# A Remark on 'Time Machines' in Honor of Howard Stein*

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## 1 Introduction

Over the past while, a few of us have been chipping away at a question posed by Howard Stein in his 1970 paper on Gödel spacetime. Here is the question (Stein 1970, 594).

> Consider either an arbitrary given cosmological model, or a model having the structure of one of the sorts assumed to hold in the real world. Then: is it ((a) ever, (b) always) possible to introduce into such a model a continuous deformation of the structure, leading through intermediate states, all compatible with Einstein's theory, to a state in which Gödel-type relationships occur?

A framework for investigating Stein's question – often interpreted to be a question concerning the possibility of 'time machines' – has been developed by John Earman and others.[1] I'll be working within that framework today. I hope to give a sense on where things stand in 2017 and articulate possible avenues for future work as well. My thesis is three-fold. First, there is a sense in which there are 'time machines' in general relativity. Second, there are 'hole machines' as well. Finally, I will conclude that (so far) it seems the 'hole machine' advocate is in a better position than the 'time machine' advocate. I will work to make clear the content of these three claims. Regarding the third claim, let me suggest at this stage that we refer to the time machine advocate as 'Tim' and the hole machine advocate as 'Hal' to make things easier. These are just idealized philosophers trying to make the case, as best they can, for the possibility of their respective machines. We will have more to say about Tim and Hal – and the tension between them – toward the end of the talk.

*This paper was presented at *The Philosophy of Howard Stein* conference on June 9, 2017 at the University of Chicago. I thank the participants and attendees for valuable discussions throughout the conference.

[1]See: Earman 1995; Earman et al. 2009; Earman et al. 2016; Krasnikov 2002, 2014, 2018; Manchak 2009a, 2011a, 2013, 2014a; Smeenk and Wüthrich 2010.

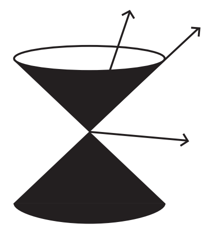
## 2 Preliminaries

Before we begin our discussion, I think it will be useful to outline some of the basic structure of relativity theory we will need later on.[2] General relativity determines a class of cosmological models or spacetimes; each model represents a physically possible world which is compatible with the theory. We take such a model to be an ordered pair $(M, g)$. The ***manifold*** $M$ captures the shape or topology of the universe and each point in $M$ represents a possible event. A number of two-dimensional manifolds are familiar to us: the plane, sphere, torus, and so on. Here we see the cylinder which will be important later on.

a manifold

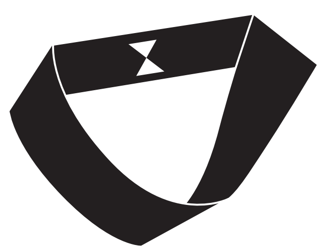
Note that any manifold with a topologically closed set of points removed also counts as a manifold. For example, the sphere with the 'North Pole' removed is a manifold. Manifolds are great for representing events in spacetime. But we need more structure to represent how these events are related to each other. It is the ***metric*** $g$ which allows us to specify this extra structure. One of the jobs of a metric is to assign a double 'cone' structure to each point in the manifold. Some cones on a manifold might be more 'narrow' than others and some might more 'tilted' than others. We only require than the cone structure vary in a smooth way. ***Minkowski spacetime*** is the spacetime of special relativity; in two dimensions, it is just the plane with a metric which does not change from point to point. We will refer to Minkowski spacetime often in what follows. Of course the cones have an intuitive physical significance. In general relativity, it seems that 'nothing can travel faster than light'; so there is an upper bound to the speeds with which particles may travel. If we think of vectors at a point as velocity vectors, then the cone structure demarcates that upper bound.

[2]The reader is encouraged to consult Hawking and Ellis (1973), Wald (1984), and Malament (2012) for details. Less technical surveys of the global structure of spacetime are given by Geroch and Horowitz (1979) and Manchak (2013).



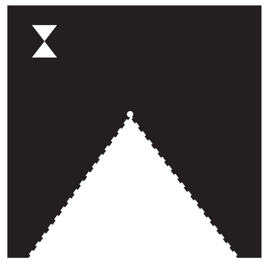
timelike, null, and spacelike vectors

Here, we see one of the cones – this one in three dimensions. Massive particles must always have velocity vectors lying inside the cone. We call such vectors ***timelike***. Photons, on the other hand, must always have velocity vectors lying on the boundary of the cone. Such vectors are called ***null***. Finally, those vectors lying outside the cone are called ***spacelike***. Every cone has two lobes. In our discussion today, we will assume that, ranging over the entire manifold, we can label these lobes as 'past' and 'future' in a way that involves no discontinuity. Such spacetimes are called ***time-orientable***. Here we see a spacetime with a Möbius strip as a manifold; it fails to be time-orientable.



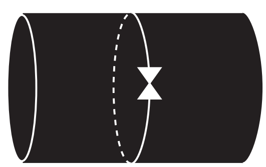
non-time-orientable spacetime

Let's now review some basic definition concerning curves on the spacetime manifold. A curve is ***timelike*** if all of its tangent vectors are timelike. Intuitively, a timelike curve 'threads' the cones at the points through which it passes. Similarly, we can define ***null*** and ***spacelike*** curves. And we'll say a ***causal*** curve is one with tangent vectors everywhere timelike or null. A causal curve is ***future-directed*** if all its tangent vectors are in or on the future lobes of the light cones; a future-directed timelike curve represents the possible life history of a massive particle. Let's use the idea of a future-directed timelike curve to define the 'timelike past' of a point. Consider a spacetime and fix any point $p$ in the manifold. The ***timelike past*** of $p$ is the set of all points $q$ such that there exists a future-directed timelike curve from $q$ to $p$; a point gets to be in the timelike past of $p$ if it's possible for a massive particle to travel from the point to $p$. Here we see the distinctive 'wedge' shape of a timelike past in Minkowski spacetime. The dotted lines indicate that the region is topologically open. Similarly, we can define the causal past of a point. The timelike future and causal future of a point are defined analogously.



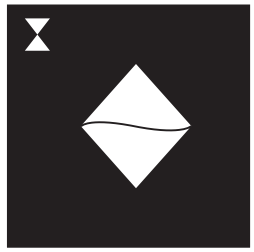
a timelike past

Now an interesting feature of general relativity is that it permits 'closed timelike curves' which allow for 'time travel' of a certain kind. A future-directed timelike curve is ***closed*** if it intersects itself. Here, we see Minkowski spacetime which has been 'rolled up' along the time axis allowing for a timelike curve to wrap back on itself. We say a spacetime is ***chronological*** if it has no closed timelike curves.



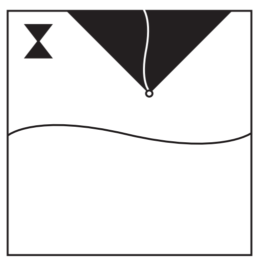
a closed timelike curve

Let's now move to a few definitions concerning surfaces on the spacetime manifold. A surface is ***spacelike*** if every every curve within the surface is a spacelike curve. A set is ***achronal*** if it is not intersected more than once by any timelike curve. A ***slice*** is a spacelike surface which is closed, achronal, and without an 'edge'; intuitively, a slice represents all of 'space' at a given 'time'. Now, consider an arbitrary set $S$ on a spacetime manifold. The ***domain of dependance*** $D(S)$ of $S$ is the set consisting of those points $q$ such that every causal curve through $q$ without endpoint intersects $S$. If 'nothing can travel faster than light', there is a sense in which conditions on $S$ will uniquely determine the physical situation in $D(S)$. Here, we see the domain of dependence of a spacelike, achronal surface in Minkowski spacetime. Note its distinctive diamond shape.



a domain of dependence

A spacetime which has a slice $S$ such that $D(S)$ is the entire manifold is said to be ***globally hyperbolic***. In such a spacetime, information on $S$ will determine the physical situation in all of spacetime. Globally hyperbolic spacetimes are causally well behaved; indeed it is a basic result that all globally hyperbolic spacetimes are chronological. Minkowski spacetime is globally hyperbolic. Minkowski spacetime with one point removed from the manifold is not; the causal curve without endpoint shown here does not intersect the indicated slice.



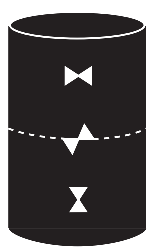
non-globally hyperbolic spacetime

Finally, we review spacetime extensions. We say that a spacetime is an ***extension*** of some other spacetime if the second can be (properly) embedded into the first while preserving the metric structure. A spacetime which has no extension is ***maximal***; otherwise, it is ***extendible***. With the use of Zorn's lemma, one can show that every extendible spacetime has a maximal extension. Finally, we say a spacetime is ***past-maximal*** if it has no extension in the past direction. Consider the bottom half of Minkowski spacetime depicted here; it is past-maximal but not maximal.

a past-maximal spacetime

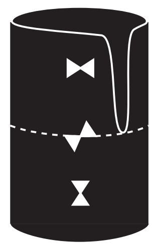
## 3 Time Machines

Now we're prepared to talk about 'time machines'. How does one characterize this notion within general relativity? Let's start by considering an extendible, past-maximal, globally hyperbolic spacetime. We might think of these models as having, in the language of Stein (1970, 594), "the structure assumed to hold in the real world" (so far). In what follows, let us say that such spacetimes are ***starters***. Now consider a 'naïve time machine' definition. A starter is a ***naïve time machine*** if all of its extensions fail to be chronological. The intuition behind the definition is straightforward. The starter represents a 'physically reasonable' universe before the machine produces the closed timelike curves. The requirement that all of its extensions fail to be chronological is supposed to capture the idea that the future universe is 'forced' into allowing for time travel.



misner spacetime

Consider Misner spacetime. The manifold is cylindrical and the metric structure is such that cones 'tip over' as they move up the cylinder. There are no closed timelike curves in the bottom half of this spacetime. But the top half contains closed timelike curves through every point. The region below the dotted line, taken as a spacetime in its own right, is a starter. Question: Is it also a naïve time machine? In other words, do all of its extensions fail to be chronological? No.



misner spacetime with 'hole'

We can take Misner spacetime and cut a hole in the manifold as indicated so as to prohibit closed timelike curves from forming. So, the bottom half of Misner spacetime is not a naïve time machine. In fact, there is a no-go result by Sergui Krasnikov (2002, 2014, 2018) which shows that no spacetime is a naïve time machine. To be sure, this is a beautiful result. Still, its physical significance can be called into question. Consider the following definition (Earman et al. 2016). A starter is a ***$\mathscr{P}$-time machine*** if (i) it has an extension with property $\mathscr{P}$ and (ii) every extension with $\mathscr{P}$ fails to be chronological. Here, property $\mathscr{P}$ is used to pare down the space of starter extensions to those which are "physically reasonable" in some sense. We also must add condition (i) to our definition to avoid a nuisance case: we do not want to consider a starter a $\mathscr{P}$-time machine simply because condition (ii) is vacuously true. Let's now consider some candidate properties.

## 4 No-Hole Properties

Recall that what seemed to keep the bottom half of Misner spacetime from being a naïve time machine was the existence of an extension which had a 'hole' of sorts which prevented any would-be closed timelike curves from forming. One wonders if there is a condition to rule out the 'hole' in the example. There certainly is. For sometime now, the condition of hole-freeness has been used to rule out such spacetimes. Here is the formulation. We say a spacetime is ***hole-free*** if, for every spacelike surface $S$, there is no metric preserving embedding of $D(S)$ into another spacetime such that the image of $D(S)$ under the embedding is a proper subset of the domain of dependence of the image of $S$ under the embedding. The intuitive idea here is beautifully simple: We require that the domain of dependence of each spacelike surface be 'as large as it can be'.

non-hole-free spacetime

To see the definition at work, consider Minkowski spacetime with one point removed. Note that the domain of dependence in the mutilated spacetime is not as large as it could be if the point were not removed; it is not the full diamond shape. So, the spacetime is not hole-free. It has been suggested by some experts that only hole-free spacetimes should be taken seriously. Here, we have Bob Geroch on the matter (others such as Ellis and Schmidt (1977) and Clarke (1993) take similar approaches).

> "One might now modify general relativity as follows: the new theory is to be general relativity, but with the additional condition that only hole-free spacetimes are permitted" (Geroch 1977, 87).

We now have everything we need to formulate a precise question: Is there a $\mathscr{P}$-time machine if $\mathscr{P}$ is the property of hole-freeness? This is the central question asked by Earman, Smeenk, and Wüthrich back in 2009. But 2009 was a strange year with respect to the property of hole-freeness.

Let's back up. In his 1977 paper on hole-freeness, Geroch claimed (without proof) that Minkowski spacetime was hole-free. That same year it was claimed (again, without proof) by Ellis and Schmidt that, not only Minkowski spacetime but every maximal, globally hyperbolic spacetime is hole-free. A proof of this latter claim was eventually given by Clarke in 1993. Thus, it seemed that a large class of 'physically reasonable' spacetimes were hole-free. But I was able to show in 2009 that the claim of Ellis and Schmidt was actually false (and that Clarke's proof contained an error); there are many maximal and globally hyperbolic spacetimes which have holes (Manchak 2009b). A few months later, Krasnikov (2009) was able to improve my result. He did so by exhibiting a bizarrely simple counterexample: Minkowski spacetime. In other words, he showed that the spacetime of special relativity has 'holes'!

minkowski spacetime

Here we see a spacelike surface (without boundary) in Minkowski spacetime and its associated domain of dependence. Note that the boundary of the domain of dependence – the dotted line – is not itself part of the domain of dependence. But we can embed this diamond shaped domain of dependence into Minkowski spacetime which has been 'rolled up' along the space axis. And we can do it in such a way that the domain of dependence of the embedded spacelike surface now contains some of its boundary points (the portion of the boundary not dotted). So it's 'larger' than it was in Minkowski spacetime.

'rolled' minkowski spacetime

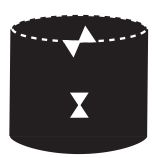
The upshot is that the property of hole-freeness does not seem to be a 'physically reasonable' one. Where does this leave the situation with time machines? Is there another property, more 'physically reasonable', which can rule out holes? There is. Before we present the condition, let's review a few facts concerning timelike and causal pasts (analogous facts hold for timelike and causal futures). First, note that, given any point in any spacetime, the timelike past of that point is always topologically open. In Minkowski spacetime, the causal past of every point is closed; but in general, the causal past of a point is not closed. Consider Minkowski spacetime with a point removed.

a non-closed causal past

We see that the causal past of the indicated point is neither open nor closed. This suggests a new type of hole-freeness property. We say a spacetime is ***J-hole-free*** if all causal pasts and futures are closed. Is this property more 'physically reasonable' than hole-freeness? We can breathe a sigh of relief since we have a proof that Minkowski spacetime is J-hole-free; in fact, one can show that all globally hyperbolic spacetimes – maximal or not – are J-hole-free (see Hawking and Sachs 1974). It turns out that one can show that if $\mathscr{P}$ is J-hole-freeness, there is a $\mathscr{P}$-time machine (Manchak 2011a).

## 5 Hole Machines?

Let's take a few steps back. What should we make of the time machine existence result just mentioned? Consider again the bottom half of Misner spacetime.



the bottom half of misner spacetime

We know that some extensions are chronological. And we know that every chronological extension has J-holes. Perhaps we ought think of the bottom half of Misner spacetime as a 'hole machine' of a certain type? Consider the following quite general 'machine' definition. A starter is a ($\mathscr{P}$, $\mathscr{Q}$)***-machine*** if (i) it has an extension with property $\mathscr{P}$ and (ii) every extension with $\mathscr{P}$ has $\mathscr{Q}$. As before property $\mathscr{P}$ is used to pare down the space of starter extensions to those which are “physically reasonable” in some sense. Property $\mathscr{Q}$ is the one intended to be ‘produced’ by the machine.

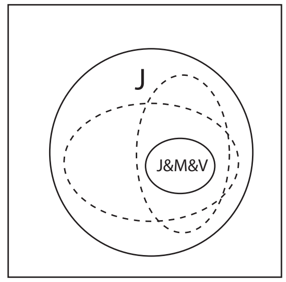
We see there is a ($\mathscr{P}$, $\mathscr{Q}$)-machine where $\mathscr{P}$ is J-hole-freeness and $\mathscr{Q}$ is the failure of chronology. But also we have a ($\mathscr{P}$, $\mathscr{Q}$)-machine where $\mathscr{P}$ is chronology and $\mathscr{Q}$ is the failure of J-hole-freeness. So which is it? Is the bottom half of Minser spacetime a type of ‘time machine’ or a type of ‘hole machine’? One way to break the stale-mate is to investigate how robust the results are with respect to different choices of the background class of ‘physically reasonable’ spacetimes. This turns out to be quite a project. Here’s why.

Suppose for some properties $\mathscr{P}$ and $\mathscr{Q}$ one finds there is a ($\mathscr{P}$, $\mathscr{Q}$)-machine. It is important to note that one’s choice of $\mathscr{P}$ is, in general, crucial for the existence result to go through: If $\mathscr{P}_0 \Rightarrow \mathscr{P} \Rightarrow \mathscr{P}_1$ for some properties $\mathscr{P}_0$ and $\mathscr{P}_1$, there is no guarantee that either a ($\mathscr{P}_0$, $\mathscr{Q}$)-machine or a ($\mathscr{P}_1$, $\mathscr{Q}$)-machine exists. The former is not guaranteed since $\mathscr{P}_0$ may be so strong that the starter used to exhibit the ($\mathscr{P}$, $\mathscr{Q}$)-machine may not even have a ‘physically reasonable’ $\mathscr{P}_0$ extension. The latter is not guaranteed either; if the class of ‘physically reasonable’ spacetimes is enlarged by $\mathscr{P}_1$, it is possible that the starter used to exhibit the ($\mathscr{P}$, $\mathscr{Q}$)-machine may be such that one of its $\mathscr{P}_1$-but-not-$\mathscr{P}$ extensions is not $\mathscr{Q}$.

# 6 Robustness

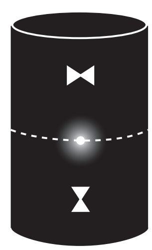
How robust are the time machine and hole machine results mentioned in the previous section? To aid our presentation a bit, consider these property abbreviations: Let C, J, M, V stand, respectively, for the properties of chronology, J-hole-freeness, maximality, and ‘being a vacuum solution’ of Einstein’s equation. This last property guarantees a ‘nice’ local metric structure; in particular, if V is satisfied, so are all of the so-called ‘energy conditions’ which place constraints on the distribution and flow of matter. Let’s now investigate the robustness of the time machine result. We know that Misner spacetime is one extension to the bottom half of Misner spacetime and we know that Misner spacetime is J-hole-free, maximal, and vacuum. We have the following.

**Proposition.** There is a ($\mathscr{P}$, $\mathscr{Q}$) machine when $\mathscr{Q}$ is the failure of chronology and $\mathscr{P}$ is such that (J & M & V) $\Rightarrow \mathscr{P} \Rightarrow$ J.



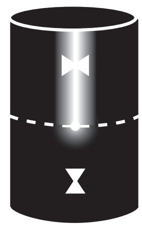

the space of spacetimes

Here is a picture to help show what's going on. The entire space represents the class of all spacetimes. The dotted lines represent possible subclasses $\mathscr{P}$ of 'physically reasonable' spacetimes. As long as $\mathscr{P}$ is smaller than the set of J spacetimes but larger than the set of J & M & V spacetimes, the existence result will go through. Outside of that, all bets are off. What about the hole machine result – how robust is it? Once again, let us return to Misner spacetime. Let's remove a point from the boundary region between the top and bottom halves.



misner with hole and conformal factor

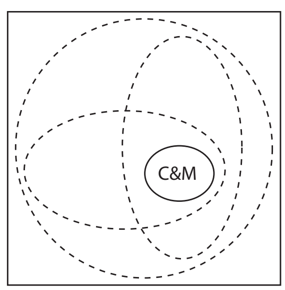
Next, we can multiply the metric by a positive smooth conformal factor – here represented by the color gradient – which approaches zero as the missing point is approached. The light cone structure remains perfectly unchanged: in particular, it is still the case that the bottom half is a starter. But I claim that any extension of this starter will have J holes. Consider any extension to the starter and note that the boundary of the starter in the extension is not part of the starter itself. Because of smoothness considerations, the extension will fail to have the 'missing' point. Now consider any point in the extension which is on the boundary of the bottom half; such a point will fail to have a closed causal past because of the 'missing' point. I also claim that one can find an extension to this starter which is maximal and chronological.



a chronological, maximal extension

Here is one. Start by considering the top half of Misner spacetime. We then cut a vertical slit as shown. Next, we multiply the metric by a conformal factor in such a way that it matches up smoothly with the bottom portion but also goes to zero as the slit is approached. The result is chronological and is maximal. We have the following result.

**Proposition.** There is a $(\mathscr{P}, \mathscr{Q})$ machine when $\mathscr{Q}$ is the failure of J-hole-freeness and $\mathscr{P}$ is such that (C & M) $\Rightarrow \mathscr{P}$.

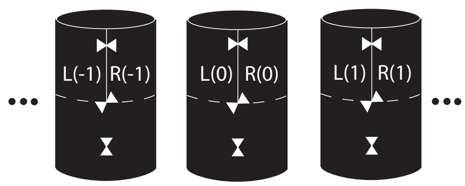



the space of spacetimes

Once again, here is the picture. As before, the entire space represents the class of all spacetimes. The dotted lines represent possible subclasses $\mathscr{P}$ of 'physically reasonable' spacetimes. As long as $\mathscr{P}$ is larger than the set of C & M spacetimes, the existence result will go through. Notice that, unlike the time machine case, there is no outer boundary to constrain $\mathscr{P}$. In other words, $\mathscr{P}$ could be some universal property like 'being a spacetime' and the result would go through. If you like, we have here a naïve hole machine existence result. So it seems we have a clear sense in which Hal, our hole-machine advocate is in better position than Tim, our time machine advocate.

"But wait!" Tim might say. "That conformal factor used to construct the starter in that example will likely make any starter extension 'physically unreasonable' in the sense that its local metric structure will be badly misbehaved.

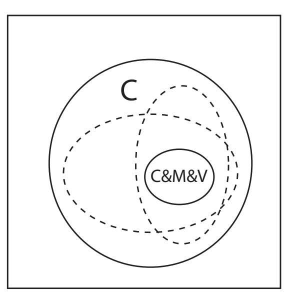
In particular, the energy conditions won't be satisfied." This is good point. But Hal has another trick up his sleeve. Consider, one final time, the bottom half of Misner spacetime. We know that any chronological extension to this starter has J-holes. How nice can we make one of its chronological extensions? Pretty nice it turns out.




a (C & M & V) extension

Consider an infinite number of copies of Misner spacetime indexed by the integers and cut a vertical slit in each of them like so. Now, label the left and right sides of the slits as I have done here. Finally, for each integer $n$, identify the slit L($n$) with the slit R($n+1$). So the left slit in spacetime zero is identified with the right slit in spacetime one; the left slit in spacetime one is identified with the right slit in spacetime two; and so on. And so on in the other direction as well. The result is a maximal, chronological, vacuum spacetime. Aside from the having holes – which were 'produced' by the machine – the spacetime is about as nice as one could demand. We have the following.

**Proposition.** There is a ($\mathscr{P}$, $\mathscr{Q}$)-machine when $\mathscr{Q}$ is the failure of J-hole-freeness and $\mathscr{P}$ is such that (C & M & V) $\Rightarrow \mathscr{P} \Rightarrow$ C.




the space of spacetimes

Here is the picture. As long as $\mathscr{P}$ is smaller than than the set of C spacetimes but larger than the set of C & M & V spacetimes, the existence result will go through.

## 7 Conclusion

We have yet to identify a privileged class of 'physically reasonable' spacetimes. Indeed, I have argued that we can never know such a thing (see Manchak 2011b). But the way I see it, Hal has the upper hand at the moment because – if you'll allow me a poker metaphor – it seems like there are just more 'outs' for Hal as compared with Tim. We have three existence results on the table.

1. There is a time machine for $\mathscr{P}$: (J & M & V) $\Rightarrow \mathscr{P} \Rightarrow$ J.
2. There is a hole machine for $\mathscr{P}$: (C & M & V) $\Rightarrow \mathscr{P} \Rightarrow$ C.
3. There is a hole machine for $\mathscr{P}$: (C & M) $\Rightarrow \mathscr{P}$

If the class of 'physically reasonable' spacetimes is relatively 'small', then both Hal and Tim are in good position. Tim has result 1; Hal has result 2. There is a strong symmetry between the two results and so, in this scenario, their hands seem to be roughly equal in strength. But if the class of 'physically reasonable' spacetimes turns out to be relatively 'large', then Hal has result 3 as a sort of ace in the hole.

You may do the accounting differently and that's fine. The main point I want to emphasize at the stage is that the game is far from over. Other 'no-hole' properties besides J-hole-freeness could be considered here.[3] And one would like to see a systematic investigation of ($\mathscr{P}$, $\mathscr{Q}$)-machine results under other 'physically reasonable' properties $\mathscr{P}$. One wonders if the fortunes of the Tim and Hal will remain consistent as we explore these possibilities.

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