Does Modern Physics Permit the Operation of Time Machines?*

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14 March 2003

Abstract

Recently, many physicists have published on a topic that their predecessors ruminated over only on weekends: time travel and time machines. Most of these publications concern the prospect of time travel or of time machines in classical general relativity. A smaller number investigates the same issues in quantum gravity and quantum field theory. For the purposes of this paper, I will confine myself to results in classical general relativity. My ambition will be to communicate these highly abstract results to a general audience. To this end, I will start out by explicating the concepts of time travel and of time machines. Time travel will be associated with the presence of closed causal curves in a spacetime. A time machine, to put it crudely, is a device that produces such closed causal curves. The physics literature has evolved in the absence of any precise delineation of the spacetime structure that would characterize the operation of these devices. My goals are, first, to specify the spacetime structure required to implement a time machine and, second, to assess an attempted no-go results against time machines due to Sergei Krasnikov (2002a, 2002b), which seems to amount to the prohibition of a very general class of such devices. I argue that this theorem leaves open the possibility of an *incremental time machine*, a device that increases the probability of the emergence of closed timelike curves. I close by discussing some of the technical difficulties arising from such a reformulation of the problem.

*I am indebted to Phil Dowe, John Earman, Arthur Fine, Brian Hepburn, John Norton, Christopher Smeenk, and James Tabery for discussions and comments.

1. Introduction. Philosophers have long been intrigued by the prospect of travelling back in time. They have debated the paradoxical consequences that arise from this possibility, in particular the infamous grandfather paradox.[1] The grandfather paradox states that a time traveller undertakes the assassination of his grandfather before Grandfather gets the opportunity to beget his father, thereby precluding his own birth, and consequently preventing himself from travelling back in time to execute his mean intention. In general, discussions of the issue have focused on the agency of bringing about some event in the past, which then produces some contradiction to present facts of the matter. The causal loops at stake were usually taken to involve an agent who initiates a change in the past by means of backward causation. Until a few years ago, the received view in philosophy maintained that time travel is therefore not possible on logical or conceptual grounds.

In recent years, also under the impression of an emerging consensus in the physics community that the possibility of time travel had to be taken seriously, the front lines of the debate have significantly changed. It is widely believed today that the existence of closed causal loops in itself does not engender paradox.[2] However, the possibility of such loops imposes consistency constraints on the range of admissible scenarios. The current debate centres on whether these consistency constraints can be generated from the resources of physical theories or are dictated by merely logical considerations. It seems reasonable to surmise that the answer to this question has to be found in a conceptual analysis of the relevant physical theories.

2. Time travel in Classical General Relativity. The possibility of time travel (TT) in classical general relativity (CGR) has long been known, at least since Gödel (1949) found a solution of the Einstein field equations (EFEs) which contains closed timelike curves (CTCs). CTCs represent permitted paths for material particles that are continuous, timelike, future-directed curves intersecting themselves, thus forming causal loops. These CTCs, nota bene, emerge as a result of the geometric structure of spacetime rather than from an action performed by an agent attempting to travel back in time. I call a spacetime that does not contain CTCs a *causal* spacetime, and *acausal* otherwise. It is important to note that CTCs are not due to some form of backward causation, but, as they are timelike everywhere, only require standard forward causation. Thus, many of the original philosophi-

[1] The *loci classici* of this debate are Dummett 1964, Lewis 1976, and Mellor 1998, 132-135.

[2] And that some of the adduced arguments against the admissibility of causal loops are thus fallacious. See e.g. Berkovitz 2001 and Dowe 2002.

cal worries do not apply.

As we have no indication that the spacetime region we inhabit is afflicted by the presence of causal circularities, there is widespread agreement that we do not live in a globally acausal universe. Most of the spacetimes containing CTCs, therefore, are not taken to represent a relevant cosmological model. However, when it comes to astrophysical objects, the situation changes. The most prominent example of a spacetime representation of such an object, the Kerr-Newman solution, describes the gravitational collapse of a star and harbours CTCs in its maximal extension (Hawking and Ellis 1973, section 5.6). The resulting ring singularity has a mass, rotates around its axis of symmetry, and is electromagnetically charged. Although it is believed that such objects do indeed exist and that the Kerr-Newman solution thus gains physical relevance, there remain several challenges to the practicability of time travel in Kerr-Newman spacetimes, such as the astronomical energy requirements for a spacecraft scheduled to follow the CTCs.

Because all spacetimes contaminated with CTCs turned out either to be unphysical entirely or to contain CTCs only in inaccessible regions, the problem of time travel was largely regarded as academic. All this changed as a result of two seminal articles by Morris and Thorne in 1988, which communicated the possibility that an advanced civilisation might produce CTCs where otherwise none would have existed. Physicists started to take the possibility of time machines (TMs) seriously and devoted their attention, as Hawking would put it, 'to making the universe safe for historians'. A TM is a device that creates CTCs in a region to the future of its operation, where otherwise none would have transpired. Thus, spacetimes that allow for TMs stand in contrast to spacetimes with 'naturally' occurring CTCs, i.e. physically possible worlds where the time traveller can take advantage of the pre-existing acausal structure of the spacetime to travel along a CTC without the need to produce one. TT, therefore, can occur in a much wider range of scenarios than only as a result of the operation of a TM.

The physicists' attempts to achieve the goal of making the universe safe for historians focused on extracting no-go theorems for TMs from the resources of CGR itself, generally by imposing further conditions such as the weak energy condition (WEC). The most promising of these results was Hawking's Chronology Protection Theorem (Hawking 1992, 2002).[3] Several other no-go theorems for limited cases have been proved. But, as Earman et al. (2003) argued, this and other partial no-go theorems have not conclusively established the impossibility to operate a TM. They propose a

[3]For a serviceable survey of the results obtained up to 1995, see Earman 1995.

necessary condition for the operation of a TM, the so-called 'potency condition' (PC). In section 3, I review PC and other general properties that need to be satisfied such that an arbitrarily advanced civilisation could operate a TM.

On 7 August 2002, Krasnikov (2002b; cf. also 2002a) published a new theorem pertaining to the possibility of TMs. In fact, Krasnikov's theorem suggests that the PC must be violated in a very general class of spacetimes. I discuss this novel result, its relevance for TMs, and its implications for the PC in section 4. This will lead me to reconsider the PC in section 5 and to conclude that Krasnikov's Theorem does not prohibit a weaker version of the PC to hold. Such a weaker PC entails that the operator does not have the full control over her TM. Rather, if a mitigated PC holds, she could only increase the probability of the emergence of CTCs by operating her TM. In section 5, I will evaluate the prospect of definite results in this direction.

3. Time Machines and the Potency Condition. We need to specify some general features a spacetime must display in order to qualify as a universe which allows for the operation of TMs. Unfortunately, it is in principle impossible to list conditions on some finite spacetime region that are sufficient to causally determine the emergence of CTCs. However, there are necessary conditions that have to be fulfilled for the operation of a proper TM in relativistic spacetimes. To these, I now turn.

First, the spacetime $(\mathcal{M}, g_{\mu\nu})$ must permit a global spacelike hypersurface Σ that divides $\mathcal{M}$ into a 'before' and an 'after'. Given the failure of absolute simultaneity, of course, these temporal relations should not be taken to imply that all points in Σ are simultaneous, but rather that the hypersurface Σ intersects all future-directed timelike curves (henceforth 'chronological curves'), demarcating a past and a future section. An assignment of past and future sections of those chronological curves that intersect Σ is *unique* if and only if the curves intersect Σ only once. A spacelike hypersurface Σ is then called a *partial Cauchy surface* if no causal (i.e. future-directed and non-spacelike) curve intersects Σ in more than one point. Apart from insisting that Σ be a partial Cauchy surface, we also demand that $\mathcal{M}$ is causal up to, and including, 'time' Σ. If this were not the case, then why should anyone bother to construct a TM? To capture this idea more precisely, some terminology is in order.

A TM requires more than a spacelike hypersurface. It involves initial data on Σ such that their manipulation within some finite and compact region K—the TM region—of the future domain of dependence $D^+(\Sigma)$, i.e. the region of spacetime for which all causal influences emanate from Σ,[4] brings about the existence of a region where CTCs occur. This region is termed the *chronology-violating domain* V. If any causal signals are supposed to reach V from K at all, then $V \subset J^+(K)$, where $J^+(\mathcal{U})$ is the *causal future of* $\mathcal{U}$, defined as the set of all points in $\mathcal{M}$ which can be reached from $\mathcal{U}$ by a causal curve in $\mathcal{M}$. ($J^-(\mathcal{U})$, the causal past of $\mathcal{U}$, is defined analogously) For an illustration, see Fig. 1. Similarly, $I^{\pm}(\mathcal{U})$ denotes the *chronological*

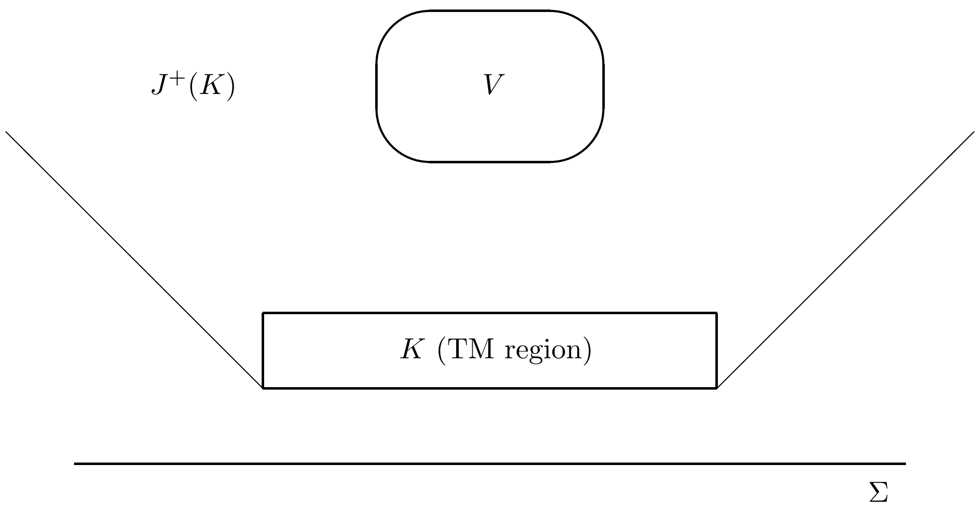

Figure 1: Basic structure of a TM spacetime.

future (past) of $\mathcal{U}$ defined as the set of all points in $\mathcal{M}$ which can be reached from $\mathcal{U}$ by a chronological curve in $\mathcal{M}$ (set of all points in $\mathcal{M}$ from which $\mathcal{U}$ can be reached by a chronological curve in $\mathcal{M}$). In what follows, I want to make the following explicit

Assumption 1. *No CTCs exist in* $I^-(\Sigma)$.

A sufficient condition for the operation of a TM would be the time traveller's ability to bring about the emergence of CTCs in a causally deterministic way, i.e. such that *all* causal curves that reach V intersect Σ. Clearly,

[4]The past domain of dependence $D^-(\Sigma)$ is defined analogously. The domain of dependence $D(\Sigma)$ is defined as $D^+(\Sigma) \cup D^-(\Sigma)$.

the above requirement that $V \subset J^+(K)$ does not preclude the possibility that causal influences from outside $J^-(V) \cap \Sigma$ penetrate V. Causal influences on V emanating from outside Σ are avoided if and only if $V \subset D^+(\Sigma)$, which cannot be the case since V contains CTCs and Σ is a partial Cauchy surface. Therefore, there exist causal curves that reach V and yet do not intersect Σ. Although it may thus become a daunting task to define *sufficient* criteria for the operation of a TM, it is possible to find more stringent necessary conditions.

The possibility of creating CTCs as an unavoidable result of the operation of a TM in K in terms of causal determinism is hence precluded. However, there must be some sense in which the operation of a TM brings about the emergence of CTCs, for otherwise the device could not rightfully be called a TM. The task at hand, then, is to find the strongest sense in which the appearance of CTCs can be due to the operation of a TM in K and to define a necessary condition that has to be met in order for the scenario to qualify as a case of a TM in this sense. Earman et al. (2003) have suggested such a necessary criterion, viz. what they dub the

Potency Condition (PC). *In a TM scenario, every smooth, maximal, hole-free extension of $D^+(\Sigma)$ contains CTCs. These extensions must be solutions of the Einstein field equations (EFEs) and satisfy energy conditions.*

The PC requirements for admissible extensions as specified are widely agreed upon as watermarks of physical plausibility. In particular, the hole freeness is important as it prevents additional causal influences from reaching V apart from those from outside of $J^-(V) \cap \Sigma$ we had to accept earlier. Hole freeness assures the absence of tears in the spacetime fabric and thus minimises the causal influences on V not emanating from Σ.

4. Krasnikov's No-Go Theorem. The evolution of a spacetime in CGR is fundamentally non-unique. Into whatever extension $\mathcal{U}' \supsetneq \mathcal{U}$ the initial spacetime $\mathcal{U}$ evolves, there always exists a spacetime $\mathcal{U}''$—and in fact, infinitely many—which also represents a possible evolution of $\mathcal{U}$. The question of no-go theorems can thus be reformulated as the search for general classes of spacetimes for which all maximal extensions contain CTCs, or at least all maximal extensions satisfying certain criteria. Krasnikov (2002a, 2002b) has recently proved a theorem suggesting that whatever happens in the causal region of a spacetime $\mathcal{M}$, it can always evolve according to a maximal extension where $V = \emptyset$, thereby violating PC and disallowing TMs.

That the operation of a TM is indeed impossible is suggested by a recent theorem due to Krasnikov (2002b):

Krasnikov's Theorem (KT). *Any spacetime $\mathcal{U}$ has a maximal extension $\mathcal{M}_{max}$ such that all closed causal curves in $\mathcal{M}_{max}$ (if they exist there) are confined to the chronological past of $\mathcal{U}$.*

In other words, there is always a possible evolution of a causal spacetime beyond the Cauchy horizon such that it preserves its causal nature. KT entails that any set of initial data on Σ can be evolved without creating CTCs. Therefore, in any causal spacetime, the laws of motion, which, for their validity inside a region $\mathcal{U}$, do not depend on anything beyond $\mathcal{U}$, are compatible with any initial data in this causal region. If a TM is understood as a device which necessarily has to comply with PC, then KT effectively claims to prohibit their operation (Wüthrich 2002).

While it does not outlaw TT altogether, KT prohibits the TM operator to bring about an *inevitable* appearance of CTCs to the future of Σ. There may still pop up, at some point into the future of Σ, CTCs. Typically, a causal spacetime can still evolve into one of infinitely many extensions containing CTCs. Nothing was said as to which one of these extensions the initial spacetime will actually evolve into. KT only asserted that there always exists the possibility that the operation of a TM fails.

Thus, CTCs can emerge, as Krasnikov puts it, 'spontaneously', as opposed to the 'artificially crafted' CTCs. The problem is that this is true in spite of the locally causal character of the dynamical laws. Arntzenius and Maudlin (2000) have argued that TT generically results not in contradictions in V nor in constraints on the initial data on Σ, but rather in an underdetermination of what happens beyond the future Cauchy horizon by the initial data. The task at hand, it seems, should be to try and find natural laws or additional conditions that restrict the class of admissible extensions beyond the future Cauchy horizon and whose validity can be independently confirmed. But this is not what KT achieves: rather than confining the range of possibilities, it shows that no setting of initial data on Σ can necessitate the emergence of CTCs.

What should we make of Krasnikov's claim that his result shows that PC must be violated? Surely, the possibility that the time traveller can comply with PC is saved if it turns out that there are cases in which all CTC-free maximal extensions of $D(\Sigma)$ violate one or several of the further requirements of PC. The TM operator could maintain her hope on the basis that the spacetimes Krasnikov considers are only minimally specified in that they have to be manifolds with Lorentz metrics. In other words, how can it be ascertained that if $D(\Sigma)$ is hole-free, and it satisfies the EFEs and energy conditions, that at least one of its evolutions-*sans*-CTCs does as well?

In spite of the lack of a conclusive result, there seem to be no problems with respect to hole freeness. The concept of *causal convexity* of spacetimes central to Krasnikov's proof seems to bar the danger of holes appearing in the spacetime fabric. Also with respect to EFEs and energy conditions, Krasnikov's result seems to dash the hopes of our TM operator. If we impose local requirements on the metric by specifying the properties of the stress-energy tensor, then for any manifold $\mathcal{U}$ with a metric that satisfies these requirements, there is a maximal extension such that all CTCs are confined to the chronological past of $\mathcal{U}$ and this maximal extension also satisfies the same local conditions on its metric.[5] In particular, if $(\mathcal{U}, g_{\mu\nu}|_{\mathcal{U}})$ satisfies EFEs and energy conditions, then it can be extended to a CTC-free spacetime that does so as well. Thus, KT establishes the violation of PC.

5. Incremental Time Machines. What retreat strategies are open to a would-be TM operator in the aftermath of KT? Now that KT has effectively dismantled her hopes to necessitate the appearance of CTCs, the TM operator finds herself in dire need of realigning the conceptual support for her business. First, it turned out to be impossible to uniquely determine an extension containing CTCs by setting the initial data on Σ appropriately, because any initial data uniquely determine (up to a diffeomorphism) an extension only within the domain of dependence $D(\Sigma)$ and the causality violation region V lies without this domain. Next, the prospect of suitably manipulating the initial data on Σ such as to restrict the range of admissible extensions to those which contain CTCs was shattered by KT. But, as was stated in the previous section, nothing so far precludes the emergence of spontaneous CTCs.

In order to stem the spontaneous appearance of CTCs in future extensions into which a causal spacetime with suitable physical properties can evolve, one would have to appeal to—and prove—robust no-go theorems. Lacking these, the TM operator may still identify loopholes to be exploited to her end. An obvious attempt to save her from bankruptcy is to reformulate PC into a somewhat less rigid criterion which has to be met in order for her craft to qualify as a TM. Define an *incremental time machine* (ITM) as a device that creates a tendency of a spacetime to evolve towards an extension with CTCs. Creating a tendency of a spacetime to evolve into CTC-containing extensions means to increase the 'measure' of evolutions with non-empty causality-violating regions V. The PC would then have to

[5] I wish to thank Serguei Krasnikov for a personal communication which helped me to appreciate this point.

be restated accordingly as a

Mitigated Potency Condition (MPC). *The operation of an ITM must increase the measure of those extensions of $D(\Sigma)$ containing CTCs among the set of all suitable extensions. Admissible extensions must be smooth, maximal, hole-free, and satisfy EFEs and WEC in order to be suitable.*

By construction, KT does not have any implications for MPC over and above the acknowledgment that the operation of an ITM cannot increase the 'probability' that CTCs emerge in the extension to 1.[6] Intuitively, it should be possible to operate an ITM, if only for the reason that the choice of initial data on Σ should affect in some way how history unfolds. Also, MPC is not an unreasonable criterion for the operation of a device that qualifies as a time machine. After all, even advanced technology may fail and regular aircrafts do not, unfortunately, always reach their destination. In this sense, it seems too demanding to require that CTCs transpire in *any* evolution as the result of the operation of a time machine. If the device would be potent enough to reliably create CTCs in almost all cases, obtaining risk capital to start a time travel agency should not be a problem.

The most powerful insights could be gained, of course, if we developed an understanding of the physical mechanisms associated with the production of CTCs. Such a theory of time machines would provide probabilities as a measure of how likely some manipulations of the initial data are to produce CTCs. Such a theory would have to allow for physical probabilities as opposed to measures over non-stochastically produced evolutions of $D(\Sigma)$. In order for these probabilities to be calculable, the mechanism which is unleashed by the operation of an ITM and which conveys the causal signal into the future extension of $D(\Sigma)$ must be known. If we do not want to open a Pandora's box of counterfactual discourse, this mechanism must provide a calculable alteration of the relevant probabilities. However, the prospects of this path seem rather dim.

Although knowledge of the mechanics of an ITM may be practically unattainable, definite results may still be obtained by determining the measure of the set of extensions harbouring CTCs. Ideally, measures of this set could be compared between two possible worlds, in one of which the ITM operates while in the other it does not. The great advantage of this approach is the weakness of the former: it requires no understanding of the details of the operation of an ITM.

[6] It still could, however, increase the *measure* to one as the CTC-free extensions might be of measure zero.

The first problem, then, is to find the set of admissible extensions for any given causal spacetime. The main difficulty in this respect derives from the non-linearity of the EFEs which has so far frustrated attempts to find their analytic solution. The self-interaction of the gravitational field instils this non-linearity even in the absence of other fields. In other words, in CGR, the underlying spacetime cannot considered as a fixed background on which the field evolves. Rather, the joint system of a field-*cum*-spacetime must co-evolve. But as long as the most general solution of the EFEs is unknown, it is unclear how the set of admissible evolutions could be established.

The second difficulty concerns the assignment of measures to the 'space' of admissible extensions, once we have found this space. Unfortunately, there is not much in the literature that would help in assigning such measures. Most of the attempts to define canonical measures over sets of solutions focus on causally well-behaved spacetimes, such as the Friedmann-Lemaître-Robertson-Walker cosmological models.[7] Mostly, these measures have been designed to deal with the 'flatness problem' of standard cosmology in an attempt to avoid inflationary scenarios. However, extant results in this field can hardly be applied to the present purpose as they only extend to a particular parameter family of well-understood solutions. Without the most general analytic solution at hand and thus lacking the parameters over which these solutions range, introducing measures to the space of all possible solutions of the EFEs will be astronomically difficult if possible at all.

In principle, results can be obtained without reference to measures. Rather than measuring extensions with CTCs, we could count them. Presumably, a theorem analogous to KT may be found which shows that it is always possible to find an extension which respects certain local conditions while displaying CTCs. Maybe we can establish a theorem of 'parallel existence' according to which there exists, for every causally virtuous extension, an extension with CTCs. Take, for instance, any 'clean' extension received with the help of KT. It seems that any one of these extension could be infected e.g. with a Deutsch-Politzer gate, thus producing CTCs (Deutsch 1991; Politzer 1992). However, such limited theorems could at best serve to strengthen our intuitions. In order to obtain more conclusive statements about the genericity of causal and acausal extensions, one would have to establish theorems asserting the open density of one of the two families of extensions, causal or acausal, thus showing that it is of measure 1, while its complement is 'nowhere dense' and therefore of zero measure. Such a proof,

[7]Hawking and Page 1988; Cho and Kantowski 1994; Coule 1995. I wish to thank Chris Smeenk for references and helpful comments on this topic.

however, would again require a metrical structure on the space of extensions.

Unfortunately, to sum up, unlike in the case of the original PC where knowledge of the mechanism of the TM was not necessary, the notions of ITM and MPC remain rather vague as long as we are ignorant of how an ITM can be realised in terms of calculable physical processes and how these processes interact with the spacetime structure. Also, as long as no canonical measure over extensions can be introduced, assessing the prospect of an ITM remains a daunting task. I see no obvious way out of the quandary.

6. Conclusions. The fact that CGR allows for evolutions that host CTCs has renewed interest among physicists and philosophers of science in the possibility of time travel and time machines. In the present paper, I have discussed the possibility of the operation of a device that produces CTCs in the light of recent results.

According to PC, such a device can be dubbed a TM if it brings about the appearance of CTCs in all its future extensions by manipulation of the initial data on a (global) partial Cauchy surface that delimits the causal past of the time travelling age. A recent theorem due to Krasnikov, however, shows that for a very general class of scenarios, the emergence of CTCs can be circumvented. He proved that any spacetime can be maximally extended such that all CTCs, if they transpire at all, are confined to the chronological past of the spacetime. The result was a violation of the PC in our typical TM scenario. However, the time traveller can retreat to a mitigated PC according to which the operation of an incremental TM increases the likelihood that any physically suitable extension of the domain of dependence of Σ contains CTCs. The assessment of MPC, however, faces difficulties regarding the definition (and justification) of a measure on the space of extensions as well as the challenge to find an intelligible, i.e. calculable, physical mechanisms that would amount to an ITM. But without having overcome these obstacles, there is little hope of a fruitful investigation of ITMs.

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