Constraints on Data in Worlds with Closed Timelike Curves

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It is claimed that unacceptable constraints on initial data are imposed by certain responses to paradoxes that threaten time travel, closed timelike curves (CTCs) and other backwards causation hypotheses. In this paper I argue against the following claims: to say "contradictions are impossible so something must prevent the paradox" commits in general to constraints on initial data, that for fixed point dynamics so-called grey state solutions explain why contradictions do not arise, and the latter have been proved to avoid constraints on initial data.

1. Introduction. Spacetimes containing closed timelike curves (henceforth, CTCs) may appear to allow for data that leads, by the normal operation of local physics, to contradictions. So why will such contradictions not arise? Some (e.g., Arntzenius and Maudlin 2002) appear to hold that there are two approaches to such contradictions. The first simply says contradictions are not possible so something must happen to prevent them. This is claimed to entail unacceptable constraints on initial data. There is debate over whether these constraints really are unacceptable constraints (Smith 1997; Sider 2002; Dowe 2003), but I will not engage that debate here. The second approach, due originally to Wheeler and Feynman (1949) in the context of their hypothesis of advanced and retarded radiation, provides a 'grey state' solution to paradoxes. This, it is claimed, does not entail constraints on initial data. I will argue that grey state solutions are not likely to throw much light on standard grandfather paradoxes.

2. Logic or Physics? The first approach has as its exemplar, David Lewis (1976). Arntzenius and Maudlin (2002, 170) call his the "stonewalling response"; I will use the label 'logic'. Time-travelling Tim attempts to kill his grandfather. He will not succeed, but what will happen? "The forces

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of logic will not stay his hand" (Lewis 1976, 148). Rather, something will happen to prevent it. "Perhaps some noise distracts him at the last moment, perhaps he misses despite all his target practice, perhaps his nerve fails, perhaps he even feels a pang of unaccustomed mercy" (Lewis 1976, 149). Perhaps he slips on a banana skin. Continue the story with one of these 'explanations'. As Maudlin puts it, when paradox threatens, "the circumstances always act to thwart the killing" (1990, 304) and again, "If success is logically impossible then failure, however baroquely contrived, must occur" (304). Arntzenius and Maudlin say, "by logic indeed inconsistent events cannot both happen. Thus in fact all such schemes to create paradox are logically bound to fail. So what is the worry?" (2002, 170).

But Arntzenius and Maudlin have two worries. First, there is a need to explain why such schemes always fail. Lewis has an explanation for failure in each particular case: a banana skin in one, and earthquake in another. But these are disparate independent explanations with nothing to unify them. So there is no explanation for why such schemes always fail. Second, 'logic' entails unacceptable constraints on initial data. This is unacceptable, says Maudlin, because it appeals to "deus ex machina" solutions (1990, 304). There are two sorts: (*a*) miracles, that is, violations of laws. For example, Tim's bullet just stops midair. I will not consider miracles in this paper. (*b*) Then there are "conspiracies," or constraints on initial conditions. Lewis needs a banana skin or an earthquake or . . . lurking in the background conditions. A set of background conditions that lacks any means to prevent the paradox is ruled out. Hence initial data is constrained. This is unsatisfactory, says Maudlin, because "miracles and conspiracies are rejected in serious physical inquiry" (1990, 305). It is also problematic because in a deterministic world constraints on data entails earlier constraints, and hence we might have empirical evidence in the world now that there will never be time machines.

The second approach, I will call 'physics'. This has as its exemplar, the work of Kip Thorne and his students (e.g., Echeverria, Klinkhammer, and Thorne 1991), and draws on the approach due to Wheeler and Feynman (1949). Take a paradox machine yielding two contradictory trajectories. Assuming a Postulate of the Continuity of Nature, there will always be a consistent solution intermediate to the two paradox states, involving self-interaction. Thorne et al. studied the motion of 'billiard balls' (particle surrounded by a hard sphere, two-body potential) through a time-shifted wormhole (a time machine). Suppose we have a wormhole with a certain short time shift, depicted in Figure 1a. One can set initial conditions a_1 such that the dynamics lead to a paradoxical state: if b_1 and c_1 obtain then there will be a collision, meaning b_1 and c_1 will not obtain (the so-called 'Polchinski paradox', e.g., Thorne 1994, 51). Thorne and his students showed that in addition to the paradox solution, there is also the

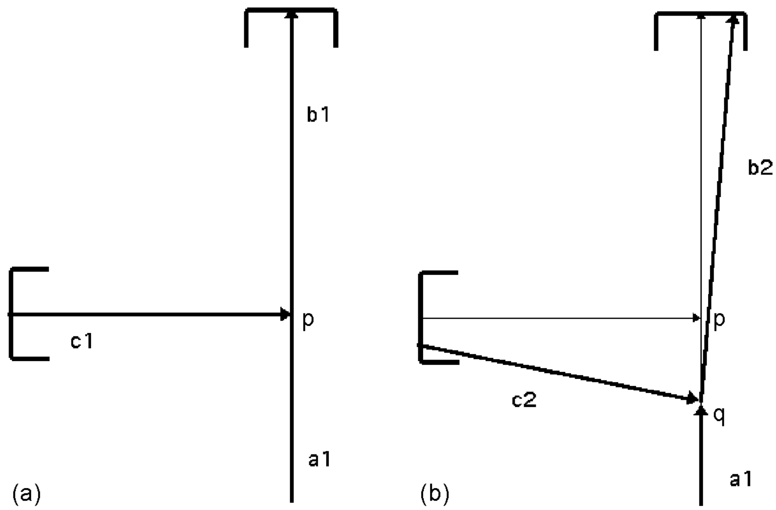

Figure 1. Spatial representations of (a) the Polchinski Paradox and (b) Grey State Solution.

'grey state' solution, where the ball grazes itself, deviating its trajectory slightly to b_2, and c_2, leading to the grazing collision (Figure 1b). Indeed, there are many such solutions, and that is so for any initial data. Thus there is no need to constrain the initial data, that is, no need for conspiracies. Says Maudlin, "Time travel is possible without the expedient of miracles or conspiracies" (1990, 307). Says Novikov, "The laws of physics automatically prevent the paradox" (1998, 260).

This grey state solution is a superior explanation, one might infer from Arntzenius and Maudlin's treatment, because it explains why there is never a contradiction, it does not appeal to conspiracies, and it provides a unified explanation similar to the way gravity provides a unified explanation for why you can never walk up a wall no matter how often you try (Novikov 1998, 260). As a matter of physical necessity paradox states will not arise.

We should note, as do Arntzenius and Maudlin, that the grey state approach is not completely general because there might be dynamics that do not admit of fixed-point solutions (see especially Maudlin 1990). My argument will not trade on this.

The claim, then, is that 'physics' (grey state solutions) is superior to 'logic' (contradictions cannot happen, something must happen to prevent the contradiction) for three reasons: One, 'Physics' avoids initial constraints (except for dynamics with no fixed point solution); Two, 'Physics', but not 'logic', explains why no contradictions arise; and Three, 'Logic'

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entails constraints on initial data that in turn entail constraints on earlier initial data. This would seem to indicate that grey state solutions are more apt than 'logic' to throw light on grandfather paradoxes. Maudlin says, "Lewis' appeal to conspiracies in the avoidance of paradox is not nearly as stimulating as Wheeler and Feynman's project" (1990, 314). Arntzenius expresses the same sentiment: "While philosophers of time have been yammering on about banana peels, physicists have been calculating whether such 'glancing blow' solutions always exist" (Arntzenius 2006, 608). However, in Section 3 I show that C is not true in general, in Section 4 I show that B is false, and in Sections 5 and 6 I provide arguments that undermine A. I conclude that grey state solutions are not likely to throw much light on standard grandfather paradoxes.

3. The Lion, the Switch, and the Banana. The first curious thing about the alleged dichotomy between logic and physics is that the proofs about consistent grey state solutions concern cases where data is posed before the time travel region, that is, the region containing CTC's. But standard grandfather paradoxes, if they are to be realised in space-times containing CTC's, must involve data posed in the time travel region. Thorne and associates never claimed that there were no constraints on data posed in the time travel region, as Arntzenius and Maudlin report, for such cases "there is no clear pattern" (in this section I will illustrate this) (2002, 190). Versions of the grandfather paradox can be given where the 'initial data' is such that it could be posed before the time travel region: Tim decides (somehow irreversibly) that if he ever comes across a time machine he will use it to go back and kill his earlier self. But these are not the standard grandfather paradox. It seems, then, that the claim that 'logic' entails constraints but 'physics' doesn't turns merely on the causal structure of the examples employed. But even so, we shall see that the 'logic' response to standard grandfather paradoxes does not in general entail constraints.

The basis for the claim that 'logic' (contradictions cannot happen, something must happen to prevent the contradiction) entails constraints on initial data is the reading that 'logic' commits to a scenario I will call 'bananas'. Suppose we attempt to pose data c_1 in Figure 1a. To do so we take a region R including c_1 such that all points in R are timelike to each other. Say R also includes a_1. Then 'bananas' is the solution that something present in the region will prevent the paradoxical collision, something that has a causal history independent of c_1 and a_1. The claim, then, is that 'bananas' entails constraints because it is not possible to pose data in R that includes c_1 and a_1 but no such banana.

But is such data open to a grey state solution? Yes and no. In everyday cases, such as Tim's attempt to kill his grandfather, the data is vague and underspecified. Say it's posed in such a way as to allow for c_1 or c_2 (see

Figure 1a and b). Then indeed the grey state solution in Figure 1b is indeed possible. Tim has inherited a brain condition that causes him to be slightly inaccurate in his shooting, thus merely wounding Grandfather, producing the heritable brain condition. But it is open to the paradox monger to disambiguate: The Empire sends back only those grandfather killers who lack the brain condition.

Actually, it is possible to pose data in R that includes c_1 and a_1 but no banana. In the ball case, there could be a second ball that interacts with the first ball after the collision, reinstating trajectory b_1. For the sake of the section title, call this the 'switch'. (Bananas allow the first of the two paradox states at *p*, the switch allows the second, and grey state solutions involve neither.) Perhaps Grandfather had made a sperm deposit, or perhaps he was a time traveller who travels forwards in time, sires offspring, then travels back to sit around awaiting his death. In discussions of standard grandfather paradoxes switch solutions are generally dismissed with a chuckle or a sneer, but in the case of ideal elastic balls they are every bit as good and bad as bananas. They equally resolve the paradox, and equally entail constraints. So we should say that it is not possible to pose data in R that includes c_1 and a_1 but no banana or switch.

But there is another kind of solution, which, following Krasnikov (2002), I will call 'lions'. Lions are loop objects, objects that exist just as a loop along a CTC, without beginning or end. Arntzenius and Maudlin give a nice example of a simple lion (2002, 182). Here is another: Dr. Who removes a steel ball from a pillar in Trafalgar Square in 2000, takes it back to 1900 and places it on the pillar, where it remains until 2000. (There is no 'hard and fast' distinction between loop objects and complex casual loops in general, but we will ignore that for simplicity.) Lions require internal consistency constraints, for example, requiring entropy reversals, but so do any complex data on CTCs. Deutch (1991) rules out all but the simplest cases of this kind of solution on dubious grounds which he calls a Principle of Philosophy of Science—Popper's Evolutionary Principle which claims that knowledge takes time to develop, which in Deutch's story turns into the principle that entropy in a region with a closed timelike curve cannot be less that it is before Cauchy horizon.

Suppose, then, a lion appears, temporally between R and *p*, and disrupts the trajectory, preventing the paradox. Our point is that lions fit "something must happen to prevent the paradox" just as well as bananas. Whether it is possible for a lion to appear between R and *p* but not appear in R depends on where region R is located with respect to the wormhole. But to assert that 'logic' (contradictions cannot happen, something must happen to prevent the contradiction) entails constraints is false. Tim's attempt could be located such that a lion may appear before he succeeds in killing grandfather.

But even if data is posed in a region such that it's not possible for a lion to appear between R and *p*, there could be lions in region R, and this is so for any R in a time travel region. This means that constraints in the time travel region do not entail earlier constraints (e.g., here now), and hence the worry that 'logic' could be refuted by present observations is also misplaced.

Further let us allow Lewis to "yabber on" a bit further. On Lewisian metaphysics, what would happen if Tim tried to kill his grandfather? According to Lewis' similarity relation for evaluating counterfactuals high value is placed on maximising regions of perfect match. Without pausing to figure out how Lewis' semantics work within time travel regions, we can in any case note that the closest worlds in which Tim tries to kill grandfather involve lions, not bananas, since the latter entail changes to all previous history. Thus Lewis' program favors lions over bananas and hence does not in general require constraints on initial data.

4. Does 'Physics' Explain Why Contradictions Do Not Occur? According to Novikov the laws of physics automatically prevent the paradox just like gravity prevents people walking up walls. How are they supposed to do this? We should think of the laws as acting on the initial conditions. Then we must ask why the physics gives us the grey state rather than the paradox state. Unfortunately the physics does not tell us this. At least, the dynamics of the particular phenomenon, acting locally as physics does, does not tell us. Applying the physics locally to the initial state in the fashion customary in physics leads just as well to the paradox state as to a grey state. To rule out the paradox state in favor of the grey state one needs the 'Global Consistency Constraint', something like: "The possible states include only those which can be continued to a consistent global solution." There is a debate about the status of the Global Consistency Constraint: is it part of the laws or not? (Earman 1995, 175; Riggs 1997; Kutach 2003, 1111–1112; Freidman et al. 1990). I suppose one could go either way on this.

But either way, Global Consistency amounts to a demand for logical consistency: the problem with the Polchinski paradox solution is one cannot both have a collision and not have a collision at one and the same space-time location. In effect, Global Consistency tells us you cannot have a contradiction, something else must happen. But this is exactly the 'logic' solution to paradoxes. Thus it would be disingenuous to appeal to Global Consistency to demonstrate the superiority of the 'physics' approach over the 'logic' approach. 'Physics' only explains why there never are contradictions by appeal to Global Consistency; but Global Consistency is pretty much logical consistency, the very thing that Artnzenius and Maudlin say does not explain why there never are contradictions. Thus the claim that 'physics' but not 'logic' explains why there never are contradictions is just false.

Some physicists have argued that Global Consistency is a demand for no new physics, which seems to make it very different to a demand for logical consistency. According to Friedman et al., it might be that CTC's trigger new kinds of local physics for a quantum mechanical system such that there is a multi valued wave function involving all the consistent and inconsistent trajectories, and new physics to determine the outcomes of measurements (1990, 1917). Global Consistency rules this out, they say, otherwise one would take it to be "tautological" and "trivial."

While the suggestion is of interest, allowing as it does that for such 'new physics' it would be physically possible for something to kill its own quantum-mechanical grandfather; as a claim about Global Consistency it is misleading, for the following reason. Global Consistency is not a claim for logical consistency simpliciter, it is a claim for logical consistency given a certain physics. To see this, note that it rules out for example the local state (call it state *D*) where the ball passes without collision point *p* in Figure 1a. This state cannot be continued to a globally consistent solution since it will continue to the state (call it state *E*) where, at the same space time point, collide with itself, and where state *E* is of course logically inconsistent with state *D*. But to suppose *D* 'continues to state *E*' we assume our laws. It is logically but not physically possible to have state *D* where it does not continue to state *E*, but rather comes to a stop before the collision in violation of Newton's first law of motion. Similarly, it is logically but not physically possible to kill your grandfather, where he subsequently rises from the dead. Thus Global Consistency—that only local states that can be continued to a globally consistent solution are possible—assumes a physics. It is a requirement that a given physics is logically consistent (see Deutsch 1991 for a similar response).

This allows us to restate Friedman et al's claim. Under their 'new physics' Global Consistency is an inadequate statement of the requirement for logical consistency and therefore should not be considered completely general; under our physics it is an adequate requirement. This does not change our claim that Global Consistency amounts at root to a claim for logical consistency, and that it supplies no substantial distinction between the 'logic' and physics' approaches.

5. No-Initial-Constraints Arguments. "[Echeverria, Klinkhammer, and Thorne] did not produce a rigorous proof that every initial trajectory has a consistent continuation, but suggested that it is very plausible that every initial trajectory has a consistent continuation. That is to say, they have made it very plausible that, in the billiard ball wormhole case, the time travel structure of such a wormhole space-time does not result in constraints on states on spacelike surfaces in the non-time travel region" (Arntzenius and Maudlin 2002, 189). If this is right then the "argument that no constraints are imposed by time travel" is an inductive argument, not a rigorous proof (Arntzenius and Maudlin 2002, 170). How good an inductive argument? What follows is an argument that at least undermines the inductive argument so far as it is based on grey state solutions. ('Lion' solutions considered above support the induction, but these are not grey state solution and are available to 'logic'.)

Proofs of consistent grey state solutions exist only for limited classes of cases. Consequently, it has not been proved for any case that no initial constraints are required. I will present the argument in terms of one single case, but it can easily be translated into an argument about a class of cases. I speak of 'initial constraints' in a single case, when of course what is proved in a single case is that a particular set of data can be continued to a consistent solution. I ask the reader to bear with me on this until the discussion following the proof.

The proof is this: Take a case, say of a single ball, where a consistent grey state solution has been demonstrated, and suppose for the moment that there is a unique consistent solution. A paradox monger could respond by introducing a second ball with a trajectory intended to knock out the consistent solution, but leave the paradox trajectory untouched. Two obvious possibilities suggest themselves. First, there is a pair of grey state collisions that allow a globally consistent solution to this two-body problem. Or, second, there is no such pair of grey state collisions, and hence there are initial constraints—the two-body initial state is not possible. If the latter is the case, then there are indeed initial constraints in the *original* one-ball case, namely, there cannot be a second ball with the trajectory just described. This is not so much a constraint on the initial state of the single ball, but one built into the background conditions when one asserts this is a one-ball case in the manner of the physicist. But it is an initial constraint all the same.

To prove that no initial constraints are involved in the one-ball case it is necessary to prove that there are grey state solutions for both the one-ball and two-ball cases. But it is not sufficient, because a paradox monger could introduce a third ball to knock out the two-ball consistent trajectory but not the original paradox trajectory, etc. Therefore in proving there exists a consistent solution to the one-ball case one has not thereby proved no initial constraints are required, ditto for the two-ball case, etc.

Suppose now that there is more than one consistent solution to the original one-body case. The paradox monger might then require more than one additional ball to reinstate the paradox. But otherwise the argument goes through in the same way. Suppose then there is an infinite number of consistent solutions to the original one-ball case. Could one conclude that no set of additional background factors could be fixed in such a way as to reinstate the paradox? This would need to be proved. Only then could one say that a proof of a consistent set of solutions proves that no initial constraints are required, and then only in the case where the set is infinite. Of course no such proof exists. QED.

It may be objected that all I have proved is the trivial point that solutions in the one-ball case are not solutions for a two-ball case. But consider again the context here. A problem is supposed to exist for 'logic' approach even in a single case such as Tim's banana slip: it looks like the background is "cooked," that is, the solution requires a special background configuration. Grey state solutions are claimed to not be cooked in this way. What I have shown is that there is no proof that grey state solutions are not cooked.

It may be objected that one merely needs to be clear about how the inductive argument is supposed to go. It cannot be: no constraints in this case, no constraints in that case, . . . therefore, no constraints anywhere. Rather, it should be: consistent solution here, consistent solution here, . . . therefore, consistent solutions everywhere. Therefore, no constraints. But, I would reply, if every instance of a proven consistent solution lacks a proof that the solution requires no special background constraints, then this indeed undermines that inductive argument to the conclusion that every possible initial configuration can be continued to a consistent solution.

6. The Difficulty of More Complex Grey State Solutions. If results concerning grey state solutions are to be applied to discussions of standard grandfather paradoxes then the inductive argument discussed in the previous section need to carry us from the idealised physics to messy real cases. But it is a long way from idealised elastic balls to people killing each other. The existence of grey state mechanisms in tractable idealised physics is not a strong indication that there exist plausible mechanisms in highly complex real life cases. 'Tim tries to kill grandfather but merely inflicts heritable brain damage which Tim inherits and which causes him to wound but not kill' is not a plausible mechanism. In this final section we illustrate the challenge of finding plausible mechanisms even for slightly more complex cases.

Consider a 'proof' due to Novikov (1992), involving a piston in a tube. Tubes are connected to the mouths of a small wormhole. An object, call it a 'piston', travels along the tubes. The paradox argument says you could set this up so that the piston travels through the wormhole and blocks itself, contradiction. This inconsistent solution occurs as follows. Let L_1 and L_2 be the lengths of the tube segments connecting the center-point Z with wormhole mouths A and B respectively. Let δt be the time

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shift (into the past) resulting from travel through the wormhole from A to B. Assume that the length and hence time of travel through the wormhole is negligible. Let δt_1 be the difference between the moments of arrival at Z of the younger and older versions of the piston assuming no collision. Let v_1 be the velocity of the piston, which is constant since we assume friction from the tube is negligible. (We might add this also assumes nothing happens to the piston velocity as it travels through the wormhole). We also suppose that the piston length is negligible compared to L_1 and L_2. Taking $t=0$ as the point where the piston first reaches the junction, we can then write the 'inconsistent solution':

$$(L_1 + L_2)/v_1 + \delta t_1 - \delta t = 0, \tag{1}$$

where the first term gives the time it takes the piston to travel from Z back to Z. (1) gives the solution of δt_1 in terms of v_1. Thus any choice of v_1 will give a paradox provided it give a value of δt_1 large enough that the older version of the piston arrives before the younger.

However, argues Novikov, there is another solution which is consistent. For the same input velocity v_1, suppose the piston versions arrive at roughly the same time so the younger scrapes the end of the older one. Let δt_2 be the difference between the moments of arrival at Z of the younger and older versions of the piston assuming now that there is a collision. Let δv be the change in velocity due to the action of friction, that is, $\delta v = v_1 - v_2$. δv is a function $\delta v(\delta t_2, v_2)$. "This function is known," says Novikov, although he does not say what it is except that its dependence on δt_2 is "very steep."

Novikov then writes:

$$(L_1 + L_2)/v_2 + \delta t_2 - \delta t = 0, \tag{2}$$

$$v_2 = v_1 - \delta v(\delta t_2, v_2). \tag{3}$$

We need to solve these two equations together. Novikov claims it can be done, and so it can be demonstrated that any initial conditions can be continued to a consistent solution. I will, however, follow a different route.

$\delta v(\delta t_2, v_2)$ is the change in velocity due to the action of friction. It is a function of δt_2 because that gives the time for which the friction force acts, and it is a function of v_2 because that affects the size of the impact force. However, let us simplify to illustrate how the physics works; firstly by ignoring the latter.

Suppose then that $\delta v(\delta t_2)$. δv approaches its maximum δv_{MAX} as δt_2 approaches 0, although it cannot actually be zero. δv approaches its minimum as δt_2 approaches $\delta t_{2\mathrm{MAX}}$, the point at which the older self of the puck just clips the end of its earlier self. The latter is a constant set by

v_1 and the dimensions of the puck. δv_{MAX} is set by the facts of friction and v_1. Suppose, again for simplicity, that $\delta v(\delta t_2)$ is linear (with t_2 for δt_2):

$$\delta v/\delta v_{\mathrm{MAX}} = 1 - t_2/t_{2\mathrm{MAX}}. \quad (4)$$

With (3) this gives

$$v_2/\delta v_{\mathrm{MAX}} = t_2/t_{2\mathrm{MAX}} + v_1/\delta v_{\mathrm{MAX}} - 1. \quad (5)$$

With (2) this gives v_2 in terms of initial and standing conditions

$$v_2^2/\delta v_{\mathrm{MAX}} - v_2(\delta t/t_{2\mathrm{MAX}} - v_1/\delta v_{\mathrm{MAX}} + 1) - (\mathrm{L}_1 + \mathrm{L}_2)/t_{2\mathrm{MAX}} = 0. \quad (6)$$

This function (on the left hand side) is continuous and the equation has one or two solutions. A number of difficulties arise. First, the physics of the grey state remains paradoxical even if there is a solution. Equation (4) tells us the larger t_2, the smaller δv, and hence the larger v_2. This makes sense because the effects of friction should be smaller the shorter the period of contact. However, the kinematics tells us the smaller v_2, the larger t_2, since the older version of the piston arrives later. Thus there is a paradox in the very physics of the grey state.

But we may leave this aside, because there are other difficulties lurking. There are range restrictions imposed by the standing conditions obtaining in the grey state. The general form of equation (6) has sometimes two solutions and sometime one, for $v_2 > 0$. The solution depends on the various initial and standing conditions in the function. However there are also upper and lower bounds set by the fact that the earlier and later versions of the piston must collide, *viz*.:

$$v_1 - \delta v_{\mathrm{MAX}} > v_2 > v_1.$$

There is in general no guarantee that there is a solution for (6) within this range. The function on the left hand side of (6) starts, for $v_2 = 0$, at $-(\mathrm{L}_1+\mathrm{L}_2)/t_{2\mathrm{MAX}}$, then drops, before heading towards positive values. One hopes it passes the solution point after the lower bound but before the upper bound. When one writes out the values of the function at these two bounds, it seems that whether the solution lies between them depends on the initial and standing conditions, for example, on a friction function, which could be changed by greasing the end of the piston. So then we would have to dream up another grey state mechanism to deal with a case that supposed to be settled.

REFERENCES

Arntzenius, Frank (2006), "Time Travel: Double Your Fun", *Philosophy Compass* 1: 599–616.

Arntzenius, Frank, and Tim Maudlin (2002), "Time Travel and Modern Physics", in Craig

https://doi.org/10.1086/525617 Published online by Cambridge University Press

Callender (ed.), *Time, Reality and Experience*. Cambridge: Cambridge University Press, 169–200.
Deutsch, David (1991), "Quantum Mechanics Near Closed Timelike Curves", *Physical Review D* 44: 3197–3217.
Dowe, Phil (2003), "The Coincidences of Time Travel", *Philosophy of Science* 70: 574–589.
Earman, John (1995), *Bangs, Crunches, Whimpers, and Shrieks: Singularities and Acausalities in Relativistic Spacetimes*. New York: Oxford University Press.
Echeverria, F., G. Klinkhammer, and Kip Thorne (1991), "Billiard Ball in Wormhole Spacetimes with Closed Timelike Curves: Classical Theory", *Physical Review D* 44: 1077–1099.
Feynman, Richard, and John Wheeler (1949), "Classical Electrodynamics in Terms of Direct Interparticle Action", *Reviews of Modern Physics* 21: 425–434.
Friedman, John, M. Morris, Igor Novikov, F. Echeverria, G. Klinkhammer, Kip Thorne, and U. Yurtsever (1990), "Cauchy Problem in Spacetimes with Closed Timelike Curves", *Physical Review D* 42: 1915–1930.
Krasnikov, Sergei (2002), "Time Travel Paradox", *Physical Review D* 65: 064013.
Kutach, Doug (2003), "Time Travel and Consistency Constraint", *Philosophy of Science* 70: 1098–1113.
Lewis, David (1976), "The Paradoxes of Time Travel", *American Philosophical Quarterly* 13: 145–152.
Maudlin, Tim (1990), "Time Travel and Topology", in Arthur Fine, Micky Forbes, and Linda Wessels (eds.), *PSA 1990*. Vol. 1. East Lansing, MI: Philosophy of Science Association, 303–315.
Novikov, Igor (1992), "Time Machine and Self-Consistent Evolution in Problems with Self-Interaction", *Physical Review D* 45: 1989–1994.
——— (1998), *The River of Time*. Cambridge: Cambridge University Press.
Riggs, Peter (1997), "The Principal Paradox of Time Travel", *Ratio* 10: 48–64.
Sider, Ted (2002), "Time Travel, Coincidences and Counterfactuals", *Philosophical Studies* 110: 115–138.
Smith, Nick (1997), "Bananas Enough for Time Travel?" *British Journal for the Philosophy of Science* 48: 363–389.
Thorne, Kip (1994), *Black Holes and Time Warps*. New York: Norton.