Time machine (1988–2001)

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> "...don't drive yourself crazy try-
> ing to resolve the paradoxes of
> time travel."
>
> L. S. de Camp [1]

The time machine (in its science fiction incarnation) was born back in 19-th century [2], i. e. well before the concept of spacetime appeared. However, it was relativity that provided an adequate language for discussing and studying time machines. In particular, according to special relativity, our world is the Minkowski space and the life history of a pointlike particle is a curve in this space, see Fig. 1. In these terms one can formulate, in quite a meaningful
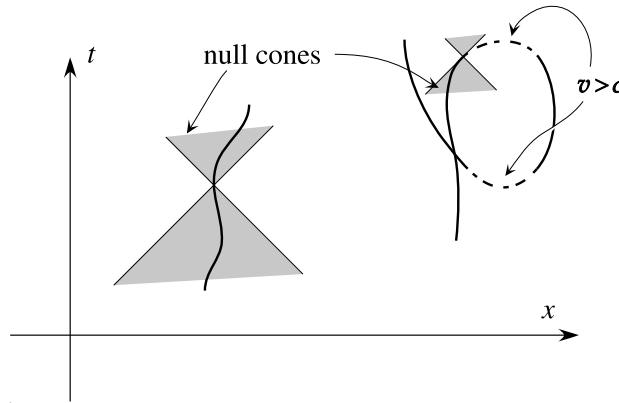

Figure 1: No time machine in special relativity.

way, the question about the existence of time machines, or — which is the

same — about the possibility of an observer meeting his older self. Namely, one can ask, whether a world line of a particle may have a self-intersection. The answer is straightforward. To make a loop a curve must somewhere leave the null cone as shown in Fig. 1. A particle with such a world line would exceed the speed of light and, insofar as no tachyons have been found yet, the time machine is impossible in special relativity.

In general relativity the situation is much less trivial. According to this
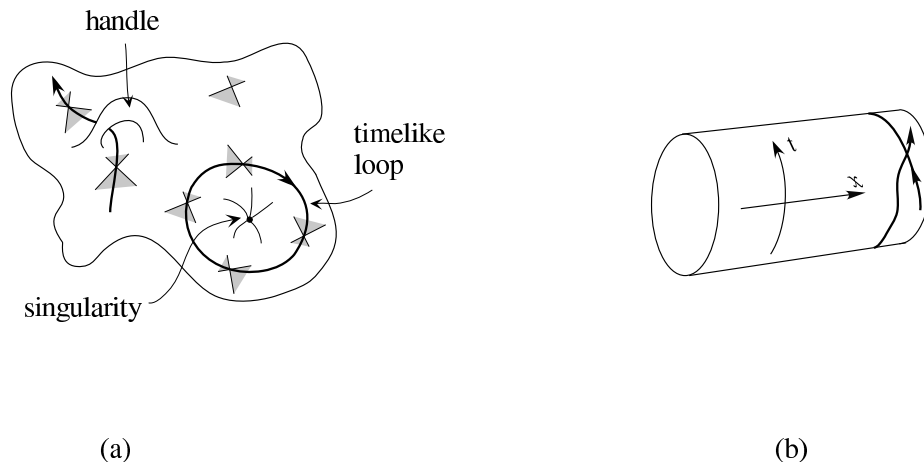

(a)   (b)

Figure 2:   Timelike loops due to the non-trivial geometry (a), or topology (b) of the spacetime.

theory, our spacetime must be a smooth Lorentzian manifold, i. e. in sufficiently small regions it must be 'approximately Minkowskian', but at large scale (as long as the Einstein equations with a reasonable matter source hold), it may have any geometry and topology. There may be holes, handles, see Fig. 2a; almost whatever one wants. And the null cones need not any more look all in the same direction. In particular, spacetimes are conceivable with closed or self-intersecting timelike curves.

A simple example is the Minkowski space rolled into a cylinder, see Fig. 2b. Locally everything is fine in this spacetime, but due to its non-trivial global structure, an observer can meet his younger self. Such spacetimes [3, 4], however, do not deserve the name 'time machine', because the closed timelike curves *always* exist in them. They are not *created* at some

moment. In this sence, a better example is the Deutsch–Politzer (DP) space [5], which we shall describe as a result of the following surgery. Make two cuts in the Minkowski space and glue the upper bank of lower cut to the
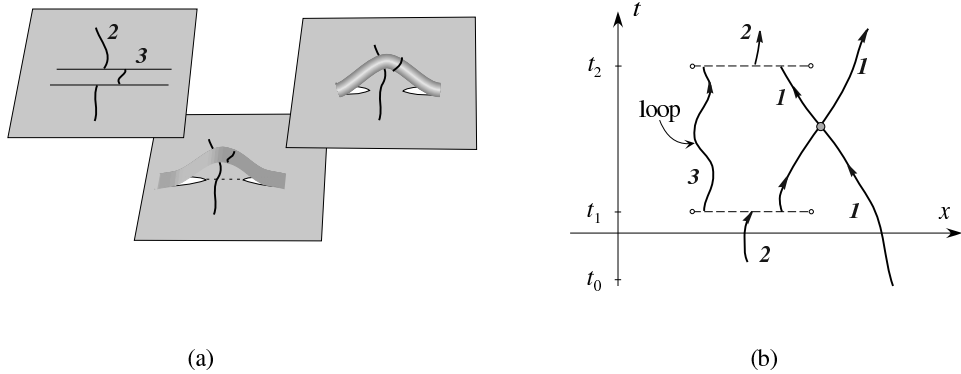

(a)   (b)

Figure 3: (*a*) Preparation of the DP spacetime from the Minkowski plane. (*b*) All lines (1,2,3) are actually continuous.

lower bank of the upper cut and vice verse, as shown in Fig. 3a, so that a cylinder appears attached to the plane. It is convenient to draw the resulting spacetime still as the Minkowski plane, see Fig. 3b, and just to keep in mind that any curve reaching the lower segment must be continued from the upper and, vice verse.

The DP space contains timelike loops, which all lie to the future of a good (causal) region, so it fits the name 'time machine'. This model, of course, in unsuitable for tackling the problem of *building* a time machine (it gives no clue into what could *force* the spacetime to evolve into the time machine instead of just remaining Minkowskian, see below), but is quite adequate in studying what can happen, if for some reason or other a time machine did appear.

One can often read that the existence of a time machine would lead to awful paradoxes contradicting common sense and the notion of free will, or even proving the impossibility of the time machine. Now we can verify this assertion. Let us begin with the notorious grandfather paradox, which is a story of a researcher $\mathscr{R}$, who asks his grandson $\mathscr{G}$ to trip (by time machine) to the past and to kill him ($\mathscr{R}$) in infancy. The grandson tries to grant his wish

(see Fig. 4a), but the problem is: if $\mathscr{G}$ succeeds than the baby does not grow
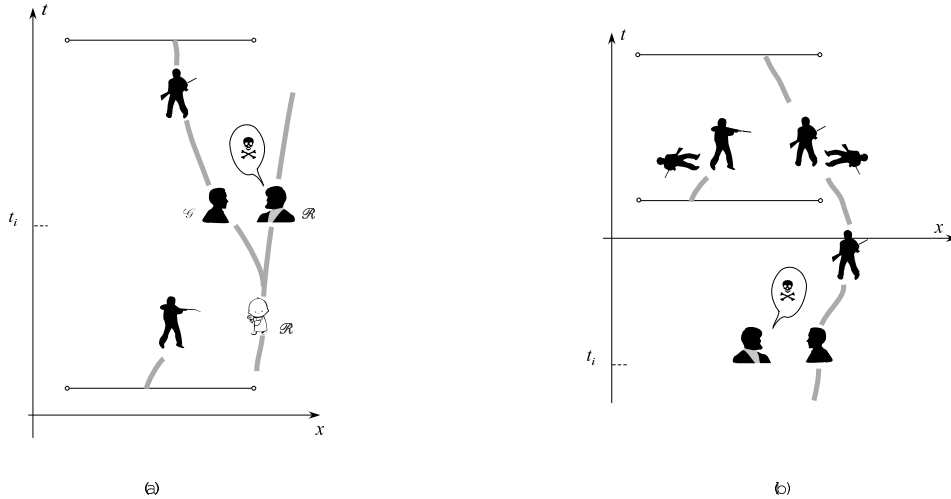

(a)   (b)

Figure 4: A paradox admits a *simple* solution, when the initial conditions being fixed at $t_i \in (t_1, t_2)$ are affected by the outcome of the experiment (*a*), and *none* otherwise (*b*).

up and, correspondingly, does not have any grandchildren that could kill him. Which proves that the grandson *fails* to kill the baby. The circumstances are not detailed, so there is much room for explanations *just why* he fails.

Say, the gun can jam, or the shooter can miss. However, if we arm grandsons again and again (hundreds of times) and *always* only bad shooters get reliable guns, this, of course, would look miraculous. Why cannot we give a good gun to a marksman? Is not this a restriction on our freedom of will?

In fact, the solution of the grandfather paradox is quite simple. The point is that only those persons are *available* for our experiment whose grandfathers by whatever reasons were *not* killed. So, what prevents us from arming a sufficiently good shooter with a sufficiently good gun is not problems with our freedom of will[1], but just the shortage of such shooters. And the better our guns are the fewer marksmans are at our disposal.

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[1]The grandson, being born with already known future life, is such an unusual object that we need not worry about *his* freedom of will.

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A more detailed analysis shows [6] that to avoid such simple solutions one must consider experiments performed *before* the time machine appeared [5]. Indeed, suppose one kindly requests a person to wait until a time machine is built (at some time in the *future*), to enter it, and to kill his (the traveler's) younger self (see Fig. 4b). The situation in the time machine is exactly as paradoxical as in the grandfather case — if the test person is dead when he meets his younger self, he cannot kill the latter, so why he is dead? And if he is alive and shooting, then how come the victim survived? This time, however, the initial conditions do not depend on what occurs in the time machine and the paradox has no simple resolutions. Moreover, being formulated in terms of pointlike particles (which allows one to check *all* possibilities) it has no resolutions *at all* [6].

How to fight the time travel paradox? The most obvious way out would be to forbid the time machines by fiat, to *postulate* causality. But this is not so easy. In 1988 Morris, Thorne, and Yurtsever (MTY) published a paper, where they considered a spacetime M shown in Fig. 5. Geometrically M can
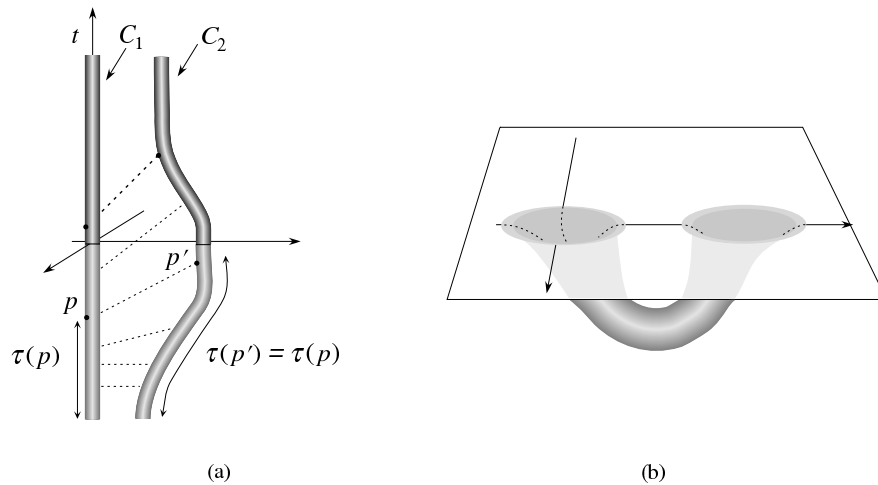

(a)   (b)

Figure 5: (*a*) The dashed lines connect the identified points. (*b*) The section $t = -2$ of M.

be obtained by removing two close cylinders C_1 and C_2 from the Minkowski space and gluing together the boundaries $\mathcal{B}_{1,2} \equiv \mathrm{Bd}\, C_{1,2}$ of the resulting holes

(the junction is then smoothed out by curving appropriately a close vicinity of $\mathcal{B}_1 = \mathcal{B}_2$). The cylinders are taken to be parallel to the t-axis except that C_2 has a bend at, say, $-1 < t < 1$. The gluing must respect the following rule

$$p = p' \quad \Rightarrow \quad \tau(p) = \tau(p'), \tag{$*$}$$

where $\tau(x)$ is defined to be the length of the longest (recall that the metric is Lorentzian) timelike curve lying in $\mathcal{B}_{1,2}$ and connecting x with the surface $t = -2$. Due to the bend, τ grows with time slower on $\mathcal{B}_2$ than on $\mathcal{B}_1$ (the 'twin paradox'). Correspondingly, some of the identified points were causally related in the 'initial' (Minkowski) space. So, there are timelike loops in M. Physically, M presents a spacetime in which a wormhole (see Fig. 5b) evolves so that the distance (in the ambient flat space) between its mouths changes at $-1 < t < 1$ without significant changes in the form or length of the throat (it is this last condition that necessitates the rule $(*)$).

The MTY time machine cannot be banished as easily as the DP one, because we have (in assumption that wormholes exist, they are large and stable, etc.) a specific prescription of how to build it. Precisely this was the point of [7]: assuming the time machines *are* prohibited, exactly how this prohibition is enforced? Suppose, one finds a wormhole, pushes one of its mouths, then pulles it back. What *exactly* will go wrong? What will prevent a closed causal curve from appearance? It was such statement of the problem that gave birth to the time machine as an element of the physical, rather than philosophical, or science fiction realm.

A mechanism that could prevent the appearance of a closed timelike curve was sought for more than a decade, but has never been found [8]. In this sense causality still remains unprotected [9]. But does it mean that an advanced civilization can build a time machine and face the ensuing paradoxes? No, it does not. The point is that there is a great difference between *observing* a time machine appearing by itself and *creating* one. And while the former seemingly is possible, the latter is not. The difference is well exemplified by the DP space. We can prepare a flat region in our spacetime and, for all we know, a time machine well may appear there. But just as well it may not, and we shall have a usual Minkowski space. The choice is up to the spacetime and we can do nothing to affect it. Surprisingly, exactly the same is true for *any* time machine, be it based on a wormhole [7], a cosmic string [10], or whatever else [9]. A theorem [11] proved in 2001 says: *Any spacetime obeying local laws and having no causal loops in its past, has a causal maximal*

extension. Which means (since the Einstein equations are local) that within general relativity a time machine cannot be built.

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