11 Recent work on time travel

JOHN EARMAN

Introduction

Over the last few years leading scientific journals have been publishing articles dealing with time travel and time machines. (An unsystematic survey produced the following count for 1990–1992. *Physical Review D*: 11; *Physical Review Letters*: 5; *Classical and Quantum Gravity*: 3; *Annals of the New York Academy of Sciences*: 2; *Journal of Mathematical Physics*: 1. A total of 22 articles involving 22 authors.[1]) Why? Have physicists decided to set up in competition with science fiction writers and Hollywood producers? More seriously, does this research cast any light on the sorts of problems and puzzles that have featured in the philosophical literature on time travel?

The last question is not easy to answer. The philosophical literature on time travel is full of sound and fury, but the significance remains opaque. Most of the literature focuses on two matters, backward causation and the paradoxes of time travel.[2] Properly understood, the first is irrelevant to the type of time travel most deserving of serious attention; and the latter, while always good for a chuckle, are a crude and unilluminating means of approaching some delicate and deep issues about the nature of physical possibility. The overarching goal of this chapter is to refocus attention on what I take to be the

1 See Carroll, Farhi, & Guth (1992); Charlton & Clarke (1990); Cutler (1992); Deser, Jakiw, & 't Hooft (1992); Deutsch (1991); Echeverria, Klinkhammer, & Thorne (1991); Friedman & Morris (1991a, 1991b); Friedman, Morris, Novikov, Echeverria, Klinkhammer, Thorne, & Yurtsever (1990); Frolov (1991); Frolov & Novikov (1990); Gibbons & Hawking (1992); Gott (1991); Hawking (1992); Kim & Thorne (1991); Klinkhammer (1992); Novikov (1992); Ori (1991); 't Hooft (1992); Thorne (1991); Yurtsever (1990, 1991). See also Deser (1993); Goldwirth, Perry, & Piran (1993); Mikheeva & Novikov (1992); Morris, Thorne, & Yurtsever (1988); and Novikov (1989).

2 A representative but by no means complete sample of this literature is given by Brown (1992); Chapman (1982); Dummett (1986); Dwyer (1975, 1977, 1978); Ehring (1987); Harrison (1971); Horwich (1987); Lewis (1976); MacBeath (1982); Mellor (1981); Smith (1986); Thom (1975); and Weir (1988).

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important unresolved problems about time travel and to use the recent work in physics to sharpen the formulation of these issues.[3]

The plan of the chapter is as follows. Section 1 distinguishes two main types of time travel – Wellsian and Gödelian. The Wellsian type is inextricably bound up with backward causation. By contrast, the Gödelian type does not involve backward causation, at least not in the form that arises in Wellsian stories of time travel. This is not to say, however, that Gödelian time travel is unproblematic. The bulk of the chapter is devoted to attempts, first, to get a more accurate fix on what the problems are and, second, to provide an assessment of the different means of dealing with these problems. Section 2 provides a brief excursion into the hierarchy of causality conditions on relativistic spacetimes and introduces the concepts needed to assess the problems and prospects of Gödelian time travel. Section 3 reviews the known examples of general relativistic cosmological models allowing Gödelian time travel. Since Gödel's discovery,[4] it has been found that closed timelike curves (CTCs) exist in a wide variety of solutions to Einstein's field equations (EFE). This suggests that insofar as classical general relativity theory is to be taken seriously, so must the possibility of Gödelian time travel. Section 4 introduces the infamous grandfather paradox of time travel. It is argued that such paradoxes involve both less and more than initially meets the eye. Such paradoxes cannot possibly show that time travel is conceptually or physically impossible. Rather the parading of the paradoxes is a rather ham-fisted way of making the point that local data in spacetimes with CTCs are constrained in unfamiliar ways. The shape and status of these constraints has to be discerned by other means. Section 5 poses the problem of the status of the consistency constraints in terms of an apparent incongruence between two concepts of physical possibility that diverge when CTCs are present. Section 6 considers various therapies for the time travel malaise caused by this incongruence. My preferred therapy would provide an account of laws of nature on which the consistency constraints entailed by CTCs are themselves laws. I offer an account of laws that holds out the hope of implementing the preferred therapy. This approach is investigated by looking at recent work in physics concerning the nature of consistency constraints for both non-self-interacting systems (section 7) and self-interacting systems (section 8) in

[3] Although it is a truism, it needs repeating that philosophy of science quickly becomes sterile when it loses contact with what is going on in science.

[4] Gödel (1949a).

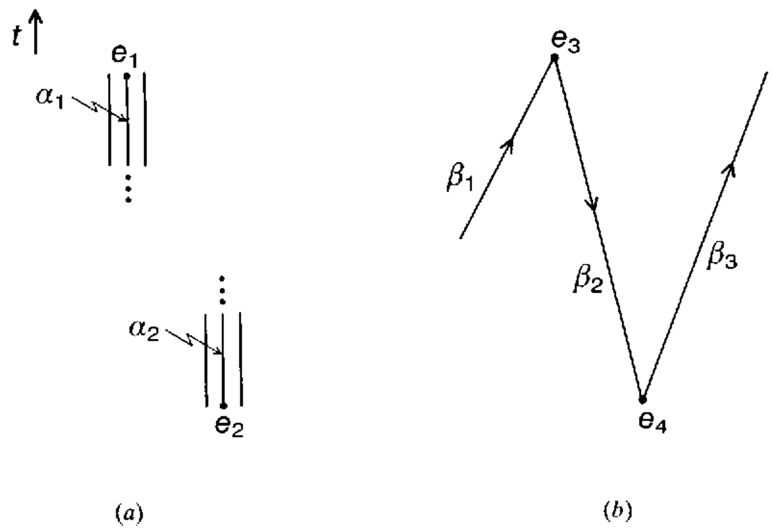

Fig. 1. Two forms of Wellsian time travel

spacetimes with CTCs. Section 9 investigates a question that is related to but different from the question of whether time travel is possible; namely, is it possible to build a time machine that will produce CTCs where none existed before? Some concluding remarks are given in section 10.

1 Types of time travel; backward causation

Two quite different types of time travel feature in the science fiction and the philosophical literature, though the stories are often vague enough that it is hard to tell which is intended (or whether some altogether different mechanism is supposed to be operating). In what I will call the *Wellsian type*[5] the time travel takes place in a garden variety spacetime – say, Newtonian spacetime of classical physics or Minkowski spacetime of special relativistic physics. So the funny business in this kind of time travel does not enter in terms of spatiotemporal structure but in two other places: the structure of the world lines of the time travellers and the causal relations among the events on these world lines. Figure 1 illustrates two variants of the Wellsian theme. Figure 1(*a*) shows the time traveller α_1 cruising along in his time machine. At e_1 he sets the time travel dial to 'minus 200 years', throws the

[5] This appellation is suggested by some passages in H. G. Wells' *Time Machine* (1895), but I do not claim to have captured what Wells meant by time travel. For a review of and references to some of the science fiction literature on time travel, see Gardner (1988).

switch, and *presto* he and the machine disappear. Two hundred years prior to e_1 (as measured in Newtonian absolute time or the inertial time (t) of the frame in which α_1 is at rest) a person (α_2) exactly resembling the time traveller both in terms of physical appearance and mental state pops into existence at e_2. Even if we swallow these extraordinary occurrences, the description given so far does not justify the appellation of 'time travel'. That appellation requires that although α_1 is discontinuous with α_2, α_2 is in some appropriate sense a continuation of α_1. Whatever else that sense involves, it seems to require that events on α_1 cause the events on α_2. Thus enters backward causation.

Figure 1(*b*) also involves funny world line structure, but now instead of being discontinuous, the world line 'bends backwards' on itself, the arrows on the various segments indicating increasing biological time. Of course, as with the previous case, this one also admits an alternative interpretation that involves no time travel. As described in external time, the sequence of events is as follows. At e_4 a pair of middle aged twins are spontaneously created; the β_3 twin ages in the normal way while his β_2 brother gets progressively younger; meanwhile, a third person, β_1, who undergoes normal biological aging and who is the temporal mirror image of β_2, is cruising for a fateful meeting with β_2; when β_1 and β_2 meet at e_3 they annihilate one another. Once again, the preference for the time travel description seems to require a causal significance to the arrows on the world line segments so that, for example, later events on β_1 (as measured in external time) cause earlier events on β_2 (again as measured in external time).

Much of the philosophical literature on Wellsian time travel revolves around the question of whether backward causation is conceptually or physically possible, with the discussion of this question often focusing on the 'paradoxes' to which backward causation would give rise. I will not treat these paradoxes here except to say that they have various similarities to the paradoxes of Gödelian time travel that will receive detailed treatment in section 4. But aside from such paradoxes, there is the prior matter of whether the phenomena represented in figure 1 are physically possible, even when shorn of their time travel/backward causation interpretations. In figure 1(*a*), for example, the creation *ex nihilo* at e_2 and the extinction *ad nihilo* at e_1 are at odds with well entrenched conservation principles. Of course, the scenario can be modified so that conservation of mass–energy is respected: at e_1 the time traveller and the time machine dematerialize as before but now their mass is replaced by an equivalent amount of energy, while at e_2

a non-material form of energy is converted into an equivalent amount of ponderable matter. But this emended scenario is much less receptive to a time travel/backward causation reading. For the causal resultants from e_1 can be traced forwards in time in the usual way while the causal antecedents to e_2 can be traced backwards in time, thus weakening the motivation for seeing a causal link going from e_1 to e_2.

At first blush Gödelian time travel would seem to have three advantages over Wellsian time travel. First, on the most straightforward reading of physical possibility – compatibility with accepted laws of physics – Gödelian time travel would seem to count as physically possible, at least as regards the laws of the general theory of relativity (GTR). Second, unlike stories of Wellsian time travel, Gödelian stories are not open to a rereading on which no time travel takes place. And third, no backward causation is involved. On further analysis, however, the first advantage turns out to be something of a mirage since (as discussed below in sections 5–8) Gödelian time travel produces a tension in the naive conception of physical possibility. And the second and third advantages are gained in a manner that could lead one to object that so-called Gödelian time travel is not time travel after all.

To begin the explanation of the claims, I need to say in some detail what is meant by Gödelian time travel. This type of time travel does not involve any funny business with discontinuous world lines or world lines that are 'bent backwards' on themselves. Rather the funny business all derives from the structure of the spacetime which, of course, cannot be Newtonian or Minkowskian. The funny spacetimes contain continuous and even infinitely differentiable timelike curves such that if one traces along such a curve, always moving in the future direction as defined by the globally defined external time orientation, one eventually returns to the very same spacetime location from whence one began. There is no room here for equivocation or alternative descriptions; hence the second advantage. (More cautiously and more precisely, there are some spacetimes admitting Gödelian time travel in the form of closed, future directed timelike curves, and the curves cannot be unrolled into open curves on which events are repeated over and over *ad infinitum* – at least such a reinterpretation cannot be made without doing damage to the local topological features of the spacetime; see section 3.) As for the third advantage, consider a CTC γ that is instantiated by, say, a massive particle. Pick two nearby events $x, y \in \gamma$ such that x chronologically precedes y ($x \ll y$ in the notation defined in section 2). One might be tempted to say that backward causation is involved since although y is chronologically later than x, y causally affects x. But the situation here is quite different from that in Wellsian time travel. In universes with Gödelian time travel it is consistent to assume – and, in fact, is implicitly assumed in standard relativistic treatments – that all causal influences in the form of energy–momentum transfers propagate forward in time with a speed less than or equal to that of light. So in the case at issue, y is a cause of x because $y \ll x$ and because there is a continuous causal process linking y to x and involving *always future directed causal propagation*. Of course, one could posit that there is another kind of causal influence, not involving energy–momentum transfer, by which y affects x backwards in time, so that even if the future directed segment of γ from y to x were to disappear, y would still be a cause of x. But the point is that Gödelian time travel need not implicate such a backward causal influence.

We are now in a position to see why the second and third advantages have been purchased at a price. One can object that Gödelian time travel does not deliver time travel in the sense wanted since so-called Gödelian time travel implies that there is no time in the usual sense in which to 'go back'. In Gödel's universe,[4] for example, there is no serial time order for events since for every spacetime point x, $x \ll x$; nor is there a single time slice which would permit one to speak of the Gödel universe at-a-given-time. I feel that there is a good deal of justice to this complaint. But I also feel that the phenomenon of 'time travel' in the Gödel universe and in other general relativistic cosmologies is a worthy object of investigation, whether under the label of 'time travel' or not. The bulk of this chapter is devoted to that investigation.

Before turning to that investigation, it is worth mentioning for sake of completeness other senses of time travel that appear in the literature. For example, Chapman and Zemach[6] devise various scenarios built around the notion of 'two times'. One interpretation of such schemes would involve the replacement of the usual relativistic conception of spacetime as a four-dimensional manifold equipped with a pseudo-Riemannian metric of signature $(+ + + -)$ (three space dimensions plus one time dimension) with a five-dimensional manifold equipped with a metric of signature $(+ + + - -)$ (three space dimensions and two time dimensions). This scheme is worthy of investigation in its own right, but I will confine my attention here to standard relativistic spacetimes.

[6] Chapman (1982) and Zemach (1968).

2 The causal structure of relativistic spacetimes

There is an infinite hierarchy of causality conditions that can be imposed on relativistic spacetimes.[7] I will mention only enough of these conditions to give some flavor of what the hierarchy is like. The review also serves the purpose of introducing the concepts needed for an assessment of Gödelian time travel.

A *relativistic spacetime* consists of a manifold M equipped with an everywhere defined Lorentz signature metric g_{ab}. For the real world, of course, we are interested in the case $\dim(M) = 4$ and metric signature $(+ + + -)$, but for ease of illustration examples will often be given for $\dim(M) = 2$ and a metric of signature $(+ -)$. The basic presupposition of the causality hierarchy is that of temporal orientability.

(C0) M, g_{ab} is *temporally orientable* iff the null cones of g_{ab} admit of a continuous division into two sets, 'past' and 'future'.[8]

Which set is which is part of the problem of the direction of time, a problem that for present purposes we may assume to have been resolved.

With a choice of temporal orientation in place, we can say that for $x, y \in M$, x *chronologically precedes* y (symbolically, $x \ll y$) iff there is a smooth future-directed timelike curve from x to y. Similarly, x *causally precedes* y $(x < y)$ iff there is a smooth future-directed non-spacelike curve from x to y. It follows without any further restrictions on M, g_{ab} that $\ll$ and $<$ are transitive relations. The first condition of the causality hierarchy says that $\ll$ has the other property we expect of an order relation, viz. irreflexivity.

(C1) M, g_{ab} exhibits *chronology* iff $\neg\exists x \in M$ such that $x \ll x$.

Chronology is, of course, equivalent to saying that the spacetime does not permit Gödelian time travel. The next condition up the hierarchy is simple causality.

(C2) M, g_{ab} exhibits *simple causality* iff $\neg\exists x \in M$ such that $x < x$.

To go further up the hierarchy we need the definitions of the *chronological future* $I^+(x)$ and *chronological past* $I^-(x)$ of a point $x \in M$: $I^+(x) \equiv \{y \in M: x \ll y\}$ and $I^-(x) \equiv \{y \in M: y \ll x\}$.

[7] Carter (1971).

[8] One way to make (C0) precise is to require that there exists on M a continuous, everywhere defined, timelike vector field.

(C3) M, g_{ab} is *future* (respectively, *past*) *distinguishing* iff $\forall x, y \in M$, $I^+(x) = I^+(y) \Rightarrow x = y$ (respectively, $I^-(x) = I^-(y) \Rightarrow x = y$).

Stronger than both simple causality and past and future distinguishing is the condition of strong causality.

(C4) M, g_{ab} is *strongly causal* iff $\forall p \in M$ and $\forall$ open neighborhoods $N(p) \subseteq M$, $\exists$ open $N'(p) \subseteq N(p)$ such that once a future directed causal curve leaves N' it never returns.

Intuitively, (C4) not only rules out closed causal curves but also 'almost closed' causal curves. The reader can now envision how requiring no 'almost almost closed' or no 'almost almost almost closed' etc. causal curves can produce a countable hierarchy of causality conditions.

(C4) is still not strong enough to guarantee the existence of a time structure similar to that of familiar Newtonian or Minkowski spacetime, both of which possess a time function. The spacetime M, g_{ab} is said to possess a *global time function* iff there is a differentiable map $t: M \to \mathbb{R}$ such that the gradient of t is a past directed timelike vector field. This implies that $t(x) < t(y)$ whenever $x \ll y$. The necessary and sufficient condition for such a function is given in the next condition in the hierarchy.

(C5) M, g_{ab} is *stably causal* iff $\exists$ on M a smooth non-vanishing timelike vector field t^a such that M, g'_{ab} satisfies chronology, where $g'_{ab} \equiv g_{ab} - t_a t_b$ and $t_a \equiv g_{ab} t^b$.

Intuitively, (C5) says that it is possible to widen out the null cones of g_{ab} without allowing CTCs to appear.

None of the conditions given so far are enough to guarantee that causality in the sense of determinism has a fighting chance on the global scale. That guarantee is provided for in the next condition.

(C6) M, g_{ab} possess a *Cauchy surface* iff $\exists$ a spacelike hypersurface $S \subset M$ such that S is intersected exactly once by every timelike curve without endpoint.

On any spacelike hypersurface S of M, g_{ab} one can specify initial data and attempt to use the relevant laws to project the data into the future and into the past. If S is not a Cauchy surface, the attempt is liable to break down in some region of M. If M, g_{ab} admits one Cauchy surface, then it can be partitioned by them. In fact, a global time function t can be chosen so that each of the level surfaces t = constant is Cauchy.

There are even stronger conditions above (C6), but they will play no role in what follows. For future reference, a *time slice* of M, g_{ab} is defined to be a spacelike hypersurface without edges. (This is the generalization of a t = constant surface of Minkowski spacetime.) A spacelike hypersurface that is not intersected more than once by any timelike curve is said to be *achronal*. A partial *Cauchy surface* is an achronal time slice. For the familiar hyperbolic partial differential equations that govern fields in relativistic physics, initial conditions on a partial Cauchy surface S of M, g_{ab} will determine the state of the field in the *domain of dependence* $D(S)$ of S, which consists of the union of the future domain $D^+(S) \equiv \{x \in M$: every past endless causal curve through x meets $S\}$ and the past domain $D^-(S) \equiv \{x \in M$: every future endless causal curve through x meets $S\}$. Of course, if S is a Cauchy surface for M, g_{ab} then $D(S) = M$. The future boundary of $D^+(S)$, called the *future Cauchy horizon* of S, is denoted by $H^+(S)$.

The philosophical literature has devoted most of its attention to the ends of the hierarchy, principally to (C0), (C1), and (C6), and has largely neglected (C2)–(C5) and the infinity of other conditions that have not been enumerated. There are both good and dubious reasons for this selective attention. The intimate connection of (C0) and (C6) respectively to the longstanding philosophical problems of the direction of time and determinism is enough to explain and justify the attention lavished on these conditions. Focusing on (C1) to the exclusion of (C2) and (C5) and all that lies between can be motivated by two considerations. First, if one takes seriously the possibility that chronology can be violated, then one must *a fortiori* take seriously the possibility that all the higher conditions above can fail. Second, Joshi[9] showed that a good bit of the hierarchy above (C1) collapses under a natural continuity condition. Define the *causal future* $J^+(x)$ and the *causal past* $J^-(x)$ of a point $x \in M$ analogously to $I^+(x)$ and $I^-(x)$ respectively with $<$ in place of $\ll$. The continuity condition in question says that $J^{\pm}(x)$ are closed sets for all x. For this condition to fail there would have to be a situation where $x < y_n$, $n = 1, 2, 3, \dots$, with $y_n \to y$ but $\neg(x < y)$, i.e. a causal signal can be sent from x to each of the points y_n but not to the limit point y.

Despite these good reasons for the selective focus, I suspect that most of the philosophical attention lavished on (C1) derives from the fascination with the

[9] Joshi (1985).

paradoxes of time travel, and that I take to be a dubious motivation. But before taking up this matter in section 4, I turn to reasons for taking seriously the possibility of chronology violation.

3 Why take Gödelian time travel seriously?

Any relativistic spacetime M, g_{ab} based on a compact M contains closed CTCs.[10] Stronger results are derivable for cosmological models of GTR. A *cosmological model* consists of a triple M, g_{ab}, T^{ab} where M, g_{ab} is a relativistic spacetime and T^{ab} is a tensor field describing the mass–energy distribution on M. In addition to requiring the satisfaction of Einstein's field equations (EFE), general relativists typically demand that any candidate for the source T^{ab} of the gravitational field satisfies various energy conditions. For example, the *weak energy condition* requires that $T_{ab}V^aV^b \geq 0$ for any timelike V^a; intuitively, the demand is that the energy density of the source, as measured by any observer, is non-negative. By continuity, the weak energy condition entails the *null energy condition* which requires that $T_{ab}K^aK^b \geq 0$ for every null vector K^a. The model is said to be *generic* iff every timelike or null geodesic feels a tidal force at some point in its history (see Hawking and Ellis[11] for the technical details and physical motivation). Tipler[12] established that if the cosmological model M, g_{ab}, T^{ab} satisfies EFE with zero cosmological constant, the weak energy condition, and the generic condition, then compactness of M entails that the spacetime is *totally vicious* in that $x \ll x$ for every $x \in M$.

CTCs are not confined to compact spacetimes. In Gödel's cosmological model, $M = \mathbb{R}^4$.[13] This example is also important in that it illustrates that the failure of chronology can be *intrinsic* in that chronology cannot be restored by 'unwinding' the CTCs. More precisely, an intrinsic violation of chronology occurs when the CTCs do not result (as in figure 2(*b*)) by making identifications in a chronology respecting covering spacetime (figure 2(*a*)).

10 See Geroch (1967).

11 Hawking & Ellis (1973).

12 Tipler (1977).

13 Good treatments of Gödel's model are to be found in Malament (1984), Pfarr (1981), and Stein (1970). Gödel's original (1949a) cosmological model is a dust filled universe, i.e. $T^{ab} = \rho U^a U^b$ where ρ is the density of the dust and U^a is the normed four velocity of the dust. This model is a solution to Einstein's field equations only for a non-vanishing cosmological constant $\Lambda = -\omega^2$, where ω is the magnitude of the vorticity of matter. Alternatively, the model can be taken to be a solution to EFE with $\Lambda = 0$ and $T^{ab} = \rho U^a U^b + (\omega^2/8\pi)g^{ab}$; however, this energy–momentum tensor does not seem to have any plausible physical interpretation. Gödel's original model gives no cosmological redshift. Later Gödel (1952) generalized the model to allow for a redshift.

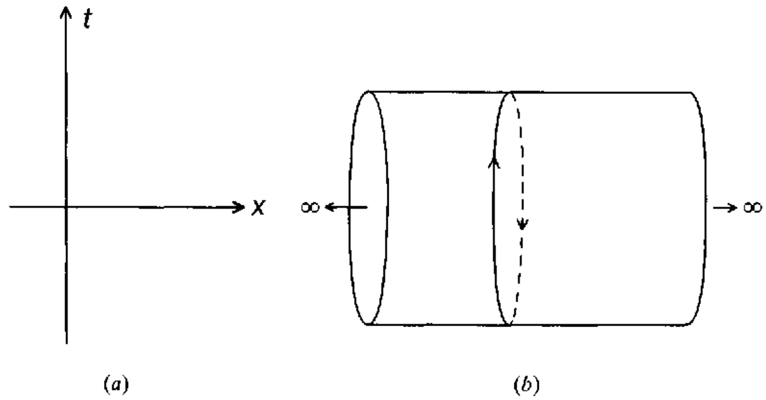

Fig. 2. (a) Two-dimensional Minkowski spacetime. (b) Rolled up Minkowski spacetime

Gödel spacetime is totally vicious. But there are other cosmological models satisfying EFE and the energy conditions where chronology is violated but not viciously. This raises the question of whether it is possible to have the chronology violating set V so small that it is unnoticeable in the sense of being measure zero. The answer is negative since V is always an open set.[11]

In the Gödel universe all CTCs are non-geodesic, necessitating the use of a rocket ship to accomplish the time travel journey. Malament[14] provided estimates of the acceleration and the fuel/payload ratio needed to make such a journey. These quantities are so large as to make the journey a practical impossibility. It was on this basis that Gödel[15] himself felt justified in ignoring the paradoxes of time travel. Such complacency, however, is not justified. Oszvath[16] produced a generalization of Gödel's model that accommodates electromagnetism. De[17] showed that in such a universe time travellers do not need to use a rocket ship; if they are electrically charged they can use the Lorentz force to travel along CTCs. Even better from the point of view of a lazy would-be time traveller would be a cosmological model with intrinsic chronology violation where some timelike geodesics are closed. An example is provided by the Taub–NUT model which is a vacuum solution to EFE (energy conditions trivially satisfied).

[14] Malament (1984).
[15] Gödel (1949b).
[16] Oszvath (1967).
[17] De (1969).

As a result of being totally vicious and simply connected, Gödel spacetime does not contain a single time slice so that one cannot speak of the Gödel universe at-a-given-time. But there are solutions to EFE which are intrinsically chronology violating but which do contain time slices. Indeed, the time slices can themselves be achronal, and thus partial Cauchy surfaces, even though CTCs develop to the future. This raises the question of whether GTR allows for the possibility of building a time machine whose operation in some sense causes the development of CTCs where none existed before. This matter will be taken up in section 9.

None of the chronology violating models discussed so far (with the exception of the trivial example of figure 2(*b*)) are asymptotically flat. But CTCs can occur in such a setting. The Kerr solutions to EFE form a two-parameter family described by the value of the mass m and the angular momentum a. The case where $m^2 > a^2$ is thought to describe the unique final exterior state of a non-charged stationary black hole. In this case chronology is satisfied. When $m^2 < a^2$ the violation of chronology is totally vicious. Charlton and Clarke[18] suggest that the latter case could arise if a collapsing rotating star does not dissipate enough angular momentum to form a black hole.

The solution to EFE for an infinite rotating cylinder source contains CTCs.[19] Tipler suggests that chronology violation may also take place for a finite cylinder source if the rotation rate is great enough.

The Gödel, Oszvath, Kerr, and Tipler models all involve rotating matter. But this is not an essential condition for the appearance of CTCs in models of GTR – recall that the Taub–NUT model is a vacuum solution. Also Morris, Thorne, and Yurtsever[20] found that generic relative motions of the mouths of traversable 'wormholes' (multiply connected surfaces) can produce CTCs, as can generic gravitational redshifts at the wormhole mouths.[21] However, the maintenance of the traversable wormholes implies the use of exotic matter that violates standard energy conditions. Such violations may or may not be allowed by quantum field theory (see section 9 below).

Gott[22] found that the relative motion of two infinitely long cosmic strings can give rise to CTCs. This discovery has generated considerable interest and

[18] Charlton & Clarke (1990).
[19] Tipler (1974).
[20] Morris, Thorne, & Yurtsever (1988).
[21] Frolov & Novikov (1990).
[22] Gott (1991).

controversy.[23] Part of the interest lies in the fact that Gott's solution, unlike the wormhole solutions, does not violate the standard energy conditions of classical GTR. The global structure of Gott's solution has been elucidated by Cutler.[24]

The upshot of this discussion is that since the pioneering work of Gödel over forty years ago, it has been found that CTCs can appear in a wide variety of circumstances described by classical GTR and semi-classical quantum gravity. And more broadly, there are many other known examples of violations of causality principles higher up in the hierarchy. One reaction, which is shared by a vocal if not large segment of the physics community, holds that insofar as these theories are to be taken seriously, the possibility of violations of various conditions in the causality hierarchy, including chronology, must also be taken seriously. (This is the attitude of the 'Consortium' led by Kip Thorne.[25]) Another vocal and influential minority conjectures that GTR has within itself the resources to show that chronology violations can be ignored because, for example, it can be proved that if chronology violations are not present to begin with, they cannot arise from physically reasonable initial data, or because such violations are of 'measure zero' in the space of solutions to EFE. (This position is championed by Hawking.[26]) If such conjectures turn out to be false, one can still take the attitude that in the short run classical GTR needs to be supplemented by principles that rule out violations of the causality hierarchy, and one can hope that in the long run the quantization of gravity will relieve the need for such *ad hoc* supplementation. Which of these attitudes it is reasonable to adopt will depend in large measure on whether it is possible to achieve a peaceful coexistence with CTCs. It is to that matter I now turn.

4 The paradoxes of time travel

The darling of the philosophical literature on Gödelian time travel is the 'grandfather paradox' and its variants. For example: Kurt travels into the past and shoots his grandfather at a time before grandpa became a father, thus preventing Kurt from being born, with the upshot that there is no Kurt

23 See Carroll, Farhi, & Guth (1992); Deser, Jakiw, & 't Hooft (1992); Deser (1993); Ori (1991); and 't Hooft (1992).
24 Cutler (1992).
25 Friedman, Morris, Novikov, Echeverria, Klinkhammer, Thorne, & Yurtsever (1990).
26 Hawking (1992).

to travel into the past to kill his grandfather so that Kurt is born after all and travels into the past . . . (Though the point is obvious, it is nevertheless worth emphasizing that killing one's grandfather is overkill. If initially Kurt was not present in the vicinity of some early segment of his grandfather's world line, then travelling along a trajectory that will take him into that vicinity, even if done with a heart innocent of any murderous intention, is enough to produce an antinomy. This remark will be important to the eventual unravelling of the real significance of the grandfather paradox.)

On one level it is easy to understand the fascination that such paradoxes have exercised – they are cute and their formal elucidation calls for the sorts of apparatus that are the stock in trade of philosophy. But at a deeper level there is a meta-puzzle connected with the amount of attention lavished on them. For what could such paradoxes possibly show? Could the grandfather paradox show that Gödelian time travel is not logically or mathematically possible?[27] Certainly not, for we have mathematically consistent models in which CTCs are instantiated by physical processes. Could the grandfather paradox show that Gödelian time travel is not conceptually possible? Perhaps so, but it is not evident what interest such a demonstration would have. The grandfather paradox does bring out a clash between Gödelian time travel and what might be held to be conceptual truths about spatiotemporal/causal order. But in the same way the twin paradox of special relativity theory reveals a clash between the structure of relativistic spacetimes and what were held to be conceptual truths about time lapse. The special and general theories of relativity have both produced conceptual revolutions. The twin paradox and the grandfather paradox help to emphasize how radical these revolutions are, but they do not show that these revolutions are not sustainable or contain inherent contradictions. Could the grandfather paradox show that Gödelian time travel is not physically possible? No, at least not if physically possible means compatible with EFE and the energy conditions, for we have models which satisfy these laws and which contain CTCs. Could the paradox show that although Gödelian time travel is physically possible it is not physically realistic? This is not even a definite claim until the relevant sense of 'physically realistic' is specified. And in the abstract it is not easy to see how the grandfather paradox would support that claim as opposed to the claim that time travel is flatly impossible.

[27] Some philosophers apparently think that time travel is logically or conceptually impossible; see Hospers (1967), 177, and Swinburne (1968), 169.

Does the grandfather paradox at least demonstrate that there is a tension between time travel and free will? Of course Kurt cannot succeed in killing his grandfather. But one might demand an explanation of why Kurt does not succeed. He has the ability, the opportunity, and (let us assume) the desire. What then *prevents* him from succeeding? Some authors pose this question in the rhetorical mode, suggesting that there is no satisfactory answer so that either time travel or free will must give way. But if the question is intended non-rhetorically, it has an answer of exactly the same form as the answer to analogous questions that arise when no CTCs exist and no time travel is in the offing. Suppose, for instance, that in the time travel scenario Kurt had his young grandfather in the sights of a 30–30 rifle but did not pull the trigger. The reason that the trigger was not pulled is that laws of physics and the relevant circumstances make pulling the trigger impossible at the relevant spacetime location. With CTCs present, *global* Laplacian determinism (which requires a Cauchy surface – see section 2) is inoperable. But *local* determinism makes perfectly good sense. In any spacetime M, g_{ab}, chronology violating or not, and any $x \in M$ one can always choose a small enough neighborhood $N(x)$ such that N, $g_{ab}|_N$ possesses a Cauchy surface S (where $g_{ab}|_N$ denotes the restriction of the metric g_{ab} to $N \subset M$). And the relevant initial data on S together with the coupled Einstein–matter equations will uniquely determine the state at x. Taking x to be the location of the fateful event of Kurt's pulling/not pulling the trigger and carrying through the details of the deterministic physics for the case in question shows why Kurt did not pull the trigger. Of course, one can go on to raise the usual puzzles about free will; viz. granting the validity of what was just said, is there not a way of making room for Kurt to have exercised free will in the sense that he could have done otherwise? At this point all of the well choreographed moves come into play. There are those (the *incompatibilists*) who will respond with arguments intended to show that determinism implies that Kurt could not have done otherwise, and there are others (the *compatibilists*) waiting to respond with equally well rehearsed counterarguments to show that determinism and free will can coexist in harmony. But all of this has to do with the classic puzzles of determinism and free will and nothing to do with CTCs and time travel *per se*.

Perhaps we have missed something. Suppose that Kurt tries over and over again to kill his grandfather. Of course, each time Kurt fails – sometimes because his desire to pull the trigger evaporates before the opportune moment, sometimes because although his murderous desire remains unabated his hand cramps before he can pull the trigger, sometimes because although he pulls the trigger the gun misfires, sometimes because although the gun fires the bullet is deflected, etc. In each instance we can give a deterministic explanation of the failure. But the obtaining of all the initial conditions that result in the accumulated failures may seem to involve a coincidence that is monstrously improbable.[28] Here we have reached a real issue but one which is not easy to tackle.

A first step towards clarification can be taken by recognizing that the improbability issue can be formulated using inanimate objects. (Consider, for example, the behavior of the macroscopic objects in my study as I write: a radiator is radiating heat, a light bulb is radiating electromagnetic waves, etc. If the world lines of these objects are CTCs, it would seem to require an improbable conspiracy to return these objects to their current states, as required by the completion of the time loop.) Since free will is a murky and controversial concept, it is best to set it aside in initial efforts at divining the implications of the grandfather paradox. After some progress has been made it may then be possible to draw some consequences for free will. As a second step we need to formalize the intuition of improbability. One method would be to define a measure on the space of solutions to EFE and to try to show that the solutions corresponding to some kinds of time travel (those involving the functional equivalent of Kurt trying over and over again to kill his grandfather) have negligible or zero measure. Even if such a demonstration is forthcoming, we still have to face the question: so what? (After all, some types of space travel will be measure zero, but this hardly shows that the concept of space travel is suspect.) The answer will depend crucially on the justification for and significance of the measure. This matter will receive some attention in section 9. But for the moment I want to note that the impression of improbability in connection with time travel stories may not be self-reenforcing. In the above example the judgment of the improbability of the failure of Kurt's repeated attempts to kill his grandfather was made relative to our (presumably chronology respecting) world; but perhaps from the perspective of the time travel world itself there is no improbability. By way of analogy, suppose that the actual world is governed by all of the familiar laws of classical relativistic physics *save for* Maxwell's laws of electromagnetism. If we peered into another world which is nomologically accessible

[28] Horwich (1987).

from our world but which is governed by Maxwell's laws we would see things that from our perspective are improbable ('measure zero') coincidences. We would find, for example, that the electric and magnetic fields on a time slice cannot be freely specified but must satisfy a set of constraints; and we would find that once these constraints are satisfied at any moment they are thereafter maintained for all time. Amazing! But, of course, from the perspective of the new world there is no improbability at all; indeed, just the opposite is true since the 'amazing coincidences' are consequences of the laws of that world. That this analogy may be apt to the case of time travel will be taken up in sections 5 and 6.

What then remains of the grandfather paradox? The paradox does point to a seemingly awkward feature of spacetimes that contain CTCs: local data are constrained in a way that they are not in spacetimes with a more normal causal structure. But the forms in which the paradox has been considered in the philosophical literature are of little help in getting an accurate gauge of the shape and extent of the constraints. And by itself the paradox is of no help at all in assessing the status of these consistency constraints.

5 Consistency constraints

The laws of special and general relativistic physics that will be considered here are all local in the following two-fold sense. First, they deal with physical situations that are characterized by local geometric object fields O (e.g. scalar, vector, and tensor fields) on a manifold M. Second, the laws governing these fields are in the form of local ordinary or local partial differential equations. The result is a *global-to-local property*: if M, g_{ab}, O satisfies the laws and $U \subseteq M$ is an open neighborhood, then U, $g_{ab}|_U$, $O|_U$ also satisfies the laws. (This property holds whether or not CTCs are present.) Thus, it would seem at first blush that the question of whether some local state of affairs is physically possible can be answered by focusing exclusively on what is happening locally and ignoring what is happening elsewhere.

In Minkowski spacetime and in general relativistic spacetimes with nice causality properties we typically have the reverse *local-to-global property*: any local solution can be extended to a global solution.[29] Consider, for example,

[29] Sometimes the local-to-global property may fail in causally nice spacetimes because singularities develop in solutions to some field equation. But one may regard such a failure as indicating that the field is not a fundamental one.

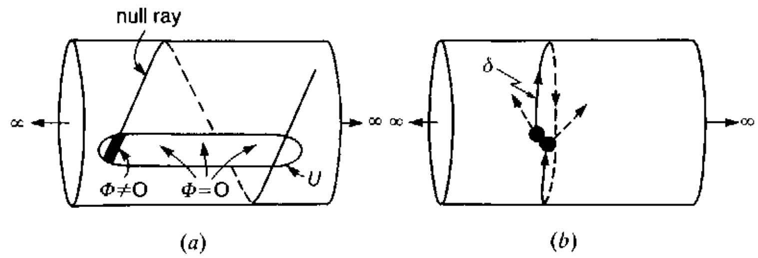

Fig. 3. Light rays and billiard balls on rolled up Minkowski spacetime

the source-free wave equation for a massless scalar field Φ: $g^{ab}\nabla_a\nabla_b\Phi \equiv \Box\Phi = 0$, where ∇_a is the derivative operator associated with g_{ab}. On Minkowski spacetime ($M = \mathbb{R}^4$ and $g_{ab} = \eta_{ab}$ (Minkowski metric)), any C^∞ solution on an open $U \subset \mathbb{R}^4$ can be extended to a full solution on $\mathbb{R}^4$. But obviously this local-to-global property fails for the chronology violating spacetime of figure 2(*b*). Figure 3(*a*) shows a local solution with a single pencil of rays traversing U. This solution is obviously globally inconsistent since the light rays from U will trip around the spacetime and reintersect U, as shown in figure 3(*a*).

The point is straightforward, but some attempts to elaborate it make it sound mysterious. Thus, consider the presentation of the Consortium:

> The only type of causality violation the authors would find unacceptable is that embodied in the science-fiction concept of going backward in time and killing one's younger self ('changing the past' [grandfather paradox]). Some years ago one of us (Novikov) briefly considered the possibility that CTC's might exist and argued that they cannot entail this type of causality violation: Events on a CTC are already guaranteed to be self-consistent, Novikov argued; they influence each other around the closed curve in a self-adjusted, cyclical, self-consistent way. The other authors have recently arrived at the same viewpoint.
>
> We shall embody this viewpoint in a *principle of self-consistency*, which states that *the only solutions to the laws of physics that can occur locally in the real universe are those which are globally self-consistent.* This principle allows one to build a local solution to the equations of physics only if that local solution can be extended to be part of a (not necessarily) unique global solution, which is well defined throughout the nonsingular regions of spacetime. (Friedman et al.[25] pp. 1916–17)

The first part of the quotation seems to invoke either a notion of pre-established harmony or else a guiding hand that prevents the formation of an inconsistent scenario. But once such connotations are removed, the 'principle of self-consistency' (PSC) threatens to deflate into a truism. Here is the Consortium's comment:

> That the principle of self-consistency is not totally tautological becomes clear when one considers the following alternative: The laws of physics might permit CTC's; and when CTC's occur, they might trigger new kinds of local physics, which we have not previously met ... The principle of self-consistency is intended to rule out such behavior. It insists that local physics is governed by the same types of physical laws as we deal with in the absence of CTC's ... If one is inclined from the outset to ignore or discount the possibility of new physics, then one will regard self-consistency as a trivial principle. (Friedman et al.[25] p. 1917)

What the Consortium means by discounting the possibility of 'new physics' is, for example, ignoring the possibility that propagation around a CTC can lead to multi-valued fields, calling for new types of laws that tolerate such multi-valuedness. I too will ignore this possibility. But I will argue shortly that CTCs may call for 'new physics' in another sense. For the moment, however, all I want to insist upon is that taking the PSC at face value seems to force a distinction between two senses of physical possibility.

In keeping with the global-to-local property introduced above, we can repeat, more pedantically, what was said informally: a local situation is *physically possible$_1$* iff it is a local solution of the laws. But the PSC – which says that the only solutions which can occur locally are those which are *globally* self-consistent – seems to require a more demanding and relativized sense of physical possibility; viz. a local situation is *physically possible$_2$* in a spacetime M, g_{ab} iff it can be extended to a solution of the laws on all of M, g_{ab}. Calling the conditions a local solution must fulfil in order to be extendible to a global solution the *consistency constraints*, one can roughly paraphrase physical possibility$_2$ as physical possibility$_1$ plus satisfaction of the consistency constraints.[30]

This distinction might be regarded as desirable for its ability to let one have one's cake and eat it too. On one hand, we have the intuition that it is physically possible to construct and launch a rocket probe in any direction we like with any velocity less than that of light. This intuition is captured by physical possibility$_1$. But on the other hand it is not possible to realize all of the physically possible$_1$ initial conditions for such a device in spacetimes with certain

[30] The need for such a distinction has been previously noted by Bryson Brown (1992).

kinds of CTCs since the traverse of a CTC may lead the probe to interfere with itself in an inconsistent way. (Or so it would seem; but see the discussion of section 8 below.) This impossibility is captured by the failure of physical possibility$_2$.

But on reflection, however, having one's cake and eating it too is, as usual, too good to be true. Thus, one might maintain with some justice that to be physically impossible just is to be incompatible with the laws of physics – as is codified in the definition of physical possibility$_1$. So as it stands the notion of physical impossibility$_2$ seems misnamed when it does not reduce to physical impossibility$_1$, and it appears not to when CTCs are present. To come at this point from a slightly different angle, let us reconsider the grandfather paradox. It was suggested in the preceding section that Kurt's failure to carry out his murderous intentions could be explained in the usual way – by reference to conditions that obtained before the crucial event and the (locally) deterministic evolution of these conditions. But while not incorrect, such an explanation deflects attention from a doubly puzzling aspect of spacetimes with CTCs. First, it may not even be possible for Kurt to set out on his murderous journey, much less to carry out his intentions. And second, the ultimate root of this impossibility does not lie in prior contingent conditions since there are no such conditions that can be realized in the spacetime at issue and which result in the commencement of the journey. The ultimate root of this impossibility taps the fact that (as we are supposing) there is no consistent way to continue Kurt's journey in the spacetime. But, one might complain, to call this impossibility 'physical impossibility$_2$' is to give it a label that is not backed by any explanatory power since the way the story has been told so far the local conditions corresponding to the commencement of Kurt's journey are compatible with all of the postulated laws. In such a complaint the reader will detect a way of trying to scratch the residual itch of the grandfather paradox.

The itch must be dealt with once and for all. I see three main treatments, the first two of which promise permanent cures while the third denies the existence of the ailment.

6 Therapies for time travel malaise

(T1) This treatment aims at resolving the tension between physical possibility$_1$ and physical possibility$_2$ by getting rid of the latter. The leading idea is to argue that GTR shows that, strictly speaking, the notion of consistency constraints is incoherent. For example, looking for consistency constraints in a spacetime M, g_{ab} for a scalar field obeying $\Box\Phi = 0$ makes sense if Φ is treated as a test field on a fixed spacetime background. But (the argument continues) this is contrary to both the letter and spirit of GTR. For Φ will contribute to the total energy–momentum – the usual prescription being that $T_{ab}(\Phi) = \nabla_a\Phi\nabla_b\Phi - 1/2g_{ab}\nabla_c\Phi\nabla^c\Phi$ – that generates the gravitational field cum metric. And (one could conjecture) if Φ and Φ' are interestingly different (say, they differ by more than an additive constant), then the metrics g_{ab} and g'_{ab} solving EFE for the corresponding $T_{ab}(\Phi)$ and $T'_{ab}(\Phi')$ will be different (i.e. non-isometric). This therapy is radical in that if it succeeds it succeeds by the draconian measure of equating the physically possible$_1$ local states with the actual states. This is intuitively unsatisfying. If we restrict attention to Φ's such that $T_{ab}(\Phi)$ is small in comparison with the total T_{ab} and the spacetime is stable under small perturbations of T_{ab}, then Φ can to a good approximation be treated as a test field. Questions of stability will be examined in section 9, but meanwhile I will assume that they can be set aside. One could also object that (T1) is inapplicable in cases where there are CTCs and where the laws entail that the spacetime structure is non-dynamical and that a variety of physically possible$_1$ states can be realized on a given local region of the fixed spacetime. However, the strength of this objection is hard to grasp since the laws in question would have to be rather different from those of our world, at least if something akin to GTR is true. And recall that the success of GTR is the main reason for taking Gödelian time travel seriously.

(T2) The second treatment strategy is to naturalize physical possibility$_2$. The idea is, first, to insist that physical possibility$_2$ (relative to a world) just is the compatibility with the laws (of that world) and, second, to go on to argue that physical possibility$_2$ can be brought into the fold by showing that in chronology violating environments the consistency constraints of physical possibility$_2$ have law status. Thus, (T2) insists that, contrary to the Consortium's explanation of the PSC, there is a sense in which CTCs do call forth 'new physics'.

(T2) can take two forms. (a) The naturalization of physical possibility$_2$ would amount to a reduction to physical possibility$_1$, understood as consistency with the local laws of physics, if the consistency constraints/new laws were purely local so that, even in the chronology violating environments, what is physically possible locally is exactly what is compatible with the (now augmented) local laws of physics. (b) Unfortunately, the reduction of (a) can be expected in only very special cases. In general the consistency constraints may have to refer to the global structure of spacetime. In these latter cases, insofar as (T2) is correct, the concept of physical possibility$_1$ must be understood to mean consistency of the local situation with all the laws, local and non-local. The patient who demands a purely local explanation of the difference between local conditions that are physically possible and those which are not will continue to itch.

(T3) If the first two therapies fail, the discomfort the patient feels can be classified as psychosomatic. The therapist can urge that the patient is getting over excited about nothing or at least about nothing to do specifically with time travel; for global features of spacetime other than CTCs can also impose constraints on initial data. For example, particle horizons in standard big-bang cosmologies prevent the implementation of the Sommerfeld radiation condition which says that no source-free electromagnetic radiation comes in from infinity.[31] Here the patient may brighten for a moment only to relapse into melancholy upon further reflection. For the constraints entailed by the particle horizons are of quite a different character than those entailed by the typical chronology violating environment; the former, unlike the latter, do not conflict with the local-to-global property and thus do not drive a wedge between physical possibility, and physical possibility$_2$. And in any case the choice of the particle horizons example is not apt for therapeutic purposes since these horizons are widely thought to be so problematic as to call for new physics involving cosmic inflation or other non-standard scenarios.[32] Clearly this line of therapy opens up a number of issues that require careful investigation; but such an investigation is beyond the scope of this chapter.

My working hypothesis favors (T2). This is not because I think that (T2) will succeed; indeed, I am somewhat pessimistic about the prospects of success. Nevertheless, making (T2) the focus of attention seems justified on several grounds: the success of (T2) would provide the most satisfying resolution of the nagging worries about time travel, while its failure would have significant negative implications for time travel; whether it succeeds or fails, (T2) provides an illuminating perspective from which to read recent work on the physics of

31 See Penrose (1964).
32 For a review of the horizon problem and attempted solutions, see Earman (1994).

time travel; and finally, (T2) forces us to confront issues about the nature of the concept of physical law in chronology violating spacetimes, issues which most of the literature on time travel conveniently manages to avoid.

It is well to note that my working hypothesis is incompatible with some analyses of laws. For example, Carroll[33] rejects the idea that laws supervene on occurrent facts, and adopts two principles which have the effect that laws of the actual world $W_@$ are transportable *as laws* to other possible worlds which are nomologically accessible from $W_@$. The first principle says that 'if P is physically possible and Q is a law, then Q would (still) be a law if P were the case'. The second says that 'if P is physically possible and Q is not a law, then Q would (still) not be a law if P were the case'. Let P say that spacetime has the structure of Gödel spacetime or some other spacetime with CTCs. And let us agree that P is physically possible because it is compatible with the laws of $W_@$ (which for the sake of discussion we may take to be the laws of classical general relativistic physics). It follows from Carroll's principles that if spacetime were Gödelian, the laws of $W_@$ would still be laws and also that these would be the only laws that would obtain.

I will not attempt to argue here for the supervenience of laws on occurrent facts but will simply assume it. In exploring my working hypothesis, I will rely on an account of laws that can be traced back to John Stuart Mill;[34] its modern form is due to Frank Ramsey and David Lewis.[35] The gist of the M-R-L account is that a law for a logically possible world W is an axiom or theorem of the best overall deductive system for W (or what is common to the systems that tie for the best). A deductive system for W is a deductively closed, axiomatizable, set of (non-modal) sentences, each of which is true in W. Deductive systems are ranked by how well they achieve a compromise between strength or information content on one hand and simplicity on the other. Simplicity is a notoriously vague and slippery notion, but the hope is that, regardless of how the details are settled, there will be for the actual world a clearly best system or at least a non-trivial common core to the systems that tie for best. If not, the M-R-L theorist is prepared to admit that there are no laws for our world.

The M-R-L account of laws is naturalistic (all that exists is spacetime and its contents); actualistic (there is only one actual world); and empiricistic (a world is

33 Carroll (1994).
34 Mill (1904).
35 Ramsey (1978) and Lewis (1973).

a totality of occurrent facts; there are no irreducible modal facts). In addition I would claim that this account fits nicely with the actual methodology used by scientists in search of laws. The reader should be warned, however, that it is far from being universally accepted among philosophers of science.[36] I will not attempt any defense of the M-R-L account here. If you like, the ability to illuminate the problems of time travel can be regarded as a test case for the M-R-L account.

Suppose for sake of discussion that the actual world has a spacetime without CTCs; perhaps, for example, its global features are described more or less by one of the Robertson–Walker big-bang models. And suppose that the M-R-L laws of this world are just the things dubbed laws in textbooks on relativistic physics, no more, no less. Now consider some other logically possible world whose spacetime contains CTCs. But so as not to waste time on possibilities that are too far removed from actuality, let us agree to restrict our attention to worlds that are nomologically accessible from the actual world in that the laws of the actual world, taken as non-modal propositions, are all true of these worlds. Nevertheless, we cannot safely assume that the M-R-L laws of our world 'govern' these time travel worlds in the sense that the set of laws of our world coincides with the set of laws of time travel worlds.

One possibility is that the M-R-L laws of a time travel world W consist of the M-R-L laws of this world *plus* the consistency constraints on the test fields in question. If so, we have a naturalization of physical possibility$_2$, though it would remain to be seen whether the naturalization takes the preferred (a) form or the less desirable (b) form. Additionally, time travel would have implications for free will. In cases where an action is determined by the laws plus contingent initial conditions, compatibilists and incompatibilists split on whether the actor could be said to have the power to do otherwise and whether the action is free. But all parties to the free will debate agree that if an action is precluded by the laws alone, then the action is not in any interesting sense open to the agent. Thus, under the scenario we are discussing, there are various actions that, from a compatibilist perspective at least, we are free to perform in the actual world that we are not free to perform in the time travel world.

Other possibilities also beg for consideration. For instance, it could turn out that although (by construction) the M-R-L laws of this world are all *true* of a time travel world W, they are not all *laws* of W, except in a very tenuous

36 See, for example, van Fraassen (1989) and my response in Earman (1993a).

sense. I will argue that this possibility is realized in cases where the consistency constraints are so severe as to supplant the laws of this world. In such cases the time travel involved is arguably such a remote possibility that it loses much of its interest. But note that since the consistency constraints are still subsumed under the laws of the time travel world, we retain the desirable feature that physical possibility$_2$ is naturalized.

Finally, these remarks point to the intriguing possibility that purely local observations can give clues to the global structure of spacetime without the help of a supplementary 'cosmological principle'; namely, local observations may reveal the absence of consistency constraints that would have to obtain if we inhabited certain kinds of chronology violating spacetimes.

What is needed as a first step in coming to grips with these matters is a study of the nature of consistency conditions on test fields that arise for various chronology violating spacetimes. The recent physics literature has made some progress on the project. In the next two sections I will report on some of the results for self-interacting and non-self-interacting fields. On the basis of these results I will advance some tentative conclusions about the nature of physical possibility and laws in chronology violating spacetimes.

7 Test fields on chronology violating spacetimes: non-self-interacting case

The simplest regime to study mathematically is the case of a non-self-interacting field, e.g. solutions to the source free scalar wave equation $\Box\Phi = 0$. Of course, the grandfather paradox and the related paradoxes of time travel that have been discussed in the philosophical literature typically rely on self-interacting systems. Even so we shall see that non-trivial consistency conditions can emerge in the non-self-interacting regime. But on the way to illustrating that point it is worth emphasizing the complementary point that in small enough regions of some chronology violating spacetimes the consistency constraints for non-self-interacting fields do not make themselves felt so that local observations in such regions will not reveal the presence of CTCs.

Following Yurtsever,[37] call an open $U \subseteq M$ *causally regular* for the spacetime M, g_{ab} with respect to the scalar wave equation iff for every C^∞ solution Φ of $\Box\Phi = 0$ on U, there is a C^∞ extension to all of M, i.e. there is a $C^\infty\bar{\Phi}$ on M

[37] Yurtsever (1990).

such that $\Box\tilde{\Phi} = 0$ and $\tilde{\Phi}|_U = \Phi$. In addition M, g_{ab} can be said to be *causally benign* with respect to the scalar wave equation just in case for every $p \in M$ and every open neighborhood U of point p there is subneighborhood $U' \subset U$ which is causally regular.

The two-dimensional cylinder of figure 2(*b*) is causally benign with respect to the scalar wave equation. The following remarks, while not constituting a proof of this fact, give an indication of why it holds in the optical limit. In that limit Φ waves propagate at the speed of light (i.e. along null trajectories). At any point on the cylinder a small enough neighborhood can be chosen such that any null geodesic leaving this neighborhood in either the future or past direction never returns. Consider then any solution on this neighborhood. To extend this local solution to a global one, simply propagate the solution out of the base neighborhood along null geodesics. If the propagated field does not reach a point $q \in M$, set $\Phi(q) = 0$. If two null geodesics from the base neighborhood cross at q, obtain $\Phi(q)$ by adding the propagated fields.

Consider next the toroidal spacetime $T_{(1,r)}$ obtained from two-dimensional Minkowski spacetime by identifying the points (x, t) and (x', t') when $x = x'$ mod 1 and $t' = t$ mod r, where $r > 0$ is a real number. For r rational, $T_{(1,r)}$ is benign with respect to the scalar wave equation, as shown by Yurtsever.[37] Through any point on $T_{(1,r)}$ there is a time slice that lifts to many $t =$ constant surfaces in the Minkowski covering spacetime $\mathbb{R}^2$, η_{ab}. Consider one such surface, say, $t = 0$. Any solution $\Phi(x, t)$ on $T_{(1,r)}$ induces on $t = 0$ initial data $\Phi_0(x) \equiv \Phi(x, 0)$ and $\dot{\Phi}_0(x) \equiv \mathrm{d}/\mathrm{d}t\, \Phi(x, t)|_{t=0}$. By considering solutions on $\mathbb{R}^2$, η_{ab} of the wave equation that develop from this initial data it follows that both Φ_0, and $\dot{\Phi}_0$ must be periodic with periods 1 and r respectively. Further, $\dot{\Phi}_0$ must satisfy the integral constraint

$$\int_{\{t=0\}} \dot{\Phi}_0(s)\, \mathrm{d}s = 0.$$

When r is rational we can choose a small enough neighborhood of any point on $T_{(1,r)}$ such that arbitrary initial data Φ_0 and $\dot{\Phi}_0$ can be extended so as to meet the periodicity and integral constraints.

Friedman et al.[25] argue that the benignity property with respect to the scalar wave equation also holds for a class of chronology violating spacetimes that are asymptotically flat and globally Minkowskian except for a single wormhole that is threaded by CTCs. In some of these spacetimes there is a partial Cauchy surface S such that chronology violations lie entirely to the future of

S. It is argued that the formation of CTCs place no consistency constraints on initial data specified on S.

In all the examples considered so far the chronology violations are non-intrinsic in that they result from making identifications of points in a chronology preserving covering spacetime. Unfortunately, because of the non-trivial mathematics involved, almost nothing is known about the benignity properties of spacetimes with intrinsic chronology violations. I conjecture that Gödel spacetime is benign with respect to the scalar wave equation. If correct, this conjecture would cast new light on a puzzling feature of Gödel's own attitude towards the grandfather paradox in Gödel spacetime.[15] Basically his attitude was one of 'why worry' since the fuel requirements for a rocket needed to realize a time travel journey in Gödel spacetime are so demanding as to be impossible to meet by any practical scheme. But consistency constraints are constraints whether or not they can be tested by practical means. Thus, whatever puzzles arise with respect to the status of such constraints are unresolved by appeal to practical considerations. However, the above conjecture, if correct, suggests that for non-self-interacting systems the consistency constraints in Gödel spacetime are much milder than one might have thought. Similarly, Gödel's remarks can be interpreted as suggesting that the constraints will also be mild for self-interacting systems. Some further information on this matter is presented in section 8.[38]

It should be emphasized at this juncture that in spite of the connotations of the name, benignity does not necessarily imply physics as usual. For it does not imply that there are no non-trivial consistency constraints nor that the constraints cannot be detected locally. Benignity implies only that the constraints cannot be felt in sufficiently small neighborhoods, but this is compatible with their being felt in regions of a size that we typically observe.

To give an example of a non-benign spacetime we can return to $T_{(1,r)}$ and choose r to be an irrational number. Now the periodicity constraints on the initial data cannot be satisfied except for Φ_0 and $\dot{\Phi}_0$ constant. The integral constraint then requires that $\dot{\Phi}_0 = 0$, with the upshot that the only solutions allowed are Φ = constant everywhere. No local solution that allows the tiniest variation in Φ can be extended to a global solution.

I turn now to the question of the status of the consistency constraints for chronology violating spacetimes. By way of introduction, I note the assertion

[38] Gödel took the possibility of time travel to support the conclusion that time is 'ideal'. For discussions of Gödel's argument, see Savitt (1994) and Yourgrau (1991).

of the Consortium that a time traveller 'who went through a wormhole [and thus around a CTC] and tried to change the past would be *prevented by physical law* from making the change ...' (Friedman et al.[25] p. 1928; italics added). One way of interpreting this assertion is in line with my working hypothesis that the consistency constraints entailed by the presence of CTCs in a nomologically accessible chronology violating world are laws of that world. This position is arguably endorsed by the M-R-L account of laws. For it is plausible that in each of the above examples the consistency constraints would appear as axioms or theorems of (each of) the best overall true theories of the world in question.

For the reasons discussed in sections 5 and 6, such a result is devoutly to be desired. But to play the devil's advocate for a moment, one might charge that the result is an artifact of the examples chosen. Each of these examples involves a spacetime with a very high degree of symmetry, and it is this symmetry one suspects of being responsible for the relative simplicity of the consistency constraints. If this suspicion is correct, then the consistency constraints that obtain in less symmetric spacetimes may be so complicated that they will not appear as axioms or theorems of any theory that achieves a good compromise between strength and simplicity. Due to the technical difficulties involved in solving for the consistency constraints in non-symmetric spacetimes, both the devil and his advocate may go blue in the face if they hold their breaths while waiting for a confirmation of their suspicions. If the devil's advocate should prove to be correct, the proponent of the naturalization could still find comfort if the cases where the naturalization fails could be deemed to be very remote possibilities.

An illustration of how time travel can be justly deemed to involve very remote possibilities occurs when the chronology violating world W is so far from actuality that, although the laws of the actual world are *true of* W, they are not *laws of* W except in a very attenuated sense. In the case of $T_{(1,r)}$ with r irrational we saw that $\Phi = \text{constant}$ are the only allowed solutions of the scalar wave equation. I take it that $\Box\Phi = 0$ will not appear as an axiom of a best theory of the $T_{(1,r)}$ world so that the scalar wave equation is demoted from fundamental law status. Presumably, however, $\Phi = \text{constant}$ will appear as an axiom in any best theory. Of course, this axiom entails that $\Box\Phi = 0$; but it also entails any number of other differential equations that are incompatible with one another and with the scalar wave equation when Φ is not constant. Thus, in the $T_{(1,r)}$ world the scalar wave equation and its rivals will have much the same status as 'All unicorns are red', 'All unicorns are blue', etc. in a world where it is a law that there are no unicorns. In this sense $\Box\Phi = 0$ has been supplanted as a law. This still is a case where physical possibility$_2$ is naturalized by reduction in the strong sense to physical possibility$_1$ since the consistency constraint is stated in purely local terms. But the more remote the possibility the less interesting the reduction. And in this case the possibility can be deemed to be very remote since the relation of nomological accessibility has become non-symmetric – by construction the toroidal world in question is nomologically accessible from the actual world, but the converse is not true because the toroidal law $\Phi =$ constant is violated here.

One might expect that such supplantation will take place in any world with a spacetime structure that is not benign. What I take to be a counterexample to this expectation is provided by the four-dimensional toroidal spacetime $T_{(1,1,1,1)}$ obtained from four-dimensional Minkowski spacetime by identifying the points (x, y, z, t) and (x', y', z', t') just in case the corresponding coordinates are equal mod 1. This spacetime is not benign with respect to the scalar wave equation. But solutions are not constrained to be constant; in fact, the allowed solutions form an infinite-dimensional subspace of the space of all solutions.[37] The consistency constraint imposes a high frequency cut off on plane wave solutions propagating in certain null directions. This constraint by my reckoning is simple and clean enough to count as an M-R-L law, but it supplements rather than supplants $\Box\Phi = 0$.

It is possible in principle to verify by means of local observations that we do not inhabit a non-causally regular region of some non-benign spacetime. And if we indulge in an admittedly dangerous inductive extrapolation from the above examples, we can conclude that we do not in fact inhabit a non-regular region. For it follows from the (source-free) Maxwell equations – which we may assume are laws of our world – that the components of the electromagnetic field obey the scalar wave equation. But the electromagnetic fields in our portion of the universe do not satisfy the restrictions which (if the induction is to be believed) are characteristic of non-benign spacetimes. Further experience with other examples of non-benign spacetimes may serve to strengthen or to refute this inference.

It is also possible to use local observations to rule out as models for our world certain benign chronology violating spacetimes, but only on the assumption that we have looked at large enough neighborhoods to reveal the consistency constraints indicative of these spacetimes. It is not easy to see how we would come by a justification for this enabling assumption.

8 Test fields on chronology violating spacetimes: self-interacting case

I begin with a reminder of two lessons from previous sections. First, the grandfather paradox is in the first instance a way of pointing to the presence of consistency constraints on local physics in a chronology violating spacetime. And second, while the usual discussion of the grandfather paradox assumes a self-interacting system, we have found that non-trivial and indeed very strong constraints can arise even for non-self-interacting systems. Of course, one would expect that the constraints for self-interacting systems will be even more severe. To test this expectation one could carry out an analysis that parallels that of section 7 by considering a test field obeying an equation such as $\Box\Phi = k\Phi^3$ ($k = \text{constant}$), which implies that solutions do not superpose. Results are not available in the literature. What are available are results for the simpler and more artificial case of perfectly elastic billiard balls.

One assumes that between collisions the center of mass of such a ball traces out a timelike geodesic in the background spacetime and that in a collision the laws of elastic impact are obeyed. Under these assumptions the initial trajectory δ of the (two-dimensional) billiard ball in the spacetime of figure 3(*b*) leads to an inconsistent time development. The ball trips around the cylinder and participates in a grazing collision with its younger self, knocking its former self from the trajectory that brought about the collision (grandfather paradox for billiard balls). We saw in the previous section that the cylinder is benign for the scalar wave equation. But obviously the corresponding property fails for billiard balls: for any point x on the cylinder it is not the case that there is a sufficiently small neighborhood $N(x)$ such that any timelike geodesic segment on N, representing the initial trajectory of the ball, can be extended to a globally consistent trajectory. Nor are the forbidden initial conditions of measure zero in any natural measure.

For a single sufficiently small billiard ball, Gödel spacetime is benign, not just because all timelike geodesics are open but also because they are not almost closed. And it seems safe to conjecture that Gödel spacetime is benign with respect to any finite system of small billiard balls since it seems implausible that collisions among a finite collection can be arranged so as to achieve the sustained acceleration needed to instantiate a closed or almost closed timelike curve.

Echeverria et al.[39] have studied the behavior of billiard balls in two types of wormhole spacetimes that violate chronology. The first type is called the 'twin paradox spacetime' because the relative motion of the wormhole mouths gives rise to a differential aging effect which in turn leads to CTCs since the wormhole can be threaded by future directed timelike curves. This spacetime contains a partial Cauchy surface S. Chronology is violated only to the future of S, indeed to the future of $H^+(S)$. The other type of wormhole spacetime is called the 'eternal time machine spacetime' because CTCs that traverse the wormhole can reach arbitrarily far into the past. There are no partial Cauchy surfaces in this arena; but because of asymptotic flatness the notion of past null infinity $\mathscr{I}^-$ is well defined, and initial data can be posed on $\mathscr{I}^-$.[40]

For initial conditions (specified on S for the twin paradox spacetime or on $\mathscr{I}^-$ for the eternal time travel spacetime) that would send the billiard ball into the wormhole, one might expect to find that strong consistency constraints are needed to avoid the grandfather paradox. But when Echeverria et al. searched for forbidden initial conditions, they were unable to find any. Thus, it is plausible, but not proven, that for each initial state of the billiard ball, specified in the non-chronology violating region of the spacetime, there exists a globally consistent extension. Mikheeva and Novikov[41] have argued that a similar conclusion holds for an inelastic billiard ball.

Surprisingly, what Echeverria et al. did find was that each of many initial trajectories had a countably infinite number of consistent extensions. The consistency problem and the phenomenon of multiple extensions is illustrated in figure 4. In figure 4(*a*) we have yet another instance of the grandfather paradox. The initial trajectory ζ, if prolonged without interruption, takes the billiard ball into mouth 2 of the wormhole. The ball emerges from mouth 1 along η, collides with its younger self, converting ζ into ζ' and preventing itself from entering the wormhole. Figures 4(*b*) and 4(*c*) show how ζ admits of self-consistent extensions. In figure 4(*b*) the ball suffers a grazing collision which deflects it along trajectory ζ''. It then reemerges from mouth 1 along ψ and suffers a glancing blow from its younger self and is deflected along ψ'.

39 Echeverria, Klinkhammer, & Thorne (1991).

40 Intuitively, $\mathscr{I}^-$ is the origin of light rays that come in from spatial infinity. For a formal definition, see Hawking & Ellis (1973).

41 Mikheeva & Novikov (1992).

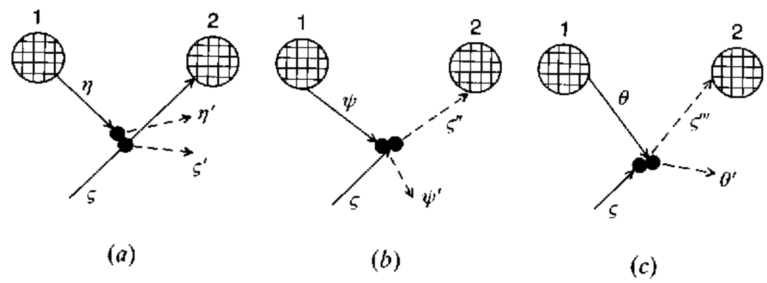

Fig. 4. Self-inconsistent and self-consistent billiard ball motions in a wormhole spacetime (after Echeverria et al.[39])

Readers can provide the interpretation of figure 4(*c*) for themselves. The demonstration of the existence of initial conditions that admit an infinite multiplicity of consistent extensions involves the consideration of trajectories that make multiple wormhole traversals; the details are too complicated to be considered here.

These fascinating findings on the multiplicity of extensions are relevant to the question of whether it is possible to operate a time machine; this matter will be taken up in section 9. Of more direct relevance to present concerns are the findings about consistency constraints for self-interacting systems. The results of Echeverria et al.[39] indicate that in the twin paradox spacetime, for instance, the *non*-chronology violating portion of the spacetime is benign with respect to all billiard ball trajectories, including those dangerous trajectories that take the ball into situations where the grandfather paradox might be expected. But the chronology violating region of this spacetime is most certainly *not* benign with respect to billiard ball motions. Perhaps it is a feature of non-benign spacetimes that the failure of benignity only shows up in the chronology violating region, but one example does not give much confidence.

The study of more complicated self-interacting systems quickly becomes intractable at the level of fundamental physics. What one has to deal with is a coupled set of equations describing the self- and cross-interactions of particles and fields. Deriving properties of solutions of such a set of equations for chronology violating spacetimes is beyond present capabilities. Instead one studies the behavior of 'devices' whose behavior is described on the macrolevel. The presumption is that if these devices were analyzed into fundamental constituents and if the field equations and equations of

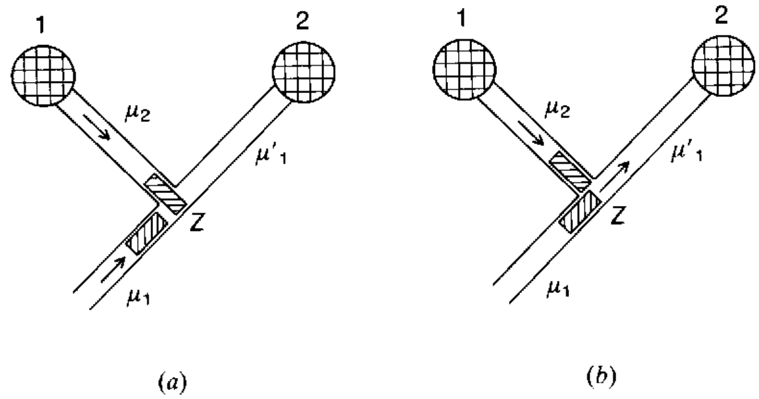

Fig. 5. Self-inconsistent and self-consistent motions for a piston device (after Novikov[42])

motion for these constituents were solved for some relevant range of initial and boundary conditions, then the solutions would display the behavior characteristic of the type of device in question. From this point of view, a perfectly elastic billiard ball might be considered to be one of the simplest devices.

A slightly more complicated device consists of a rigid Y shaped tube and a piston which moves frictionlessly in the tube. Imagine that the branches at the top of the Y are hooked to the mouths of the wormhole in the twin paradox spacetime. Because of the constraints the tube puts on the motion of the piston, it is not true that every initial motion of the piston up the bottom of the Y has a self-consistent extension. Figure 5(*a*) shows an initial motion that takes the piston up along the sections μ_1 and μ_1', into the wormhole mouth 2, through the wormhole, out of mouth 1 at an earlier time, down the section μ_2 to the junction Z just in time to block its younger self from entering the μ_1' section.

Novikov[42] argues that self-consistent solutions are possible if the device is made slightly more realistic by allowing the older and younger versions of the piston to experience friction as they rub against one another. In figure 5(*b*) the piston starts with the same initial velocity as in figure 5(*a*). But when the piston tries to pass through the junction Z it is slowed down by rubbing against its younger self. This slowing down means that when the piston

[42] Novikov (1992).

traverses the wormhole it will not emerge at an earlier enough time to block the junction but only to slow its younger self down. Novikov gives a semi-quantitative argument to show that, with self-friction present, for any initial motion of the piston that gives rise to an inconsistent/grandfather paradox evolution as in figure 5(*a*), there is a self-consistent extension as in figure 5(*b*). For initial trajectories that have the time travelling piston arriving at the junction well before its younger self reaches that point, there is also arguably a self-consistent continuation. Thus, it is plausible that there are no non-trivial consistency constraints on the initial motion of the piston up the μ_1 section of the tube.

The work of Wheeler and Feynman and Clarke[43] suggests that the absence of consistency constraints or at least the benignity of the constraints can be demonstrated generally for a class of devices for which the evolution is a continuous function of the parameters describing the initial conditions and the self-interaction, the idea being that fixed point theorems of topology can be invoked to yield the existence of a consistent evolution. However, Maudlin[44] showed that if the topology of the parameter space is complicated enough, a fixed point/self-consistent solution may not exist for some initial conditions. And one would suppose that in the general case the problem of deciding whether the relevant state space topology admits a fixed point theorem is as difficult as solving directly for the consistency constraints.

One might expect that with sufficiently complicated devices there may be no (or only rare) initial conditions that admit a self-consistent continuation in a chronology violating environment that allow the device to follow CTCs. Consider Novikov's device[42] consisting of a radio transmitter, which sends out a directed beam; a receiver, which listens for a signal; and a bomb. The device is programmed to detonate the bomb if and only if it detects a signal of a strength that would be experienced by being, say, 30 m from the device's transmitter. A self-consistent traverse of the wormhole of the twin paradox spacetime is possible if the device undergoes inelastic collisions; for then such a collision between the older and younger versions can produce a change in orientation of the transmitter such that the younger self does not receive the signal from its older self and, consequently, no explosion takes place. But one can think of any number of epicycles that do not admit of any obvious self-consistent solution. For example, as Novikov himself suggests,

[43] Wheeler & Feynman (1949) and Clarke (1977).
[44] Maudlin (1990).

the device could be equipped with gyro-stabilizers that maintain the direction of the radio beam.

It is all too easy to get caught up in the fascinating details of such devices and thereby to lose sight of the implications for what I take to be the important issues about time travel. As a way of stepping back, let me reiterate the point that came up in connection with the investigations of Echeverria et al.[39] of billiard ball motions in chronology violating spacetimes. The absence of consistency constraints or the benignity of these constraints with respect to initial conditions of a device, as specified in the *non*-chronology violating portion of the spacetime, does not establish the absence of consistency constraints or their benignity simpliciter. For example, assuming some self-friction of the piston of the Novikov piston device, there may be no non-trivial consistency constraints on the initial motion of the piston up the bottom of the Y. But there most certainly are constraints on the motion in the chronology violating portion of the spacetime, and these constraints are not benign. Consider any spacetime neighborhood that includes the junction Z at a time when the piston is passing Z. Passing from μ_1 to μ_1' with a speed v without rubbing against a piston coming down μ_2 is a physically possible local state for every v. But for some values of v there is no self-consistent extension. Thus, contrary to what some commentators have suggested, the recent work on the physics of time travel does not dissolve the paradoxes of time travel. Whatever exactly these paradoxes are, they rest on the existence of consistency constraints entailed by field equations/laws of motion in the presence of CTCs. Showing that those constraints are trivial would effectively dissolve the paradoxes. But all the recent work affirms the non-triviality of such constraints.

Suppose that there are devices that function normally in our world but which do not admit of any self-consistent evolution in a chronology violating background spacetime M, g_{ab}. What more would this show over and above that our world does not have the spatiotemporal structure of M, g_{ab}? Well suppose also that it followed from the first supposition that the laws which hold in the actual world and which govern the constituents of the devices do not have any globally consistent solutions in M, g_{ab}. Then these laws would presumably not be basic laws of a world with the spacetime M, g_{ab}. They could not even be true of such a world except in the trivial case where the constituent particles and fields were not present. Thus, we could conclude that the sort of spatiotemporal structure represented by M, g_{ab} is an extremely remote possibility. Alas, there is no good reason to think that the second supposition holds. All that follows from the non-existence of self-consistent histories for the devices is the non-existence of solutions of the relevant laws for the restricted ranges of fundamental variables that correspond to the normal operation of the device in our world. This is why it is important to get beyond 'devices' and tackle more directly the problems of consistency constraints for the fundamental laws of self-interacting systems. But as already noted there is little hope of rapid progress on this difficult project.

Does what we have learned about self-interacting systems give reason for optimism about my working hypothesis; namely, that insofar as a chronology violating world admits a set of M-R-L laws for test fields, those laws will subsume the consistency constraints forced out by the presence of CTCs? One might see a basis for pessimism deriving from the fact that in the wormhole spacetimes the constraints that obtain in different regions are different (e.g. no constraints on the initial conditions for the billiard ball in the non-chronology violating region of the twin paradox spacetime but non-trivial constraints in the chronology violating region). Since we want laws of nature to be 'universal' in the sense that they hold good for every region of spacetime, it might seem that the wormhole spacetimes dash the hope that the consistency constraints will have a lawlike status. But the hope is not to be extinguished so easily. To be 'universal', the constraint must be put in a general form; viz. for any region R, constraint $C(R)$ obtains iff _____, where the blank is filled in with conditions formulated in terms of suitably general (non-Goodmanized) predicates. The blank will need to be filled in not only with features of R but also with features of the relation of R to the rest of spacetime. So if the consistency constraints have law status, then the laws of a chronology violating wormhole spacetime cannot all be local. But that was only to be expected. The real concern is the one that surfaced in section 7; namely, that as the spacetime gets more and more complicated, the conditions that go into the blank may have to become so complicated that the consistency constraints will not qualify as M-R-L laws. Remember, however, that this concern is mitigated if the chronology violating worlds in question can be deemed to lie in the outer reaches of the space of worlds nomologically accessible from the actual world. Here I think that intuition pumping is useless until we have more concrete examples to serve as an anchor.

9 Is it possible for us to build and operate a time machine?

The question that forms the title of this section is not equivalent to the question of whether time travel is possible. If, for example, the Gödel universe is physically possible, then so is time travel. But in such cases it is the universe as a whole that is serving as a time machine and not something that we constructed and set into motion.

In trying to characterize a time machine we face something of a conundrum. To make sure that the CTCs are due to the operation of the time machine we could stipulate that there is a time slice S, corresponding to a time before the machine is turned on, such that there are no CTCs in $J^-(S)$. Furthermore, by going to a covering spacetime if necessary, we can guarantee that S is achronal and, thus, a partial Cauchy surface. But then by construction only time travel to the future of S is allowed, which immediately eliminates the kind of time travel envisioned in the typical time travel story of the science fiction literature. I do not see any easy way out of this conundrum, and for present purposes I will assume that such an S exists.

Next, one would like a condition which says that only local manipulations of matter and energy are involved in the operation of the machine. Requiring that the spacetime be asymptotically flat would be one approach – intuitively, the gravitational field of the machine falls off at large distances. But on one hand this requirement precludes many plausible cosmologies; and on the other hand it is not evident that a condition on the space structure guarantees that something funny with the causal structure was not already in progress before the machine was switched on.

It is even more delicate to pin down what it means to say that switching on the time machine produces CTCs. Programming the time machine corresponds to setting initial conditions on the partial Cauchy surface S. These conditions together with the coupled Einstein–matter equations determine a unique evolution for the portion of $J^+(S)$ contained in $D^+(S)$. But $D^+(S)$ is globally hyperbolic and therefore contains no CTCs.[45] Moreover, the future boundary $H^+(S)$ of $D^+(S)$ is always achronal. The notion that the initial conditions on S are responsible for the formation of CTCs can perhaps be captured by the requirement that some of the null geodesic generators of $H^+(S)$ are closed

[45] Global hyperbolicity is equivalent to the existence of a Cauchy surface. Thus, $D^+(S), g_{ab}|_{D^+(S)}$ considered as a spacetime in itself is at the top of the part of the causality hierarchy discussed in section 2.

or almost closed, indicating that CTCs are on the verge of forming.[46] Perhaps it should also be required that any appropriate extension of the spacetime across $H^+(S)$ contains CTCs.

One need not be too fussy about the sufficient conditions for the operation of a time machine if the goal is to prove negative results, for then one need only fix on some precise necessary conditions. An example of such a result was obtained recently by Hawking.[26] In concert with the above discussion he assumes the existence of a partial Cauchy surface S such that $H^+(S)$ separates the portion of spacetime with CTCs from the portion without CTCs. In Hawking's terminology, $H^+(S)$ is a *chronology horizon*. If all the past directed generators of $H^+(S)$ are contained in a compact set, then $H^+(S)$ is said to be *compactly generated*.

Theorem (Hawking). Let M, g_{ab}, T^{ab} be a cosmological model satisfying Einstein's field equations (with or without cosmological constant). Suppose that M, g_{ab} admits a partial Cauchy surface S and that T^{ab} satisfies the null energy condition. Then (a) if S is non-compact, $H^+(S)$ cannot be non-empty and compactly generated, and (b) if S is compact, $H^+(S)$ can be compactly generated but matter cannot cross $H^+(S)$.

How effective is this formal result as an argument against time machines? At best, part (b) of the Theorem shows that the operator of the time machine cannot himself sample the fruits of his labor. And both parts rely on $H^+(S)$ being compactly generated, which means physically that the generators of $H^+(S)$ do not emerge from a curvature singularity nor do they come in from 'infinity'. These prohibitions might be motivated by the idea that if the appearance of CTCs is to be attributed to the operation of a time machine, then the CTCs must result from the manipulation of matter–energy in a finite region of space. But it seems to me that this motivation is served best not by Hawking's requirement that $H^+(S)$ is compactly generated but by the combination of requirements that $H^+(S)$ contains closed or almost closed null geodesic generators and that $H^+(S)$ is *compactly causally generated* in the sense that $\overline{I^-(H^+(S)) \cap S}$ is compact. If these requirements hold, then what happens if a finite region of space $Q \equiv \overline{I^-(H^+(S)) \cap S}$ causally generates a development $D^+(Q)$ on whose future boundary $H^+(Q) \supset H^+(S)$ a causality violation occurs, indicating that CTCs are just about to form. $H^+(S)$ can be compactly causally generated without being compactly generated. But if the former condition is substituted for the latter, it remains to be seen whether a

[46] $H^+(S)$ is a null surface that is generated by null geodesics.

version of Hawking's chronology protection theorem will continue to be valid. (I conjecture that it will not.)

A different approach to showing that the laws of physics are unfriendly to the enterprise of building a time machine would be to try to show that the operation of the machine involves physical instabilities. More specifically, in terms of the setting suggested above, one would try to show that a chronology horizon is necessarily unstable. This approach links back to the problem of the behavior of test fields on chronology violating spacetimes; indeed, the stability property can be explicated in terms of the existence of extensions of solutions of the test field. To return to the example of a scalar field Φ obeying the wave equation $\Box\Phi = 0$, consider arbitrary initial data on the partial Cauchy surface S (the values on S of Φ and its normal derivative to S) of finite energy.[47] Each such data set determines a unique solution in the region $D^+(S)$. Then $H^+(S)$ can be said to be *completely stable* for Φ iff every such solution has a smooth extension across $H^+(S)$.[48] Further $H^+(S)$ can be said to be *generically stable* for Φ iff a generic solution has a smooth extension across $H^+(S)$.[49]

It has been argued by Morris et al.[20] and by Friedman and Morris[50] that some asymptotically flat wormhole spacetimes with CTCs have stable chronology horizons. However, these examples violate the weak energy condition of classical GTR.[51] Such violations are tolerated in quantum field theory. But recent investigations indicate that quantum field theory may require an averaged or integrated version of the energy conditions whose violation is entailed by the maintenance of traversable wormholes.[52]

An example of a vacuum solution to EFE that contains a partial Cauchy surface S with CTCs to the future of S and where the chronology horizon $H^+(S)$ is generically unstable for Φ is the two-dimensional version of Taub–NUT spacetime (see Hawking and Ellis[11] pp. 170–8). Here the chronology horizon is not only compactly generated but is itself compact; indeed, it is generated by a smoothly closed null geodesic λ. Each time the tangent vector of λ is transported parallel to itself around the loop it is expanded by a

47 See Yurtsever (1991) for a definition of this notion and for a more precise specification of the stability property.

48 See Yurtsever (1991) for a formulation of the relevant smoothness conditions.

49 The space of initial conditions has a natural topology so that a generic set of solutions can be taken to be one that corresponds to an open set of initial conditions.

50 Friedman & Morris (1991a,b).

51 This follows from the results of Tipler (1976, 1977) which show that the weak energy condition prevents the kind of topology change that occurs with the development of wormholes.

52 Wald & Yurtsever (1991) give a proof of the *averaged null energy condition* for a massless scalar field in a curved two-dimensional spacetime.

factor of $\exp(h)$, $h > 0$, indicating a blueshift. Now consider a generic high frequency wave packet solution to $\Box\Phi = 0$ 'propagating to the right'. As it nears $H^+(S)$ it experiences a blueshift each time it makes a circuit, and as an infinite number of circuits are needed to reach $H^+(S)$, the blueshift diverges. This is already indicative of an instability, but to demonstrate that the divergent blueshift involves an instability that prevents an extension across $H^+(S)$ it has to be checked that the local energy density of the wave packet diverges as $H^+(S)$ is approached.[53] That is in fact the case in this example.[26] One could then reason that when Φ is not treated merely as a test field but as a source for the gravitational field, spacetime singularities will develop on $H^+(S)$ thereby stopping the spacetime evolution and preventing the formation of CTCs that would otherwise have formed beyond the chronology horizon.[20]

However, the classical instability of chronology horizons does not seem to be an effective mechanism for ensuring chronology protection; for example, Hawking's results[26] indicate that among compactly generated chronology horizons, a non-negligible subset are classically stable. Even in cases where instability obtains, one can wonder how this instability undermines the feasibility of operating a time machine. Then insofar as the time machine involves non-zero values of Φ, it cannot succeed. The worst case of instability would be complete instability with respect to Φ, i.e. no solution of $\Box\Phi = 0$ other than $\Phi \equiv 0$ is extendible across $H^+(S)$. The next worst case would involve instability that is not complete but is so generic that only a set of solutions of measure zero admit extensions across $H^+(S)$. Here one could argue that if the time machine operator chose the parameter setting at random (with respect to the preferred measure on initial conditions), there would be a zero probability of hitting on a setting that would lead to successful operation of the machine. This would not be a proof of the impossibility of time travel using a time machine but only a demonstration that initiating the journey requires luck. Perhaps some stronger conclusion can be derived, but I do not see how. Measure zero arguments are commonly assumed to have a good deal of force, but it is hardly ever explained why.

The quantum instability of chronology horizons is currently under intensive investigation.[54] It seems that the expectation value of the (renormalized) stress

53 The energy density depends on the behavior of the two-dimensional cross sectional area of a pencil of geodesics.

54 See Hawking (1992), Kim & Thorne (1991), and Klinkhammer (1992).

energy tensor of a quantum field diverges as the chronology horizon is approached, with the divergence being stronger for a compactly generated horizon than for a non-compactly generated horizon. In the semi-classical approach to quantum gravity, the expectation value of the stress energy tensor is fed back into EFE to determine the effects on the spacetime geometry. Whether or not the divergence of the stress energy tensor on the chronology horizon produces an alteration of the spacetime sufficient to prevent the formation of CTCs is still controversial.

If a time machine can be constructed, the main puzzle about its operation is not the grandfather paradox but something quite different. The implicit assumption in the science fiction literature is that when the time machine is switched on, some definite scenario will unfold, as determined by the settings on the machine. But the still imperfectly understood physics of time travel hints at something quite at variance with these expectations. In the first place there may be different extensions of the spacetime across the chronology horizon $H^+(S)$.[55] In the second place, even when the spacetime extension is chosen and treated as a fixed background for test fields, billiard balls, and other devices, the equations which govern these systems may permit a multiplicity, perhaps even an infinite multiplicity, of extensions across $H^+(S)$ and into the time travel region. The point is not simply that one does not know the upshot of turning on the time machine but rather that the upshot is radically underdetermined on the ontological level. And thus the new puzzle: how does the universe choose among these ontologically distinct possibilities? Of course, it is unfair to demand a mechanism for making the choice if 'mechanism' implies determinism, for that is what is expressly ruled out in this situation. But it is equally unsatisfactory to respond with nothing more than the formula that it is just a matter of chance which option will unfold. If 'just a matter of chance' is to be more than an incantation or a recapitulation of the puzzle, then 'chance' must mean something like objective propensity. But the physics of classical GTR provides no basis for saying that there are objective probabilities of, say, 0.7 and 0.3 respectively for scenarios (*b*) and (*c*) in figure 4. Here quantum mechanics may come to the rescue of time travel by showing that for any initial quantum state describing the motion of the billiard ball before it enters the region of CTCs, there is a well defined probability for each of the subsequent classically consistent extensions.[56]

55 One can conjecture that if $H^+(S)$ is stable, then suitable extensions of the spacetime across $H^+(S)$ will be unique.

56 Results of this character have been announced by Klinkhammer and Thorne; see Echeverria, Klinkhammer, & Thorne (1991).

However, when CTCs are present it is to be expected that the time evolution will not be unitary.[57] The loss of unitarity is both a problem and an opportunity: a problem because it means that quantum mechanics in its standard form breaks down, and an opportunity because unitarity is a key ingredient in generating the measurement problem. Perhaps even more disturbing than the loss of unitarity is a seeming arbitrariness in the probabilities computed by the path integral approach. Apparently, probabilities for the outcomes of measurements made before $H^+(S)$ will depend on where the sum over histories is terminated to the future of $H^+(S)$.[58] Clearly how CTCs mesh or fail to mesh with quantum mechanics will be an exciting area of investigation for some time to come.

10 Conclusion

If nothing else, I hope that this chapter has made it clear that progress on understanding the problems and prospects of time travel is not going to come from the sorts of contemplations of the grandfather paradox typical of past philosophical writings. Using modal logic to symbolize the paradox, armchair reflections on the concept of causation, and the like are not going to yield new insights. The grandfather paradox is simply a way of pointing to the fact that if the usual laws of physics are supposed to hold true in a chronology violating spacetime, then consistency constraints emerge. The first step to understanding these constraints is to define their shape and content. This involves solving problems in physics, not armchair philosophical reflections.

But philosophy can help in understanding the status of the consistency constraints. Indeed, the existence of consistency constraints is a strong hint – but nevertheless a hint that most of the literature on time travel has managed to ignore – that it is naive to expect that the laws of a time travel world that is nomologically accessible from our world will be identical with the laws of our world. I explored this matter under the assumption that laws of nature are to be constructed following the analysis of Mill–Ramsey–Lewis. In some time travel worlds it is plausible that the M-R-L laws include the consistency constraints; in these cases the grandfather paradox has a satisfying resolution. In other cases the status of the consistency constraints remains obscure; in these cases the grandfather paradox leaves a residual itch. Those who wish to scratch the

[57] See Goldwirth, Perry, & Piran (1993).
[58] See Thorne (1991).

itch further may want to explore other analyses of laws. Indeed, time travel would seem to provide a good testing ground for competing analyses of laws.

I do not see any prospect for proving that time travel is impossible in any interesting sense. It may be, however, that it is not physically possible to operate a time machine that manufactures CTCs. But if so, no proof of this impossibility has emerged in classical GTR. If the operation of the time machine is feasible there emerges a new puzzle: a setting of the parameters on the time machine may correspond to many different scenarios in the time travel region. The problem here is not that the operation of the time machine is unpredictable or calls into play an element of indeterminacy; rather, the problem lies in providing an objective content to the notion of chance in this setting. Quantum mechanics is, of course, the place to look for such content. But standard quantum mechanics is hard to reconcile with CTCs. And it would be a little surprising and more than a little disturbing if Gödelian time machines, which seemed to be characterizable in purely classical relativistic terms, turn out to be inherently quantum mechanical. Is nothing safe from the clutches of the awful quantum?

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