the motions are swift or slow, or none at all." The motions that Newton experienced would have been no faster than a galloping horse. Relativistic effects become apparent when a speed $v$ is comparable in size to c. Return to Grandfather George.

Suppose George undertakes his journey to the church (and to the future) at 99% the speed of light, so that $v/c = 0.99$. Teresa has to wait for 20 years, meaning that $\Delta t = 20$. The formula for $\Delta t_{new}$ tells us that

$$\Delta t_{new} \;=\; 20 \times \frac{1 - 0.99}{\sqrt{1 - (0.99)^2}} \;=\; 1.41776 \text{ years.}$$

Thus George does not have to live for another twenty years to be present at the wedding. He has to live for only 1.41776 years, i.e. for only 1 year and 5 months. This effect, called *time dilation*, is a well known consequence of Special Relativity and is sometimes illustrated by the so-called "twin paradox," where identical twins age at different rates because one is travelling at a high velocity relative to the other.

Although there are no flaws in the physics presented above, the engineering challenges of constructing a rocket that will accelerate a human being to 99% the speed of light, and the biological challenges of enabling a human being to withstand the force of acceleration, are daunting, to say the least. For a practical demonstration of time dilation, one needs to turn to subatomic particles -- in particular, to *muons*.

When radiation from the sun crashes into the upper atmosphere of the earth, particles called "muons" are created and begin their journey downwards to the earth's surface, 20 kilometres below. Muons have a (half-)lifetime of about 2 millionths of a second. Newton's theory predicts that the muons, like Grandfather George, will die (i.e. disintegrate) long before they reach the earth's surface. However, the muons' high velocity causes them to age more slowly -- or, equivalently, to reach the future more quickly -- and they are detected in profusion on the earth's surface. Here is firm evidence of time travelling muons. [*Technical aside: One of the best known confirmations of time dilation for high speed muons came from an experiment performed in Colorado in 1941 by University of Chicago physicists Bruno Rossi and David Hall. In a different set of experiments performed by physicists at the Organisation Européenne pour la Recherche Nucléaire (CERN) in 1966, muons which were accelerated to 99.7% of the speed of light were shown to have extended their lifetimes by a factor of 12.*]. However, time is not only affected by motion; it is also affected by gravity.

In that momentous year, when Einstein's mechanics swept away three hundred years of mechanics that had been developed by Galileo and Newton, a door that had previously been shut was suddenly opened . The theory of electricity and magnetism had been inconsistent with Newtonian mechanics, but was consistent with Special Relativity. There was now a common framework for describing the electrical, magnetic and mechanical forces that were encountered in Nature. Since the weak and strong nuclear forces were unknown in 1905, it seemed that the age old force of *gravity* was all that remained. Once this was brought into the fold, physicists would have their long sought *Theory of Everything*.

Although not exactly a Theory of Everything, Einstein's theory of gravity, which he called the *Theory of General Relativity*, was to be stunning in its originality, awesome in its depth (so much so that scholars of *GR*, like scholars of the Bible or Shakespeare, spend their entire careers in plumbing those depths), and then brilliantly verified by the eclipse expedition organized by Englishman Sir Arthur Eddington. Einstein spent ten years, 1905--1915, in developing his *General Relativity*. He needed to learn more mathematics, particularly the differential geometry of Riemann that Einstein had glossed over as a student. Luckily, the "lazy dog" was able to call on the friend from his student days, Marcel Grossmann, to come to the rescue and teach him about the metrics of curved surfaces. Minkowski had been right all along: *Physics needed to be geometrized*. There were false starts, and years when Einstein made little or no progress -- or simply got things wrong. Eddington's expedition to the Brazil eclipse of 1912 was rained out. Had he been able to take any measurements, he would have found that Einstein's theory at that time was incorrect. Eddington persisted. The English pacifist (Eddington was a Quaker) championed the cause of the German pacifist's *General Theory of Relativity* throughout the Great War. Peace brought another eclipse.

It was predicted for May 29th, 1919, and so Sir Arthur Eddington set sail from London for Principe, an island off the coast of Africa, one of the two choice locations for observing. When he returned, he gave a speech at the banquet that the Royal Astronomical Society held in his honour, and he ended it with a verse that parodied *The Rubaiyat of Omar Khayyam*:

> *Oh leave the Wise our measures to collate.*
> *One thing is certain. LIGHT has WEIGHT.*
> *One thing is certain, and the rest debate--*
> *Light-rays, when near the Sun, DO NOT GO STRAIGHT.*

The central feature of Einstein's theory of gravity, his *General Relativity*, is that matter causes spacetime to *curve*. Consequently, light particles (photons) from a distant star should not skim past the Sun in a straight line but should follow a bent path, like a ball rolling in a 4-dimensional bowl-shaped region of spacetime whose curvature is caused by the mass of the Sun. Eddington's measurements demonstrated that light was bent exactly as General Relativity had claimed. In the words of the *Berliner Illustrierte Zeitung*, Albert Einstein became "A New Giant in World History."

In the years that followed, the world of physics was turned upside down by the development of quantum mechanics and nuclear physics, and the world that Einstein knew as a professor in Berlin was lost to him forever. As his fame grew, the one-time "New Giant in World History" metamorphosed into a mythical figure whose bushy moustache and baggy trousers somehow symbolized vast intellect. Eventually, near the end of his life, he became tired of publicity and rarely left Princeton. He worked at the Institute for Advanced Study, although he admitted that he only went to the Institute for the pleasure of walking home at the end of the day with his friend Gödel.

Kurt Gödel, the dapper Princeton logician with Harry Potter spectacles, had shaken the whole of science and philosophy with his *Incompleteness Theorem*, proving once and for all that logic would not permit a complete understanding of the universe. Both he and Einstein were refugees from the Third Reich and shared the common language of their boyhood. Both of them had revolutionized their chosen areas of study.

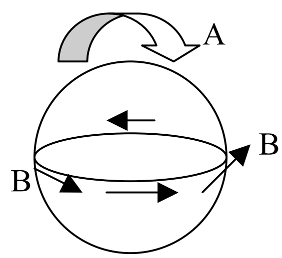
Inevitably, Gödel became interested in General Relativity and in the equations, now called the *Einstein Equations*, that matched curvature with the matter content of the universe and that were required to be satisfied when using a general relativistic *metric* to model physical structures such as stars, galaxies or the universe itself. (When he began as a graduate student, Gödel had studied theoretical physics). Gödel discovered a solution of the Einstein Equations which described a rotating universe whose gravitational pull caused light rays to be bent completely around so as to form loops that closed on themselves. Light or anything else, whether grains of dust, stars or human beings, could move along these closed timelike curves in the direction of increasing time. While flowing into the future, such objects would also flow into their own past.

Finding a solution of the Einstein Equations means finding a metric that satisfies these equations. The metric that Gödel found is as follows:

$$-(\Delta t)^2 + (\Delta A)^2 + (\sin A)^2 [(\cos A)^2 - (\sin A)^2] (\Delta B)^2 - 2 (\sin A)^2 \Delta t \, \Delta B + (\Delta z)^2.$$

[*Technical aside: This is not exactly the metric that Gödel reported in his famous paper of 1949 in Reviews of Modern Physics, but a similar and simpler metric that Gödel discussed in a later article. Note that relativists usually use the Greek letters $\theta$ and $\varphi$ instead of the symbols A and B* ].

One can immediately appreciate that metrics in General Relativity are vastly more complicated than the simple Minkowski metric that occurs in Special Relativity. For one thing, the coefficients that occur in front of the squared terms, (for example, in front of $(\Delta B)^2$), need not be merely plus or minus one, but can be complicated functions of unfamiliar variables. Since general relativistic spacetimes are usually curved, it is common practice to use curvilinear variables instead of the usual Cartesians, x, y,... For the above metric, A is the polar angle (related to latitude) and B is the azimuthal angle (equal to longitude) for a sphere:




Consider the Gödel metric. The term $(\Delta t)^2$ has a minus sign in front, thus: $-(\Delta t)^2$. This indicates that t is a *timelike* variable. The terms $(\Delta A)^2$ and $(\Delta z)^2$ have plus signs in front, indicating that A and z are not timelike, but are spacelike. How about the term $(\Delta B)^2$ ? The factor in front is

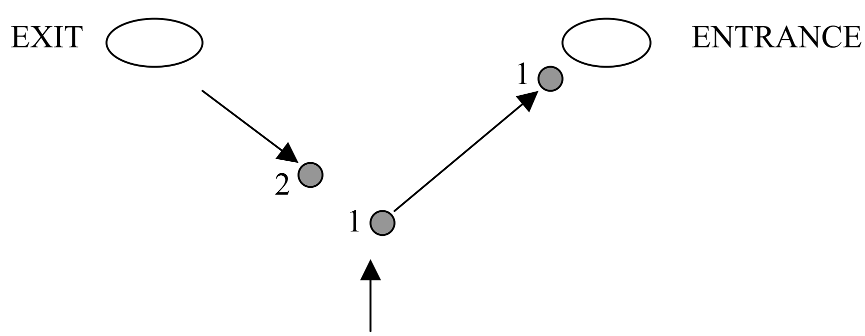
$$(\sin A)^2 [(\cos A)^2 - (\sin A)^2].$$

If this quantity is positive, then the variable B is spacelike. If this quantity is negative, then B is timelike. Since $(\sin A)^2$ is always positive, it is irrelevant to the discussion. Focus on the expression $(\cos A)^2 - (\sin A)^2$. This expression is positive when $\cos A > \sin A$, which happens, for example, when $A = 0$ (which occurs at the "North Pole" of the diagram). Thus the variable B is spacelike in this region. However, $(\cos A)^2 - (\sin A)^2$ is negative when cos A < sin A, which happens, for example, when A = 90° (which occurs at the "Equator" of the diagram). Thus the variable B is *timelike* in this region. So what?

The point is that if we take the Gödel universe seriously, then there exist timelike loops through spacetime. The "Equator" referred to above would be one example. Following such a loop is not like walking in a circular path around a running track. Walking around a running track brings one back to the same starting point in space, but at a later time. Following one of Gödel's loops brings one back to same point at the *same time* as one's journey would have started. If our universe were like Gödel's, I might leave my home at 9.00am May 3rd, 2010, take a trip around the universe (maybe frozen inside my spacecraft in some kind of suspended animation) and, having travelled countless billions of years into the future, arrive back home at 9.00am May 3rd, 2010 -- perhaps in time to catch myself leaving!

This can lead to all manner of paradoxes. Suppose I arrive back and shoot myself, thereby preventing my leaving in the first place? For many years, physicists rejected Gödel's universe as being unphysical exactly because of these paradoxes. It was also pointed out that there is little evidence that the *real* universe rotates (whereas Gödel's universe does rotate), and overwhelming evidence that the real universe expands (whereas Gödel's universe does not expand). Gödel's universe fell into disfavour and, if mentioned in the textbooks at all, was mentioned merely as a curiosity.

Nonetheless, it is a fact that, in addition to other curious effects related to time (e.g. the slowing of time in a gravitational field, the complete stopping of time at the surface of a black hole), General Relativity allows the possibility of time travel to the past. Following Gödel's work, other relativists have discovered situations in which valid general relativistic arguments lead to time travel to the past. Frank Tipler of Tulane University showed this for the gravitational field generated by a spinning cylinder. J. Richard Gott of Princeton University found similar results for cosmic strings, which are believed to have been created in the Big Bang. Prodded by writer Carl Sagan, who was working on the science fiction novel *Contact* at the time, Cal Tech theorist Kip Thorne began a study of wormholes -- tunnels through spacetime that connect two different regions of space. Such structures occur naturally within General Relativity and had been known about for decades. Under certain restricted conditions, time travel to the past (or future) was shown to be possible. The wormhole work of Thorne and his co-investigators is strikingly illustrated by a paradox arising from a game of "cosmic billiards." Billiard ball number 1, travelling in a straight line, is struck and deflected into a pocket (wormhole entrance) by billiard ball number 2 which has entered the region from a second pocket (wormhole exit):



The illustration takes on a deeper meaning when one realizes that ball number 2 is actually the *same* ball as ball number 1, having entered the wormhole and looped back in time to exit and strike itself to cause the entry into the wormhole in the first place. There is only *one* ball!

Time travel merits serious consideration because it is rooted in serious scientific theory. Forward time travel is described by Einstein's *Special Relativity*; time travel to the past is permitted by Einstein's *General Relativity*; -- and both Special and General Relativity have been verified to a high degree of accuracy by numerous experiments. This theoretical underpinning places time travel firmly in the domain inhabited by physicists and mathematicians, distinct from the domain where quacks and charlatans dwell, and where subjects such as astrology and alien abduction are likely to be found. Nonetheless, one is surely led to ask the question: "How many professional physicists or mathematicians truly believe that *macroscopic* time travel -- i.e. time travel by an everyday sized object, such as a human being -- is or ever could be possible?" The answer is: "hardly any."

Time travel is a fun subject, filled with challenging intellectual exercises. More to the point: time travel calculations allow theorists to push General Relativity to its limits. In the early years of this century, just as in the early years of the last century, the great challenge of theoretical physics is one of unification, the creation of a *Theory of Everything*, -- and gravity is very much involved. (See the recent book *Three Roads to Quantum Gravity* by Lee Smolin). The well-established Theory of General Relativity must somehow be made consistent with the equally well-established Theory of Quantum Mechanics. Either or both of these theories must be modified or perhaps rejected totally before the desired unification can be achieved. *Time*, which occurs so differently in the two theories, lies at the heart of any attempt to unify the highly causal Quantum Mechanics with the Theory of General Relativity, where time travellers declare "open season" on every aspect of causality. The history of physics teaches us that progress comes from contemplating extreme situations and bizarre paradoxes, like light having a velocity that is curiously unvarying (implying special relativity), weird behaviour in the spectra of hot objects (which led to quantum theory), or alpha particles that occasionally bounce backwards at crazy angles (which led Rutherford to his theory of the atom). Perhaps Stephen Hawking is right in his attempt to rein in General Relativity by the restrictions implied by his *Chronology Protection Conjecture*. Perhaps Nobel prizewinner (for the theory of quarks) Murray Gell-Mann and his colleagues are right, and it is the mathematical basis of Quantum Mechanics that needs to change. Only time will tell.

For now, the writers of books such as *Contact* and of television series such as *Quantum Leap*, or *Dr. Who*, the Time Lord from Gallifrey who roams the universe in his *Tardis*, will continue to delight us with their imagination. Time travel movies never lose their appeal, whether they are action based, such as *Planet of the Apes*, *The Terminator*, or the recent remake of *The Time Machine* with actor Guy Pearce, or whether they involve a romantic element, such as the 1978 *Superman* where Christopher Reeve reverses the rotation of the earth to go back in time to save Lois Lane, or *Peggy Sue Got Married* with Kathleen Turner and Nicholas Cage, or *Back to the Future* with Canadian actor Michael J. Fox, or *Somewhere in Time* (Christopher Reeve again), or the movie *Groundhog Day*, where cynical weatherman Phil Connors (played by Bill Murray) is trapped in a time loop, doomed to relive the same day, day after day, in Punxsutawney, Pennsylvania. He uses this unremitting sequence of February $2^{nd}$'s to turn himself into the kind of person that love-interest Rita (played by Andie MacDowell) can fall in love with.

Part of the movie's appeal, and the interest in time travel, stems from our wish to do things over again, to have a second chance. The extent to which this is possible,...

## BIBLIOGRAPHY


J.B. Barbour, *The End of Time* (Oxford U.P., Oxford, UK, 2000).

C. Callender and R. Edney, *Introducing Time* (Icon, Cambridge, UK, 2001).

J.L. Casti and W. DePauli, *Gödel -- A Life of Logic* (Perseus, Cambridge, MA, 2000).

P. Davies, *About Time -- Einstein's Unfinished Revolution* (Touchstone, New York, NY, 1996).

P. Davies, *How to Build a Time Machine* (Penguin, London, UK, 2002).

R. Ehrlich, *Nine Crazy Ideas in Science* (Princeton U.P., Princeton, NJ, 2002).

J.R. Gott, *Time Travel in Einstein's Universe* (Houghton Mifflin, New York, NY, 2001).

S.W. Hawking, *Black Holes and Baby Universes -- and Other Essays* (Bantam, New York, NY, 1994).

S.W. Hawking, K.S. Thorne, I. Novikov, T. Ferris and A. Lightman, *The Future of Spacetime* (Norton, New York, NY, 2002).

P.J. Nahin, *Time Machines: Time Travel in Physics, Metaphysics and Science Fiction* (Springer, New York, NY, 1999).

I.D. Novikov, *The River of Time* (Cambridge U.P., Cambridge, UK, 2001).

D. Overbye, *Einstein in Love* (Penguin, London, UK, 2000).

C.A. Pickover, *Time: A Traveller's Guide* (Oxford U.P., Oxford, UK, 1998).

L. Smolin, *Three Roads to Quantum Gravity* (Basic books, New York, NY, 2001).

K.S. Thorne, *Black Holes and Time Warps -- Einstein's Outrageous Legacy* (Norton, New York, NY, 1994).

H.G. Wells, *The Time Machine* (Heinemann, London, UK, 1895; Reprinted: Oxford U.P., Oxford, UK, 1977).