# BLACK HOLES, WORMHOLES, and TIME-MACHINES:

# SURELY YOU MUST BE JOKING, MR. THORNE!

A talk given to the Cleveland Philosophical Club

March 9, 1993

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Until recently, time travel was thought of as a literary device employed for the most part by science-fiction hacks. Mark Twain's A Connecticut Yankee in King Arthur's Court. and H.G. Wells' The Time Machine provide the required exceptions.
To my knowledge, no reputable scientist in those days ever suggested that time travel was actually feasible.

I should say here that we will in this talk consider only time travel to the past. Going forward in time is commonplace- every system in the universe does it- unavoidably. Of course, if one wants to go very far into the future, one must develop new technologies - cryogenics or relativistic time dilation, or whatever.
This may be very difficult, but it involves no contradiction. In contrast, going backward in time can involve logical contradiction, and it is this aspect of time travel that I want to explore.

Here, for instance, is a gem of a paradox invented by Rudy Rucker, a mathematician and very gifted popularizer of science. This is from his book, The Fourth Dimension.

> An inventor is in his laboratory, struggling to assemble a working time-machine. Suddenly there is a flash of light, and a man from the future appears, riding a lovely time-machine. "I'm an historian," says the man from the future. "I want to interview you, as you are the inventor of the time-machine." "But I don't know how to build one yet," replies the inventor. "I don't know if I'll ever get it right." "Well, here," says the helpful historian, "just look my machine over and build yourself a copy of it."

And thus was the time-machine invented.

The re-invention of the time-machine began in 1985. Carl Sagan, of TV's Cosmos fame, was writing a science-fiction novel, Contact, and wanted the very best in the way of scientific smoke and mirrors to allow his heroine, Dr L E Arroway, to flit about the universe disregarding the ultimate speed limit, the speed of light.

Sagan knew that Einstein's theory of gravitation admits a variety of solutions that suggest the possibility that distant regions of space may be connected by alternate paths through tunnel-like structures called "wormholes." It is believed that the distance through such a wormhole may be very, very much shorter than the usual minimum-distance path through outer space.

For advice Sagan wrote to Caltech's Kip Thome, a world renowned expert in these matters. 1

Sagan knew that Thorne was not only well qualified, but also that he has a well-deserved reputation for bold speculation in all areas of physics.

Thorne is certainly an interesting fellow. He was born in 1940 into a large Mormon family, the son of a professor of soil chemistry at Utah State University. He was very precocious - and not only in his studies: midway in his undergraduate years at Caltech he married his childhood sweetheart. Then, twenty years and considerable fame later, he divorced and married a much younger woman. Thorne did his graduate work at Princeton under John Archibald Wheeler, a tremendously influential teacher. Wheeler's students include Thorne's very gifted colleague, Charles Misner, as well as everybody's scientist-hero, Richard Feynman. Misner, Thorne and Wheeler are co-authors of the monumental tome, Gravitation. Thorne's reputation in the physics community is primarily based on his work regarding the generation and detection of gravitational waves. He wears a full beard and looks very much like a wild-eyed Mormon elder.

Solutions of the wormhole type appeared right from the start of modern gravitation theory. Karl Schwarzschild achieved an exact solution to the field equations in 1915 only weeks after Einstein's great paper was published. Early in 1916 Ludwig Flamm showed that this solution possessed a wormhole structure.

For many years the Schwarzschild solution was thought to apply only to ordinary stars. It was thought of as the "external" solution, and was mated with one of a number of "internal" solutions that were developed for various models for the material of the star's interior. But none of these internal solutions exhibit the wormhole structure, and so it remained a mere mathematical curiosity in the minds of most theorists. It is true that Herman Weyl studied wormholes in the *1920s,* and that Einstein and Rosen wrote a famous paper in 1935, but it wasn't until Chandrasekar's marvelous prediction of the inescapable collapse of massive stars was finally accepted, that the concept of the black holes, and their associated wormhole structures, was taken seriously. John Wheeler in the 1950s did much to foster interest in wormholes and in gravitational physics in general. His boldly speculative book, Geometrodvnamics, was especially important.

In 1960 a great breakthrough was achieved when M D Kruskal, arguably the most gifted mathematical physicist of recent times, invented a coordinate transformation that lays out the complete space-time structure of black holes. (At least that's how all the authorities see the situation. I have my own ideas but that's another story for which, in the phrase of Conan Doyle, the world is not yet prepared.) Progress in the theory of black holes has been very rapid, and as you know, they are presently accepted as real phenomena almost universally.

Now back to Thorne's response to Sagan's request for a minimally implausible means for very rapid inter-stellar travel. Thorne enlisted his student, Michael Morris, to help with the analysis. They concluded that no naturally occurring black hole, regardless of its mass, angular momentum, electric (or magnetic!) charge, could be used as a wormhole short-cut. They presented a long list of reasons for the unsuitability of these objects. It is amazing to me that the first item on their list was not the fact that the passage through any such natural black hole

wormhole would require an infinite length of time as judged by any outside observer. *This* seems to me to be adequate grounds to dismiss any such wormhole as a short-cut!

The primary concern of Thorne and Morris seemed to be with the terrible gravity gradients which would rip the travelers to shreds, or with the lethal Hawking radiation that would be encountered. Stability to the passage of a spaceship was another problem, and oddly enough, they also mention that such a passage has been shown to permit time travel to the past, which implies the possibility of causality violations. Later in the same paper, discussing their own tailor-made wormholes, they seem to be more comfortable with the prospect of backward time travel, although they do admit that "some readers may regard this [possibility of backward time travel] as indicating that the laws of physics will prevent the ... assembly of wormholes."

What is the connection between wormholes and time-machines? Immediately following the development of the special theory of relativity in 1905, it was recognized that faster-than-light travel would permit backward time travel. This was not seen as a problem since faster-than-light travel was deemed impossible for other reasons. It would, for instance, require an infinite investment of energy.

But if two points in space may be connected by two distinct routes, each one representing a local minimum-distance path - one through regular outer space, the other through a wormhole, a new possibility arises. A trip through the wormhole made at speeds never exceeding the speed of light, as measured by local observers in the wormhole, could have the same result as making the trip through regular space at a speed far exceeding that of light.

In fact, it is easy to concoct a scenario involving two wormholes in which a traveler returns to the origin of his journey at a time earlier than his departure. It must be stated that this scenario makes the naive assumption that wormholes moving at relativistic speeds through space produce no gravitational disturbances that would upset the validity of the special theory of relativity.

I should mention also that the black hole as a time-machine is a separate issue. Using diagrams based upon Kruskal's analysis, it is possible to identify paths through space-time that close on themselves, implying a "Groundhog Day" experience for any person or thing stuck on that path.

One last remark on the connection of wormholes and time-machines: Thorne and his collaborators in a follow-on paper present a single-wormhole time-machine in which one mouth of a wormhole is made to whirl around in a circular motion at nearly the speed of light, while the other mouth remains motionless. Fortunately this model is not critical to the discussion. It seems to me that it only serves to exhibit a total misunderstanding of the meaning of local proper time.

Having dispensed with black holes, Thorne and Morris decided to "roll their own," as it were. They devised a list of requirements that an acceptable time travel wormhole must meet. They then set out to determine what sort of special fields or structures need to be provided at the narrows of the wormhole tube in order that their requirements be met. The list of requirements

is quite reasonable:

(1&2) The wormhole must be a spherically symmetric static solution to Einstein's field equations.
(3) The solution must connect two asymptotically flat regions of space time.
(4) There must be no "event horizon," since otherwise
(a) Only one-way travel (in) is possible.
(b) Transit time is infinite, as judged by outsiders.
(5) Tidal forces must be tolerable.
(6) Transit times must be judged to be brief by external observers as well as by the travelers.
(7) The matter and fields threading the throat must have a "reasonable", .stress-energy tensor.
(8) Solution should be stable to perturbations, especially those caused by the passage of a spaceship.
(9) Required structures should be buildable by an "advanced" civilization.

Perhaps the most interesting conclusion of their study is that regarding the stress-energy tensor for the fields in the "throat" of the wormhole: they found that the material must be what they term "exotic," meaning that the stress energy must exceed the equivalent rest mass energy density. Such material is exotic indeed. For a specific gravity of unity, the required stress is a little over thirteen quadrillion pounds per square inch ($13 \times 10^{15}$ psi)! A pure static magnetic field just barely fails to be exotic, its stress energy being exactly equal to its equivalent mass energy density, but the field strength required for an adequate sized wormhole (3 km) is on the order of $1.6 \times 10^{15}$ tesla (sixteen quintillion gauss).

In a later study, Thorne and Morris, now joined by another graduate student, Ulvi Yurtsever, conclude that what's needed is a field with negative equivalent mass density. This they promise to provide by employing what is known as the Casimir effect. Two identical, perfectly conducting spherical plates are placed one on each side of the throat. Each carries a humongous electric charge, so that they repel each other. According to the quantum-mechanical analysis of Casimir, the phenomenon of virtual particle pair-production causes the time-averaged energy density of the region between the plates to be negative.

I think this is an appropriate place to leave the question as to the physics of wormholes. It seems clear to me that the universe will never see one of these wormhole short-cuts if Thorne and his colleagues are anywhere near correct regarding the difficulties of building and maintaining one. One last thing: Thorne never considers the problem of "aiming" the wormhole. I guess he'd be happy to have the other end wind up wherever it may. Might be embarrassing though.

Let's turn to the philosophical issues which the possibility of backward time travel raises. There is, first of all, a real question as to what is meant by the past. It seems to me that there should be one school of thought that holds that the past is (or perhaps one should say, was) a

definite sequence of events ordered in a definite way in space and in time.

Some people mistakenly think that relativity upsets this notion, but one of the absolutes of that theory is that the sequence in which a set of events separated by time-like intervals occur must be the same for all observers.

According to this "strict constructionist" school then, if one is to return to the past, one must do so in a way that leaves intact every facet of historical fact. This stipulation includes the sequence of mental states of all persons, including any who may be intruders from the future. Thus there can be no memory of the future unless these memories had been experienced as premonitions. The time traveler is constrained to do precisely what he did before: he cannot choose, or even think, to do otherwise. He thus has no free will: but, of course, he cannot be conscious of this absolute constraint of every aspect of his behavior. It is clear also that he can only return to times and places in which he actually lived. A little reflection shows that under this purist interpretation any or all of us may be time travelers from the future; there is no way to tell. The whole concept of backward time travel becomes vacuous.

Many people recognize that it is inconsistent to speak of returning to the past when the history of that past is altered by the very act of returning. To avoid this inconsistency they introduce the concept of "parallel universes." These are as much like the past as possible: they're just enough different to accommodate the intruder from the future. It has never been clear to me whether these are created on the spot to accommodate the junketing time traveler, or whether the have an (almost) independent existence.

The vast majority of time travel fans take a very loose view of what the past means. They are not much bothered by what they reckon to be small inconsistencies, such as buying a big chunk of Xerox stock when it was first listed, but they do worry about things like killing your own grandfather. In other words, they feel it necessary to avoid logical contradictions. This clearly requires some restriction of free will. Some feel that free will is very much like virginity - an all or nothing proposition. Others imagine that we are partly free. Personally, I have a hard time imagining what magical agency enforces this ban on behavior that is - or will turn out to be - contradictory.

It is very surprising, I think, to find that Carl Sagan and Kip Thorne not only accept the possibility of time travel, but embrace the loosest interpretation imaginable. Thus Thorne considers the possibility of returning to the very near past: perhaps ten minutes before the "departure." He imagines the returning time traveler to be a separate being, identical in almost every respect to the time traveler-to-be, except that the former remembers the future of the latter, including the trip backward in time. They can shake hands and have a chat before the traveler-to-be says, "excuse me, but I have to use the time-machine." He then enters the machine and disappears forever.

This scenario seems to violate at least one of the fundamental laws of physics. When the

machine produces a very nearly exact copy of the time traveler, it is creating an object extravagantly rich in order and information: a living, mature, educated human being. This would seem to represent a grievous violation of the second law of thermodynamics, which demands that the total disorder in a closed system must never decrease. One can perhaps calculate the amount of free energy that must be provided to the machine in order to avoid a violation of the second law, but I cannot myself imagine how one can really assess the information content of a human being.

This objection to such time travel is by no means the most serious. As already noted, the possibility of logical contradiction is inherent in time travel to the past. Consider this scenario:

Thip Korne, a timid fellow, inherits a time-machine from an eccentric uncle. He decides to try it for a short, and hence safe (he hopes), trip backward in time. Just ten minutes. He plans to execute the jump at high noon. At 11:50, just as he is sealing the envelope of his new last will and testament, he is startled by the sudden emergence from the machine of his perfect replica. Of course, he knew that this had to happen if all went according to plan, but it was just a theoretical thing. He wasn't prepared for the psychological impact of it. Terrified, he bolts from the house and moves to Brazil where he lives under an assumed name, never returning. His clone, being of the same nature, shuns the machine, but quietly assumes the life of the original Mr Korne.

Now since Mr Korne's double appeared at 11:50, it would seem that the original must have entered the machine at noon: but we know that he bugged out just after 11:50. On the other hand, if his alter ego had not appeared, Thip Korne would certainly have gone through with his plan and entered the time-machine at noon. He enters only if he does not enter: and he does not enter only if he does. A clear logical contradiction.

This "doppelganger" aspect of time travel presents all sorts of weird possibilities. The original, consistent use of the machine as envisioned by Kip Thorne may be diagrammed as shown in figure (1).

As seen from our universe, the sequence is: K' emerges from the machine and shakes hands with K: then K enters the machine and vanishes.

Now consider two "slight" variations. First imagine that after K' appears, K gets cold feet. K', anxious to help, says, "Look, there's nothing to it: watch!" And at the appointed hour he, K', enters the machine. This sequence is shown in figure (2). This case is consistent, but one must admit that it's very strange. Where did K' come from?

For the next variation, imagine that again K is fearful. This time K' reassures him saying, "Look, there's nothing to it: I'll go along and keep you company. and at high noon they enter the machine together, nevermore to be seen. In this case there are two possibilities, as shown in figure (3).

This last example is in a sense the opposite of that which transpired in the story of Mr Thip Korne, shown in figure (4). These two are not consistent, and would be ruled out in a universe in which free will is restricted to preclude such contradictions.

But demanding consistency is no guarantee against strangeness. Let us suppose that both K' and K enter the machine at noon. Then at 11:50, two doppelgangers, K' and K", must have emerged, as shown in figure (5). But there is also the possibility that it is K' and K" that enter the machine at noon: figure (6).

And there is no compelling reason to stop at two: Figure (7).

As is no doubt by now abundantly clear to you, I consider all of this to be the most incredible nonsense ever put forward, even in jest.

Surely you must be joking, Mr. Thorne!

Is it possible that he and his brilliant graduate students, Morris and Yurtsever, along with John Wheeler, Leonid Grishchuk, William Press, Saul Teukolsky, Gary Horowitz, and Carl Sagan and God knows how many other physicists are all prepared to take this dreck seriously? I am flabbergasted.

To me the world is a vast collection of objects in constant motion, tugging on one another, interacting, mixing, combining, producing out of seeming chaos structures of incredible beauty in function as well as in form. To imagine that a return to the past is possible is to deny the reality of the dynamic aspect of the universe. It becomes in this view a dusty, static four-dimensional sculpture hanging in the corner of God's closet.

I, for one, cannot accept this denial of the necessary connection between time and motion. Time is not just another dimension. It is qualitatively different from spatial dimensions. There is, in relativity theory, an absolute distinction between time-like and space-like intervals. If the existence of short-cut wormholes does indeed imply the feasibility of the time-machine, I would take that as proof that such short-cut wormholes cannot exist.

Thank you.

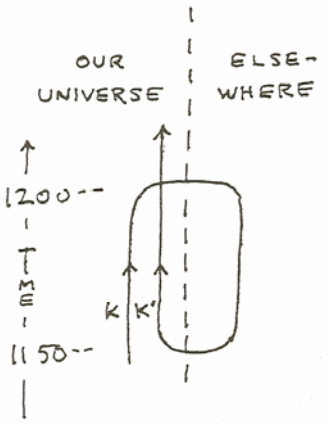


figure (1)

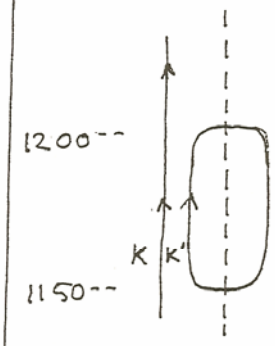


figure (2)

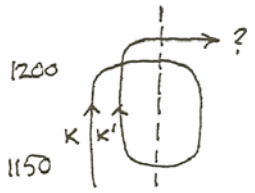


figure (3a)

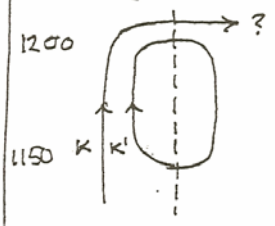


figure (3b)

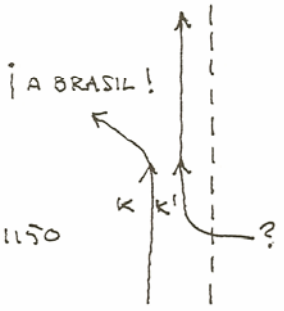


figure (4)

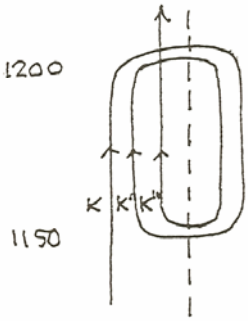


figure (5)

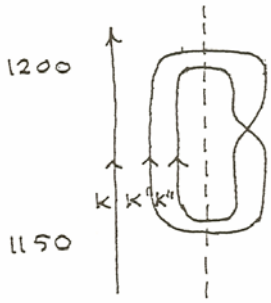


figure (6)

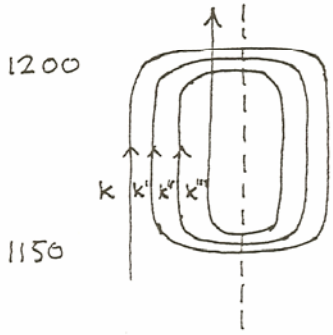


figure (7)