The Physics of Time Travel

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Abstract: ***Time Travel in a Quantum Mechanical Universe. Time is mysterious. Philosophers and scientists have pondered the question of what time might be for centuries and yet till this day, we don't know what it is. Everyone talks about time; in fact, it's the most common nouns per the Oxford Dictionary. It's in everything from history to music to culture. Despite time's mysterious nature there are a lot of things that we can discuss in a logical manner. Time travel on the other hand is even more mysterious. It's a subject that captured the interests of great writers like H.G. Wells and Mark Twain and has been the premise of T.V. shows and movies. Everyone would love the idea of getting on Doc Brown's DeLorean and taking a blast to the past but it isn't as simple as science fiction would put it. In this work, I explore the nature of time and take a side on several fundamental questions about it. I then explore a model of time that I created based on my research which allows for the possibility of time travel. I don't believe that this model accurately models time (or is complete) but in my opinion, this would be the best model that avoids a lot of paradoxes of time travel assuming time travel is possible. Finally, I explore several paradoxes of time and explain how my model of time could solve them to a certain extent.***

Keywords: Time Travel, Physics, Biological Clock, Anti-Particle, History Of Time

1. The Concept of Time

(This section is based on the works of Tannenbaum et. al 1958) Tempus Fugit is the Latin phrase for time flies, the situation that we are all too familiar with. We live our lives by the clock. Time has become an integral part of our lives; it controls when we wake up, what time we have to be at a particular place and even when we decide to die for the sake of our country. How did we come to "measure" time? Who decided how we measured time? Why is it that when it is 6:00 a.m. in New York it is 12:00 p.m. in Paris? Primitive humans' first division of time was light and darkness (i.e. day and night) but they eventually realized that smaller periods of time were needed to organize their daily life. In most parts of the modern world this division of the day is in twenty-four equal parts (hours). This division came about from the Babylonians who used a number system based on twelve. The system was adapted by the Greeks and the Romans and eventually passed down through medieval Europe to the modern Western civilization. For convenience, the hour was divided into sixty equal parts (minutes) and each minute was divided in sixty equal parts (seconds). In 1884, an international conference was held in Washington D.C. where representatives of many 2 governments decided that the meridian line that passed through the observatory in Greenwich should be the initial meridian and approved a plan to divide the entire world into fifteen degree widths resulting in twenty- four time zones. Therefore, when it is 6:00 a.m. in New York it is 12:00 p.m. in Paris. Measuring the passage of time required a great deal of insight and innovation. Before the invention of mechanical clocks, time was measured using a variety of methods. Greeks and Romans used brilliant stars such as the Big Dipper constellation to tell time. Many ancient civilizations used water, sand and fire to tell time, such as one-hour candle clocks, fire alarm clocks (used by the Chinese), sand hour glasses and water-based Clepsydras (used by the Egyptians). Eventually, in the 1200s mechanical clock tower systems started to grow and, as time passed, improved in ways such as switching from man power to electrical power. Portable forms of time keeping such as Nuremberg eggs (similar to a pocket watch) started growing and after a while, wristwatches gained popularity after World War I. Finally, time keeping came to a point where we tell time using many ways including using cellular devices. While measuring time is useful, would it be useful without putting it in context (such as what day it is)? Time was and still is being put into context using calendars. After centuries of progress, from the Egyptian Calendar to the Biblical Hebrew Calendar to the Julian calendar, we ended up with the calendar used by many nations today, the Gregorian calendar. History has shown us that the process of standardizing time had caused riots and the spilling of blood such as during the French Revolution when the government forced people to use the "Calendar of Reason" which had 12 months of 30 days and left behind 5 days to honor poor people. Eventually over the passage of history we ended up with the system of time you and I are familiar with. While we know how to measure time and utilize it to organize our daily lives, we still find it difficult to answer a deceptively simple question: what is time?

What is Time? You cannot see, hear or touch time but you feel it flow. You intuitively have a sense of what time it is. For example, you know it's almost dinner time without looking at the clock. But there are many questions you could ask: what is time? Does it really exist? Is it just a series of events? Is it linear? Does time have a beginning or an end? In this section I will try to give you, the reader, a general idea of what time is and how I view time. The discussion of time could be hundreds of pages long but I will briefly introduce you to only a few concepts of time discussed by academics that I believe are relevant to the discussion of time travel. I discuss eight different concepts related to time in the given order: classifications of time, subjectivity and objectivity of time, time and change, the beginning and end of time, the topology of time, continuity of time, flow of time and finally, the arrow of time. I ordered these concepts as stated because I believe that there is a logical question you could ask that connects one concept to the next. I. Classifications of time can be classified as physical, psychological and biological. Biological time is captured by the internal clocks within various organisms such as the rhythm of one's heartbeat. Psychological time is how we experience time such as how we feel as if time passes fast in moments of 3 excitements. Physical time is the time that is used in physics and the time that our clocks measure (Dowden 2016). While physical time is what this paper mainly concerns itself with, I believe it is important to have a brief understanding of psychological time. The reason why we feel the continuity of time is because our brain process events such that we experience a scenario. For example, if you make a cheese burger you first make the burger then cook it and finally assemble the burger.

You remember it in a order, i.e. as a scenario. The brain takes a short amount of time to interpret events and puts the events in context for you. If you touch your toe and your head at the same time, it is interpreted as if both events happened at the same time even though it may have taken longer for the signal from the toe to reach the brain. According to philosopher Craig Calendar, this “now” experience for two simultaneous events must be less than 250 milliseconds (Dowden 2016). Similarly, the processes in the brain cause the “time dilation effect” where a short period of time may feel longer. For example, a person would remember a car crash vividly as if it happened for a longer period of time even if it lasted only a second or two. Given the role of neurological processes in our experience of time, one may come to believe that time is mind-dependent (subjective) but is time subjective or is it objective?

2. The Paradoxes of Time Travel

So what is time travel? The standard answer among philosophers, given by David Lewis (1976, 68), is that time travel occurs in case the temporal separation between departure and arrival does not equal the duration of the journey.

However, this is not a necessary condition for time travel. Presumably, Lewis and everyone else should want to include a case when the time lapse between departure and arrival equals the duration of the journey but the arrival occurs before the departure.

More significantly, we also claim that Lewis’s definition does not state a sufficient condition for an interesting sense of time travel within the context of modern physics. Readers familiar with special relativity may have already asked themselves what Lewis might mean by temporal separation between arrival and departure. Due to the relativity of simultaneity, observers in relative motion will generally disagree about the temporal separation between events. We could try to skirt this difficulty by defining the temporal separation as the maximal value measured by any observer (corresponding to the proper time elapsed along a geodesic connecting the two events) or by taking advantage of symmetries in a particular model in general relativity. For example, we could exploit the symmetries of the models usually taken to be the best approximation to the large- scale structure of space time, the Friedmann-Lemaˆıtre-Robertson-Walker (FLRW) space times, in order to define an objectively preferred frame of simultaneity, a privileged way of foliating the four-dimensional space time into space and time.

The objective time elapsed between departure and arrival would be the time lapse according to this cosmologically privileged frame. Either of these proposals would allow us to assign an objective meaning to Lewis’s temporal separation between arrival and departure. But the resulting definition of time travel is far too promiscuous. On the first proposal, everyone who departs from geodesic motion — due to the slightest nudge from a non-gravitational force — counts as a time traveler, and on the second proposal everyone who moves with respect to the cosmologically privileged frame earns the distinction. Just imagine: even if the earth didn’t move with respect to the privileged frame, you would be time-traveling each time you go to the fridge. Admittedly, Lewis’s definition does seem to capture an intuitive sense of “time travel” that is useful for some purposes. But it is too broad to capture a useful distinction within relativity, given that nearly every observer would qualify as a time-traveler.

Thankfully, an alternative conception of time travel that avoids these problems is close at hand in GR. There is a sense in which GR permits time travel into the past: it allows space times containing closed timelike curves (CTCs), i.e. space times with unusual causal structures.[2] Loosely speaking, a CTC is a path in space and time that can be carved out by a material object and is closed, i.e. returns to its starting point not just in space, but also in time. A curve is everywhere timelike, or simply time like, if the tangent vectors to the curve are time like at each point of the curve. A timelike curve represents a possible spatio-temporal path carved out by material objects, a so-called world line. Of course, we also presuppose that the curves representing observers are 2Strictly speaking, as we will see in §3, spacetimes with CTCs do not allow a global time ordering and thus there is no global division into past and future. But it is always possible to define a local time ordering within a small neighborhood of a given point, and a CTC passing through the point would connect the point with its own past according to this locally defined time ordering. could be instantiated by material objects. It is evident that the presence of worldlines that intersect themselves is a sufficient condition for time travel to take place. For the rest of this essay, we shall also assume that it is a necessary condition.[3]

Both the popular and the philosophical time travel literature contain vivid debates regarding whether time travel in this sense is logically impossible, conceptually or metaphysically incoherent, or at least improbable. Let us address these three issues in turn.

Logical Impossibility: The Grandfather Paradox
Although less prevalent than a decade or two ago, the belief that various paradoxes establish the logical or metaphysical impossibility of time travel is still widespread in philosophy. The grandfather paradox introduced above is no doubt the most prominent of these paradoxes. It allegedly illustrates either how time travel implies an inconsistent past and is thus ruled out by logic,[4] or that time travel is extremely improbable. Other time travel paradoxes include the so-called predestination and ontological paradoxes. A paradox of predestination arises when the protagonist brings about an event exactly by trying to prevent it. These paradoxes are not confined to scenarios involving time travel, although they add to the entertainment value of the latter. Just imagine a time traveller traveling into her own past in an attempt to prevent the conception of her father, whose actions instead kindle the romance between her grandparents. The related ontological paradox can be

exemplified by the story of the unpainted painting. One day, an older version of myself knocks on my door, presenting a wonderful painting to me. I keep the tableau until I have saved enough money to be able to afford a time machine. I then use the time machine to travel back in time to revisit my younger self, taking the painting along. I ring the doorbell of my earlier apartment, and deliver the painting to my younger self. Who has painted the picture? It seems as if nobody did since there is no cause of the painting. All the events on the CTC have just the sort of garden- variety causes as events not transpiring on CTCs do. The causal loop as a whole, however, does not seem to have an originating cause. For all these reasons, the popular argument goes, causal loops cannot exist.

Lewis (1976) has argued that although such scenarios contravene our causal intuitions, it is not in principle impossible that uncaused and thus unexplainable events in fact occur. According to Lewis, there are such unexplainable events or facts such as the existence of God, the big bang, or the decay of a tritium atom. True. Who would have expected that time travel scenarios will be easily reconcilable with our causal intuitions anyway? The fact that phenomena transpiring in a time-travel universe violate our causal intuitions, however, is no proof of the impossibility of such a world. Analogously, predestination paradoxes can be rejected as grounds for believing that time travel is impossible: although they undoubtedly exude irony, the very fact that it was the time

[3] This might seem to be overly restrictive, as it would appear to rule out a scenario in which the time traveler follows a nearly closed trajectory rather than a CTC. We agree that this would also constitute time travel, but any spacetime which admits such trajectories would also contain CTCs (even if they are not instantiated by material objects) — so our necessary condition still holds. Monton (2009) argues that CTCs should not be taken as a necessary condition for time travel, but we believe that Monton's argument fails. If one rules out discontinuous worldlines and similarly unphysical constructs, then CTCs are arguably the only Lorentz-invariant way of implementing time travel. Cf. Arntzenius (2006, Sec. 3) for an alternative transposition of a Lewis-like understanding of time travel into the context of GR. We don't see, however, how this understanding can be extended to cover non-time orientable spacetimes, as Arntzenius seems to think (2006, 604f).

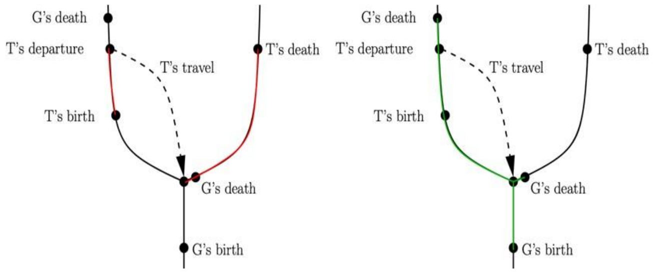
[4] In a dialethic logic, i.e. a logic in which contradictions can be true, and perhaps in other paraconsistent logics, such contradiction need not imply the impossibility of time travel. A possible reply to the grandfather paradox is thus the rejection of classical logic. This price is considered too high in this article, particularly also because the contradiction can be resolved by other means, as will be argued shortly.

[5] traveller who enabled her grandparents' union is not in any way logically problematic. What is important as far as logic is concerned is that the time traveller has timelessly been conceived at some point during the year before her birth and has not been "added" or "removed" later. If it occurred, it occurred; if it didn't, it didn't. So despite their persuasiveness, the ontological and the predestination paradoxes don't go far in ruling out time travel.

The grandfather paradox cannot be dismissed so easily. Grandpa cannot simultaneously sire and not sire the parent of the time traveller. The central point is that the grandfather paradox does not rule out time travel simpliciter, but only inconsistent scenarios. In fact, all self-contradictory scenarios are forbidden, regardless of whether they involve time travel or not. Various options can be pursued in attempts to resolve the grandfather paradox. Apart from the costly rejection of bivalent logic, one can, following Jack Meiland (1974), postulate a two-dimensional model of time such that every moment entertains its own past which is distinct from the times that preceded that moment. According to this proposal, at a given moment there are two branches, one containing the actual events that preceded it, and the other representing an alternative past into which time travel can lead. If one travels back in time, then, one doesn't arrive at a time that preceded the departure, but rather at a time in the past of the moment when one departed. Time, on this understanding, is represented by a two-dimensional plane rather than a one-dimensional line. Following Lewis (1976, 68), we do not find this resolution particularly attractive, primarily because the time traveller would on this conception never be able to revisit the very past moment when Grandpa first met Grandma. She would only be able to reach a "copy" of this moment on the past line of the moment of when the time machine is switched on. The event reached would thus be different from the one steeped in history that the intrepid traveller intended as the goal of her journey. Whatever travel this is, it is not the time travel characterized above.

An obvious, but rarely seriously entertained option tries to make sense of time travel by allowing the universe to bifurcate each time consistency would otherwise be violated. The instant the time traveller arrives in her past, the spacetime splits into two "sheets." (Unlike Meiland's proposal the branches are "created" by time travel, they are not already in existence)[5] This branching does not happen in time or space alone, but in the overall causal structure of the spacetime in which the journey takes place. In particular, the causal future of the event where the traveller arrives must permit "two-valuedness." In the case of such a "multiverse," the adventurous traveller not only journeys in time, but also to a branch distinct from the one in which she departed. A multiverse with more than one actual past history does timelessly contain the killing of Grandfather, but only in one of the branches (cf. Lewis 1976, 80). Interaction between the co-existing branches is solely possible by time travel, which does arguably not deserve to qualify for time travel as it is not a journey back in the traveller's "own" time. But the threat of inconsistency is surely banned if history along any given branch is consistent. This would for example mean that everybody's worldlines have an unambiguous beginning and end points in all branches (see Fig. 1).

Does such travel in a multiverse change the past? Only in the sense that through the traveling activity, more and more branches of past histories seem to pop into existence. If this is the picture, then time traveling necessitates an inflation of branches as it becomes more popular. But since if it is possible to change the past, we run into the same difficulties as with the grandfather paradox again, these branches must in fact eternally co-exist with the sheet we are actually living in. Thus, if time travel is physically possible, then there will be an infinitude of branches corresponding to all the possible ways in which time travel could occur. Thus, there will be an infinity of actual [5]A further contrast between the proposals is that on Meiland's view the time traveller will not have complete freedom as to how to affect the past since, presumably, both pasts must lead to the same present moment located at the bifurcation point. This constraint seems to be absent in scenarios with branching structures into the future, at least if one grants the causal fork asymmetry (cf. Horwich 1987, 97-99).



G's death T's departure T's birth
T's death
G's death T's departure T's birth
T's death T's travel
G's death G's birth T's travel
G's death G's birth

Figure 1: The worldlines of the time traveller T (red) and of Grandpa G (green) according to the multiverse proposal. Note that both figures are of the same multiverse; they are just highlighting different worldlines.

Past histories of the multiverse timelessly containing all time traveling activity. Even though such a construction does not live up to an ideal of metaphysical austerity, logic does not preclude it. However, in order to accommodate multi-valued fields in physics — which would be necessary in such a multiverse —, a radical rewriting of the laws of physics would be required. Although topology offers manifolds which could potentially deal with multi-valuedness,[6] these new types of laws would also have to tolerate it. But we do not know of a dynamical theory which could deliver this.

We concur with Earman (1995) (and, unsurprisingly, with Earman et al. (2009)) that the grandfather paradox only illustrates the fact that time-travel stories, just like any other story, must satisfy certain consistency constraints (CCs) that ensure the absence of contradictions. In other words, only one history of the universe is to be told, and this history had better be consistent. GR mandates that spacetimes satisfy what Earman dubbed a global-to-local property, i.e. if a set of tensor fields satisfy the laws of GR globally on the entire spacetime, then they do so locally in every region of spacetime.[7] This property is shared by spacetimes with CTCs. The reverse local- to-global property would imply that any local solution could be extended to a global solution of the field equations. But this property need not hold in spacetimes with CTCs: situations that are admissible according to the local dynamical laws may lead to inconsistencies when evolved through a region containing CTCs. CCs are imposed to prevent such inconsistencies. John Friedman et al. (1990) encode the demand that CCs are operative in their 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."[8] This principle guarantees the validity of the local-to-global property, at the cost of introducing non-trivial CCs.

How should we think of CCs? We can think of them as consisting of restrictions imposed on the initial data of, say, a matter field for point mass particles at a given point. Assume a single particle that moves along an inertial worldline in accordance with the dynamical laws that apply for

[6] Cf. Visser (1996, 250-255). The concerned manifolds have to be non- Hausdorff in order to permit branching, as discussed in Douglas (1997). For a thorough critique of branching spacetimes, cf. Earman (2008).

[7] Cf. Earman (1995, 173) for a more mathematically rigorous account.

[8] Friedman et al. (1990, 1916f), emphasis in original. For more advocacy of CCs, see Malament (1985b, 98f) and Earman (1995, passim). They both see the particle and assume further that the worldline is a CTC. The CCs would then have to restrict the choice of the initial velocity of the particle such that its trajectory smoothly joins itself after one loop. More generally, however, the CCs for any macroscopic object involving more complex physical processes would become very complicated indeed if spelt out explicitly. Consider a more concrete example involving macroscopic objects, such as a spacecraft venturing out to explore deep space only to discover that it in fact traces out a CTC. Here, the spacecraft would have to go over into its earlier self smoothly, including restoring the "original" engine temperature and settings of all onboard computers, refueling to exactly the same amount of propellant, and so forth. If the scenario included humans, it would become trickier still. The time traveller would have to rejoin exactly his worldline, wearing the same clothes, with the same shave, with each hair precisely in the same position, with his heart beat cycle exactly coinciding, his memory reset to the state when he entered the CTC etc. The world is rich in variety and complexity, and such strong constraints appear to conflict with our experience. However, it is not clear how exactly such a conflict could arise: if the relevant dynamical laws have the local-to-global property in a given spacetime with CTCs, then the CCs would be enforced regardless of their apparent improbability. In any case, regions of causality violations are found beyond horizons of epistemic accessibility of an earth- bound observer in realistic spacetimes. Hence, if taken as an objection against the possibility of CTCs, the difficulty of accommodating complex scenarios has little theoretical force.

But it surely shatters the prospect of sending humans on a journey into their own past in a way that has them instantiate the totality of a CTC.

Since CCs seem to mandate what time travellers can and cannot do once they have arrived in their own past, the CCs' insistence that there is only one past and that this past cannot be changed appears to give rise to a kind of modal paradox. Either John Connor's mother is killed in 1984 or she isn't. In case she survives, the deadliest Terminator with the highest firepower cannot successfully assassinate her. This inability stands in a stark contrast to the homicidal capacities that we would normally ascribe to an armed and highly trained cyborg. The modal paradox arises because the terminator can strike down Connor's mother — he has the requisite weapons, training of many years, and a meticulous plan, etc. — but simultaneously he cannot do it as Sarah Connor actually survived 1984 and the Terminator would thus violate CCs were he to successfully kill her. Lewis (1976) has resolved the looming modal inconsistency by arguing that "can" is ambivalently used here and that the contradiction only arises as a result of a impermissible equivocation. "Can" is always relative to a set of facts. If the set contains the fact that Sarah has survived 1984, then the terminator will not be able kill her (in that year). If this fact is not included, however, then of course he can. The contradiction is only apparent and Lewis concludes that time travel into one's own past is not logically impossible.

Thus, the paradoxes invoked do not establish that logic precludes time travel, although they exhibit how they constrain the sort of scenarios that can occur. Although logic does not prohibit it, time travel still faces stiff resistance from many philosophers. The resistance typically comes in one of two flavours: either it turns on the alleged improbability of time travel or on an argument barring the possibility of backward- in-time causation. Let us address both complaints in turn.

3. Implications of Time Travel

Given that time travel cannot be straightforwardly ruled out as incoherent or logically impossible, we now face the following difficult questions: In what sense is time travel physically possible, and what does this imply regarding the nature of time? More precisely, what are the novel consequences of time travel, i.e. ones that do not follow already from more familiar aspects of special or general relativity? As a first step towards answering these questions, we will consider Kurt Gödel's (in) famous argument for the ideality of time.[25]

Gödel (1949a) was the first to clearly describe a relativistic spacetime with CTCs.[26] Gödel's stated aim in discovering this spacetime was to rehabilitate an argument for the ideality of time from special relativity within the context of GR. In special relativity, Gödel asserts that the ideality of time follows directly from the relativity of simultaneity. He takes as a necessary condition for the existence of an objective lapse of time the possibility of decomposing spacetime into of a sequence of "nows" — namely, that it has the structure R × Σ, where R corresponds to "time" and Σ are "instants," three-dimensional collections of simultaneous events. But in special relativity the decomposition of the spacetime into "instants" is relative to an inertial observer rather than absolute; as Gödel puts it, "Each observer has his own set of 'nows,' and none of these various systems of layers can claim the prerogative of representing the objective lapse of time" (Gödel 1949b, 558).

This conclusion does not straightforwardly carry over to GR, because there is a natural way to privilege one set of "nows" in a cosmological setting. The privilege can be conferred on a sequence of "nows" defined with respect to the worldlines of galaxies or other large scale structures. It is natural to require the surfaces of simultaneity to be orthogonal to the worldlines of the objects taken to define the "cosmologically preferred frame." The question is then whether one can extend local surfaces of simultaneity satisfying this requirement to a global foliation for a given set of curves. For the FLRW cosmological models, as noted above, the answer is yes. These models have a natural foliation, a unique way of globally decomposing spacetime into a one-dimensional "cosmic time" and three- dimensional surfaces Σ representing "instants," orthogonal to the worldlines of freely falling bodies. (Cosmic time in this case would correspond to the proper time measured by an observer at rest with respect to this privileged frame.) Thus Gödel's necessary condition for an objective lapse of time is satisfied in the FLRW cosmological models, and in this sense the pre-relativistic concept of absolute time can be recovered.

But in Gödel's spacetime one cannot introduce such a foliation. The space time represents a "rotating universe," in which matter is in a state of uniform rigid rotation.[27] Due to this rotation it is not possible to define a privileged frame with global "instants" similar to the frame in the FLRW models.[28] An analogy due to Malament (1995) illustrates the reason for this. One can slice through a collection of parallel fibers with a single plane that is orthogonal to them all, but if the fibers are twisted into a rope there is no way to cut through the rope while remaining orthogonal to each fiber. (The "twist" of the fibers is analogous to the rotation of worldlines in Gödel's model.) The construction of global "instants" described above can be carried out if and only if there is no "twist" (or rotation) of the worldlines used to define the cosmologically privileged frame. Demonstrating that such rotating models exist by finding an explicit spacetime model solving Einstein's field equations was clearly Gödel's main aim. But the welcome discovery that in his rotating universe there is a CTC passing through every point further bolstered his argument for the ideality of time.[29] It is noteworthy that many chronology-violating spacetimes resemble Gödel's solution in the following sense: they contain rotating masses and CTCs wind around the masses against the orientation of the rotation.[30]

[25] The following papers, which we draw on below, discuss aspects of Gödel's argument: Stein (1970), Malament (1985b), Savitt (1994), Earman (1995), Dorato (2002), Belot (2005). Ellis (1996) discusses the impact of Gödel's paper.

[26] Although von Stockum (1937) discovered a solution describing an infinite rotating cylinder that also contains CTCs through every point, this feature of the solution was not discussed in print, to the best of our knowledge, prior to Tipler (1974). Gödel does not cite von Stockum's work. Others had noted the possibility of the existence of CTCs without finding an exact solution exemplifying the property (see, e.g., Weyl (1921), p. 249).

What, then, is Gödel's argument? The crucial problem is how to get from discoveries regarding the nature of time in this specific spacetime to a conclusion about the nature of time in general. Gödel could avoid this problem if his spacetime, or a spacetime with similar features, were a viable candidate for representing the structure of the observed universe. Then his results would obviously have a bearing on the nature of time in our universe. Gödel apparently took this possibility quite seriously, and subsequently discovered a class of rotating models that incorporate the observed expansion of the universe (Gödel 1952). In these models, one can construct suitable "instants" as long as the rate of rotation is sufficiently low, and recent empirical work places quite low upper limits on the rate of cosmic rotation.[31]

Gödel goes on to argue that even if his model (or models with similar features) fails to represent the actual universe, its mere existence has general implications (p. 562):[32]

The mere compatibility with the laws of nature of worlds in which there is no distinguished absolute time, and, therefore, no objective lapse of time can exist, throws some light on the meaning of time also in those worlds in which an absolute time can be defined. For, if someone asserts that this absolute time is lapsing, he accepts as a consequence that, whether or not an objective lapse of time exists ... depends on the particular way in which matter and its motion are arranged in the world. This is not a straightforward contradiction; nevertheless, a philosophical view leading to such consequences can hardly be considered as satisfactory.

Despite disagreement among recent commentators regarding exactly how to read Gödel's argument, there is consensus that even this modest conclusion is not warranted. The dynamical connection between spacetime geometry and the distribution of matter encoded in Einstein's field equations insures that, in some sense, many claims regarding spacetime geometry depend on "how matter and its motion are arranged." Nearly any discussion of the FLRW models highlights several questions regarding the overall shape of spacetime — e.g., whether time is bounded or unbounded and what is the appropriate spatial geometry for "instants" — that depend on apparently contingent properties such as the value of the average matter density. What exactly is unsatisfactory about this? What does the mere possibility of spacetimes with different geometries imply regarding geometrical structure in general? Earman (1995, Appendix to Chapter 6) challenges the implicit modal step in Gödel's argument. How can we justify this step on Gödel's behalf, and elucidate what is unsatisfactory about objective time lapse in general, without lapsing back into pre-GR intuitions?

Perhaps the argument relies on an implicit modal assumption that lapsing, in the sense described above, must be an essential property of time. Then (given that (¬P) ¬(□P)), the demonstration that (¬P) (where P is the existence of an objective lapse of time) via finding the Gödel spacetime would be decisive. But what is the basis for this claim about the essential nature of time, and how can it be defended without relying on pre-relativistic intuitions? Earman (1995) considers this and several replies that might be offered on Gödel's behalf, only to reject each one. Steve Savitt (1994) defends a line of thought (cf. Yourgrau 1991) that is more of a variation on Gödelian themes than a textual exegesis. On Savitt's line, Gödel's argument rests not on essentialist claims regarding the nature of time but instead on a claim of local indistinguishability. Suppose that it is physically possible for beings like us to exist in a Gödel spacetime, and (1) that it is possible for these denizens to have the "same experience of time" as we do. Assume further that (2) the only basis for our claim that objective time exists in our universe is the direct experience of time. Then the existence of the Gödel universe is a defeater for

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[27] More precisely, in Gödel's universe a congruence of timelike geodesics has non-zero twist and vanishing shear. Defining rotation for extended bodies in general relativity turns out to be a surprisingly delicate matter (see, especially, Malament 2002).

[28] As John Earman pointed out to us, Gödel does not seem to have noted the stronger result that Gödel spacetime does not admit of any foliation into global time slices.

[29] Malament observed that the existence of CTCs is not mentioned in three of the five preparatory manuscripts for Gödel (1949a), and it appears that Gödel discovered this feature in the course of studying the solution. In addition, in lecture notes on rotating universes (from 1949) Gödel emphasizes that he initially focused on rotation and its connection to the existence of global time slices in discovering the solution. See Malament (1995) and Stein (1995, 227-229).

[30] Cf. Andréka et al. (2008). That rotation may be responsible for the formation of CTCs is also suggested by Bonnor's (2001) result that stationary axially symmetric solutions of Einstein's field equations describing two spinning massive bodies under certain circumstances include a non-vanishing region containing CTCs.

[31] These instants are not surfaces orthogonal to timelike geodesics, as there is still rotation present, but Gödel (1952) establishes that surfaces of constant matter density can be used to define a foliation that satisfies his requirements for an objective lapse of time. For recent empirical limits on global rotation based on the cosmic microwave background radiation, see, for example, Kogut et al. (1997).

[32] As Sheldon Smith pointed out to us, if this is taken to be Gödel's main argument then it is not clear why the mere existence of Minkowski spacetime, regarded as a vacuum solution of the field equations, does not suffice. Why did Gödel need to go to the effort of discovering the rotating model granted that there is no distinguished absolute time in Minkowski spacetime?

Although we do not find a clear answer to this in Gödel (1949b), we offer two tentative remarks. First, Gödel may have objected to classifying Minkowski spacetime as physically reasonable because it is a vacuum spacetime. Second, and more importantly, Gödel took the prospect of discovering a rotating and expanding our claim to have established objective time lapse on the basis of our experience, because (for all we know) we could be in the indistinguishable situation — inhabiting a G¨odel universe in which there is no such lapse. While this variation does not require a modal step as suspect as the original version, neither ***(1) nor (2) are obviously true — and it is unclear how they*** can be established without begging the question.[33]

One response to the challenge is simply to abandon G¨odel's modal argument and formulate a different argument to the same effect. Consider an alternative argument that adopts a divide and conquer strategy rather than relying on a shaky modal step (suggested to us by John Earman). Divide the solutions of Einstein's field equations into (1) those that, like G¨odel spacetime, lack a well defined cosmic time, and (2) solutions that do admit a cosmic time.[34] The considerations model consistent with observations more seriously than most commentators allow. This suggests that the argument in the quoted passage is a fall-back position, and that Go¨del put more weight on the claim that he had discovered a viable model for the observed universe that lacks an objective lapse of time.

A different approach spelled out by Gordon Belot (2005) offers a methodological rather than metaphysical response to Earman's challenge. Belot concedes to Earman's challenge given a "natural-historical" construal of G¨odel's argument, according to which the nature of time can be established based on empirical study of "how matter and its motion are arranged." On this reading, time in our universe is characterized by the appropriate spacetime of GR that is the best model for observations – and the mere existence of alternative spacetimes is irrelevant. But on "law-structural" construal questions regarding the nature of time focus on the laws of nature rather than on contingent features of a particular solution. Belot makes a case that a law-structural con- strual of the question is more progressive methodologically, in that it fosters deeper insights into our theories and aids in the development of new theories.[35] If we grant that understanding the laws may require study of bizarre cases such as G¨odel's spacetime alongside more realistic solutions then we have the start of a response to Earman's challenge.

It is only a start, because this suggested reading remains somewhat sketchy without an account of "laws of nature," which is needed to delineate the two construals more sharply. Even if we had a generally accepted account of the laws of nature, the application of "laws" to cosmology is controversial: how can we distinguish nomic necessities from contingencies in this context, granting the uniqueness of the universe? Setting this issue aside, Earman's challenge can be reiterated by asking which spacetimes should be taken as revealing important properties of the laws. Why should G¨odel spacetime, in particular, be taken to reveal something about the nature of time encoded in the laws of GR? Suppose we expect that only a subset of the spacetimes deemed physically possible within classical GR will also be physically possible according to the as- yet-undiscovered theory of quantum gravity. How would we argue that G¨odel space time should fall within that subset, and that it should be taken to reveal a fundamental feature of the laws of GR that will carry over to quantum gravity? The features G¨odel used to establish the lack of absolute time in his model are often taken to support a negative answer to this question that does not appear to be ad hoc. Many approaches to quantum gravity simply rule out spacetimes with CTCs ab initio based on the technical framework adopted.[36] As we will discuss below, much of the physics literature on spacetimes with CTCs seeks clear physical grounds to rule them beyond the pale; insight into the laws of a future theory of quantum gravity would come from showing why the laws do not allow CTCs. But we agree with Belot that what is more unsatisfying regarding G¨odel's argument, even on the "law-structural" construal, is that an argument by counter-example does little to illuminate deeper connections between the nature of time and the laws of the theory.

Assessing the implications of G¨odel's spacetime clearly turns on rather delicate issues regarding modality and the laws of nature. Perhaps our failure to articulate a clear G¨odelian argument condition slightly weaker than global hyperbolicity.

Indicates that the properties of such bizarre spacetimes can be safely ignored when we investigate the nature of time in GR? Tim Maudlin (2007) advocates a dismissive response to CTCs, which would otherwise pose a threat to his metaphysical account of the passage of time: "It is notable in this case that the equations [Einstein's field equations] do not force the existence of CTCs in this sense: for any initial conditions one can specify, there is a global solution for that initial condition that does not have CTCs." He anticipates a critic's response that his metaphysical account of passage

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[33] See Belot (2005) and Dorato (2002) for further discussion.

[34] In terms of the causality conditions in §3, a global time function exists for "stably causal" spacetimes — above show that the spacetimes of type (1) lack an objective lapse of time in G¨odel's sense. The spacetimes of type (2) have, by contrast, an embarrassment of riches: there are many well- defined time functions, and in general no way to single out one as representing the objective lapse of time. The definition of the cosmologically preferred reference frame in the FLRW models takes advantage of their maximal symmetry. Thus we seem to have an argument, without a mysterious modal step, that generic solutions of the field equations lack an objective lapse of time.

[35] Belot finds inspiration for this position in several brief remarks regarding the nature of scientific progress in manuscript precursors to Go¨del (1949a); however, he does not take these considerations to be decisive (see p. 275, fn. 52).

[36] Go¨del's solution might be ruled out due to the symmetries of the solution, as Belot notes: symmetric solutions pose technical obstacles to some approaches to quantization, and it seems precarious to base assertions regarding features of quantum gravity on properties of special, symmetric solutions. But this argument seems too strong, in that it also would rule out the FLRW models, which are currently accepted as the best classical descriptions of the large-scale structure of the universe.

boldly stipulates that

the nature of time is not compatible with the existence of CTCs, and replies: "...But is it not equally bold to claim insight into the nature of time that shows time travel to be possible if we grant that it is not actual and also that the laws of physics, operating from conditions that we take to be possible, do not require it" (Maudlin 2007, 190). These assertions would follow from the proof of the following form: CTCs do not arise from "physically possible" initial states under dynamical evolution according to Einstein's equations. Below we will consider a more precise formulation of this "chronology protection conjecture" (in §6). But at this point we wish to emphasize that this is still a conjecture, and that there are a number of subtleties that come into play in even formulating a clear statement amenable to proof or disproof.[37] Perhaps a claim like Maudlin's, suitably disambiguated, will prove to be correct, but part of the interest of the question is precisely due to the intriguing technical questions that remain open.[38]

In any case, Maudlin's remarks usefully indicate a fruitful way of addressing the importance of solutions with exotic causal structure. Arguments by counterexample — displaying a solution to Einstein's field equations with exotic causal structure — are unsatisfying because it is usually not clear how the solution in question relates to solutions used to model physical systems or how it is related to other "nearby" solutions. For example, given a solution with CTCs is it an element of open set of solutions that also have CTCs? Or does the presence of CTCs depend upon a symmetry or some other parameter fixed to a specific value? Rather than considering a solution in isolation, we are pushed towards questions about the space of solutions to the field equations. We can ask, for example, what Einstein's field equations imply for the dynamical evolution of some class of initial data we decide to treat as "physically possible." One advantage of framing the question this way is that we can exploit the initial value formulation of GR to address it, as we will see below. But there is also an important disadvantage: we can only address the existence of chronology-violating space times indirectly, given that they lack surfaces upon which initial data can be specified. By framing the question this way we would avoid controversial questions regarding modalities in cosmology, and instead focus on whether it is possible according to GR to manipulate matter and energy in a local region such that, contra Maudlin, CTCs are the inevitable result. In more vivid language, is it possible in principle to build a time machine? Formulating this idea precisely is the task of the next section.

5. The block universe

Before we tackle the trickier problem of time travel into the past, I should say something about another aspect of Special Relativity. Einstein realized several years after publishing his work that Special Relativity implies space and time can no longer be treated as separate, but are instead part of a unified space time in which time makes up the fourth dimension. This led him to consider what is known as the block universe model in which all times— past, present and future—coexist as a static whole (figure 1). There is then nothing special about the present moment—our 'now'. Indeed different observers who are moving relative to each other will not agree on the same 'now'! Many science fiction writers, even some scientists, have seized upon this coexistence of the present past and future as proof that they are all equally real. However, this view is incorrect since it does not take into account an important lesson learnt from another important theory in physics—quantum mechanics. The block universe model is a useful tool for solving problems in relativity, but it should not be pushed too far. For the danger is that it suggests a predetermined future in which everything that is ever going to happen in our future is already fixed

Physics Education

Where are all the time travellers?

For now, the best that physicists can come up with to rule out the existence of time loops is to ask where all the time travellers from the future are. If future generations ever succeed in building a time machine then surely there will be many who would wish to visit the twenty-first century and we should see these visitors among us today. So here are five possible reasons why we should not expect to see any time travellers.

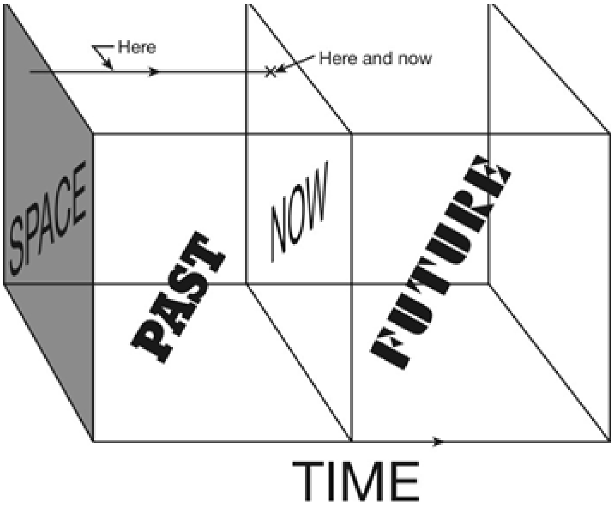
Time travel to the past is forbidden by some as yet undiscovered laws of physics. Physicists hope to discover new theories that goes beyond General Relativity and which explains why time loops are forbidden. We already have a possible candidate for such a theory, known as M- theory, but it is not yet properly understood.

Physics Education

1) If there are no naturally occurring time machines—such as might be found through a black hole—then the only way to travel back in time would be to build one ourselves. But it turns out that this would only take us as far back as the moment it was switched on (because of the way it would hook up space and time). So we see no time travellers from the future because time machines have not been invented yet.
2) Naturally occurring time machines will be found in the future and people use them to travel back to the beginning of the twenty-first century, but it turns out that another idea taken seriously by many theoretical physicists, that our universe is just one of an infinite number of parallel universes, is correct. In that case, time travel to the past slides the traveller into a parallel world. There are so many of these parallel realities that our universe is just not one of the lucky few that have been visited.

If you are not convinced by the above then I might interest you in a couple of more mundane possibilities:
1) Expecting to see time travellers among us presupposes that they would want to visit our time. May be for them there will be much nicer and safer periods to visit.
2) Time travellers from the future are among us but keep a low profile!

If I were a betting man I would say that time travel to the past will soon be shown to be impossible even in theory. Getting to the future, on the other hand, just requires building a fast enough rocket. Beware, though, that if you reach the future, there is (probably) no coming back.



4. Conclusion

The conclusion is not that time travel is impossible, but that we should treat it the way we treat the possibility of, say, tossing a fair coin and getting heads one thousand times in a row.

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