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Temporal becoming in a relativistic universe: causal diamonds and Gödel's philosophy of time

Jimmy Aames[1]

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Abstract

The theory of relativity is often regarded as inhospitable to the idea that there is an objective passage of time in the world. In light of this, many philosophers and physicists embrace a "block universe" view, according to which change and temporal passage are merely a subjective appearance or illusion. My aim in this paper is to argue against such a view, and show that we can make sense of an objective passage of time in the setting of relativity theory by abandoning the assumption that the *now* must be global, and re-conceiving temporal passage as a purely *local* phenomenon. Various versions of local becoming have been proposed in the literature. Here I focus on the *causal diamond theory* proposed by Steven F. Savitt and Richard Arthur, which models the *now* in terms of a local structure called a *causal diamond*. After defending the reality of temporal passage and exploring its compatibility with relativity theory, I show how the causal diamond approach can be used to counter the argument for the ideality of time due to Kurt Gödel, based on his "rotating universe" solution to the Einstein field equations (the *Gödel universe*). I defend the second component of his argument, the *modal step*, against the consensus view that finds it wanting, and reject the first step, showing that the Gödel universe is compatible with an objective passage of time as long as the latter is construed *locally*, along the lines of the causal diamond approach.

Keywords Time · Relativity · Causal diamond · Kurt Gödel · Gödel universe · Cosmic time

1 Introduction

Nothing is more deeply ingrained in our everyday lives than the passage or "flow" of time. It is such a ubiquitous element of our experience that it "seems to form the

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✉ Jimmy Aames
asonosakan@gmail.com

[1] Department of Humanities, National Institute of Technology, Maizuru College, Maizuru, Japan

basis of the world's and our own existence," as Kurt Gödel put it (Gödel, 1949b, p. 202).[1] Yet modern physics, in particular the theory of relativity, appears inhospitable to our common-sense conception of time and its passage. The problem is that the theory, it is commonly believed, rules out the existence of an objective, global *now*. Insofar as the passage of time presupposes an objective, global *now* that in some sense updates itself successively, there can be no genuine temporal becoming in a relativistic universe, since that would require exactly the kind of *now* precluded by relativity.

In light of this, many philosophers and physicists have embraced the idea that we live in a "block universe," a static, four-dimensional block of space-time where there is no real change or flow of time.[2] What we perceive as the passage of time in such a universe must be a merely subjective appearance, an illusion. Hermann Weyl gave expression to this view as follows:

> The objective world simply *is*, it does not *happen*. Only to the gaze of my consciousness, crawling upward along the worldline of my body, does a section of this world "come to life" and pass by as a spatial image in temporal change. (Weyl, 2009, p. 150)

The block universe view is sometimes described by saying that "all events—past, present, and future—are equally real"(Davies, 1995, p. 260). It should be noted, however, that on this view there is no distinguished present moment or *now*. What is meant by the "now" in this case is simply the set of those events that are simultaneous with the utterance of that indexical (where the choice of a hyperplane of simultaneity is arbitrary). For an observer at any given event, it is true that that event is "now," so this does nothing to mark off any event (or set of events) as distinguished. Following the philosophy of time literature, let us call the block universe view the *B-theory* of time, as opposed to the *A-theory*, which holds that there is a real passage of time (of some form or another).

Suppose we adopt the B-theory. We are then faced with a problem. Even if we grant that the passage of time is in some sense an illusion, there is no denying that the illusion itself is something that we actually experience. But how could even the *appearance* of something as peculiar and *sui generis* as the passage of time arise in a world where there is nothing corresponding to it in reality? There are certainly cases where we are systematically deceived by appearances; for example, the earth appears flat due to its immense size relative to what we can perceive visually. Could our experience of the passage of time be accounted for in way similar way? The answer,

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[1] Page references for Gödel's works will be to his *Collected Works* (Gödel, 1990, 1995).

[2] The arguments of C. W. Rietdijk (1966) and Hilary Putnam (1967) are often cited as the classic arguments defending this kind of view on the basis of relativity theory. It should be noted, however, that neither Rietdijk nor Putnam explicitly address the question of temporal passage in their papers. Rather, Rietdijk is concerned with the question of determinism, while Putnam asks whether future things (or events) are real, and whether contingent statements about future events have determinate truth values. The implications of their conclusions for questions about temporal passage, if any, are not spelled out. Another point that deserves mention is that Putnam later retracts a key element of his argument in response to the criticisms of Yuval Dolev, Mauro Dorato, and Steven Savitt, writing: "the question whether the past and the future are 'real' is a pseudo-question" (Putnam, 2008, p. 71).

I submit, is no: in what follows I will argue that our experience of the passage of time cannot be illusory (Section 2). The B-theory is therefore untenable—we must accept that there is objective temporal becoming of some kind or another.

But how do we reconcile the idea of an objective flow of time with relativity? Some writers have suggested that the idea of a *cosmic time*, which can be defined in the standard models of relativistic cosmology, enables us to recover an objective time flow in the relativistic setting. In Section 3 I will argue that it is not up to the task. A more promising approach is to drop the assumption that the *now* must be *global*, i.e., extends indefinitely through all of space. By re-conceptualizing the *now* as a local, relativistically invariant structure, we may be able to recover objective temporal becoming in a relativistic universe, albeit in a slightly novel guise. Various versions of "local becoming" have been proposed in the literature. The version which I find most compelling is the one put forward by Steven F. Savitt (2009, 2015) and Richard Arthur (2006, 2019, Sec. 6.5). On their view, the present is to be modelled in terms of what is called a *causal diamond*. There is an infinite multitude of these presents, one for each worldline, and the flow of time is modelled as the succession of these presents along their respective worldlines. We will review the causal diamond theory and its virtues in Section 3.

The Savitt-Arthur causal diamond theory offers a compelling picture of local becoming compatible with relativity. However, any view that defends an objective temporal flow must come to grips with Gödel's argument for the ideality (or unreality) of time. This will be the topic of Section 4. In 1949 Gödel published his famous "rotating universe" solution to the Einstein field equations of general relativity (Gödel, 1949a). This solution, known as the *Gödel universe*, was the first solution to be discovered that has the curious property of containing *closed timelike curves* (CTCs), everywhere-timelike paths through spacetime that return to their starting point. The existence of a CTC permits, in a certain sense, time travel into the past.

While it is generally agreed that the Gödel universe is not a valid model of our actual universe, the mere fact that it is *physically possible*—permitted by the laws of general relativity—has serious philosophical implications for the nature of time in our actual universe. Indeed, Gödel himself, using his newly discovered solution, argued that the physical possibility of the Gödel universe implies that the passage of time in our actual universe is merely ideal, and not an objective feature of reality (Gödel, 1949b). Gödel's argument consists of two steps. The first establishes that there can be no objective passage of time in the Gödel universe. The second step, often referred to as the *modal argument* or *modal step*, intends to show that the law-like compatibility of our universe with a universe in which there is no objective passage of time entails that there is no objective passage of time in our universe either. Most philosophers who have commented on Gödel's argument accept the first part—which establishes that the Gödel universe does not permit an objective passage of time—but are unconvinced by the second modal step (Stein, 1970; Savitt, 1994; Earman, 1995; Dorato, 2002; Belot, 2005; Smeenk & Wüthrich, 2011). Against this consensus view, I will defend Gödel's modal argument by adducing a line of thought which (to my knowledge) has not been addressed in the literature (Section 4). This does not mean, however, that I embrace Gödel's argument for the ideality of time. Instead of rejecting the second modal step, I reject the first step—that there cannot be an objective passage of time in the Gödel universe. In Section 4 I will show that the Gödel universe is compatible with objective becoming as long as the latter is construed *locally*, along the lines of the Savitt-Arthur causal diamond theory outlined in Section 3.

An issue related to the passage of time that will not be addressed in this paper is the *past-future asymmetry*, or the so-called *arrow of time*. Insofar as the passage of time consists in future events becoming present and present events becoming past, and not vice versa, it presupposes a distinction between the "future" direction and "past" direction of time. In other words, the past-future asymmetry seems to be a necessary condition for the passage of time. It is not, however, a sufficient condition: one can conceive of a world in which there is a past-future asymmetry but no passage of time.[3] It is therefore a good idea to deal with questions about the passage of time separately from questions about the past-future asymmetry, these being distinct aspects of time. In particular, we will not discuss the question as to the origin of the past-future asymmetry—is it a property that is somehow fundamental to time and dynamics, as argued by such thinkers as Ilya Prigogine (1980) and Tim Maudlin (2007), or is it a statistical property arising from the second law of thermodynamics, as maintained by Ludwig Boltzmann (1964, Part II, Sec. 90), Hans Reichenbach (1999), and others? Instead, unless otherwise noted, we will simply assume that time comes equipped with a past-future asymmetry, without questioning its nature or origin.

2 The reality of the passage of time

The passage of time is not a mere subjective appearance or illusion, but an objective feature of reality. Let me begin by making clear what this means.

Our experience of temporal passage is rooted in our experience of change. Take a mundane example: the melting of an ice cube. One way to analyze this process is to say that the ice is in a solid state when a given clock reads time t_1, and in a liquid state when the clock reads a later time t_2. In other words, the change of an object is analyzed by saying that the object is in different states, or has different properties, at different clock times. This kind of analysis may be sufficient for the purpose of physics, but is insufficient in capturing what we normally call "change" in everyday life. Change involves more than a mere collection of distinct states of an object labeled by varying time indicies. There is a further fact about which state the object is in *now*, and the object's changing consists in the successive updating of which state is the present one. Otherwise, if an object's changing consisted in nothing but the object having different states at different clock times, then change would have essentially the same characteristics as mere spatial variation. I take it that this is not what we mean when we commonly speak of "change." Rather, change involves a

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[3] In fact, this is the kind of world represented by John M. E. McTaggart's *B-series*, where events are related by the two-place relations of "earlier than" or "later than," but lack the determinations of "past," "present," or "future" (McTaggart, 1908). A world lacking both a past-future asymmetry and the passage of time is represented by McTaggart's *C-series*, where there is only a three-place relation of "betweenness" among events.

distinguished moment in time called the *present* or *now* that updates itself or comes into being successively. The *now* is the unique moment in time in which we actually experience the world—it is, so to speak, the moment in which the world manifests itself to us. The successive updating or coming into being of this *now*, abstracted from any reference to a changing object, is what I am calling the passage or “flow” of time. When I say that the passage of time is “objective” or “real,” I mean that it does not depend on the existence of any sentient being, human or otherwise—time would continue to flow even if all sentient beings in the universe were to be annihilated some day.

The passage of time does not appear in any physical theory. All moments in time are treated equally in physics, so there is no distinguished *now* whose successive updating could constitute the passage of time. Nor has physics uncovered any mechanism or feature of the world that might give rise to an objective time flow. Granted, there are some speculative candidates for such a mechanism that have been proposed. For example, the approach to quantum gravity known as *causal set theory* has been advertised by its proponents as restoring an objective passage of time to physics (Sorkin, 2006; Dowker, 2014; see also Callender 2017, Chap. 5). There is also Richard Muller’s *now* theory (Muller, 2016; Muller & Maguire, 2016), according to which “the Hubble expansion takes place in 4 dimensions rather than in 3,” and “[t]he flow of time consists of the continuous creation of new moments, new *nows*, that accompany the creation of new space” (Muller & Maguire, 2016, abstract). Finally, some have speculated that the passage of time is captured by the collapse of the wavefunction (interpreted realistically) in quantum mechanics (Shimony, 1998; Lucas, 1999; Smolin & Verde, 2021). However, all of these proposals are still at a speculative stage, and lack the evidential basis to establish themselves as a consensus view.

The absence of a passage of time in physics has led many philosophers and physicists to conclude that passage is an illusion, arising from the way our mind (or brain) interacts with the world. The undefinability of an objective, global *now* in relativity theory seems to lend further credence to this idea (we will return to this point in the following section). However, there is no reason to think that the passage of time is an illusion. In fact, all the evidence points to the contrary—time really flows. Let me spell out the reasons why I believe so.

Perhaps the most serious problem with the B-theory of time is that it presupposes exactly the kind of real change that it purports to deny. This point has been made by Karl Popper. In his autobiography, he records the following conversation he had with Albert Einstein:

> I tried to persuade him [Einstein] to give up his determinism, which amounted to the view that the world was a four-dimensional Parmenidean block universe in which change was a human illusion, or very nearly so. [...] I argued that if men, or other organisms, could experience change and genuine succession in time, then this was real. It could not be explained away by a theory of the successive rising into our consciousness of time slices which in some sense coexist; for this kind of “rising into consciousness” would have precisely the same character as that succession of changes which the theory tries to explain away. (Popper, 2002, p. 148)

Even if we were to suppose that change and the passage of time are an illusion, there is no denying that we *experience* change and passage, in the form of a successive "rising into consciousness" of various mental states—perceptions, emotions, thoughts, and so on. Now isn't this successive "rising into consciousness" a real change happening in the world? A similar point has also been made by William Lane Craig:

> [N]o B-theorist has successfully defended that theory against the incoherence that if external becoming is mind-dependent, still the subjective experience of becoming is objective, that is, there is an objective succession of contents of consciousness, so that becoming in the mental realm is real. (Craig, 1990, p. 485)

In response to this line of thought, Palle Yourgrau, in his book on Gödel's philosophy of time, argues that "the (mere) *appearance* (as) *of a succession* (of anything—including my own representations) should not be confused with a (genuine, or intrinsic) *succession of appearances*" (Yourgrau, 1999, p. 122, emphasis in original). Drawing on Kant, he makes the point that while "*I am constrained ... to represent my own representations as (if) in time* ... [t]o go further, and ask if the latter are 'really', 'in themselves', in time would be to violate Kant's prohibition never to take appearances as things (as they are) in themselves" (Yourgrau, 1999, pp. 121–22, emphasis in original). The claim here is that while we are indeed presented with an *appearance of a succession* (of representations), it is illicit to infer from this that there is a real *succession of appearances* taking place in the world.

I don't find this convincing. The appearance of succession, as we noted above, consists in a successive "rising into consciousness" of various mental states. Now the crucial thing to note here is that we are not disembodied subjects, but essentially embodied beings. In particular, we know that our mental states are somehow rooted in the neural and physiological processes taking place in our brain and body. Granted, we still don't know the exact nature of the relationship between mental phenomena and their neural/bodily correlates, but it is indisputable that there are specific patterns of brain activity, for example, that give rise to particular kinds of subjective experience. The successive "rising into consciousness" of various mental states, therefore, must be rooted in a real succession of events taking place in our brain and body. Thus, the *appearance of succession* presented to us in every waking hour of our lives cannot be accounted for unless we suppose that there is a real succession of events—real becoming—in the physical world. The only alternative, it seems to me, is to embrace the absurdity that the successive "rising into consciousness" of our mental states is brought about by a brain and body that are themselves completely static and changeless.

Yet there have been attempts by B-theorists in precisely this direction. Craig Callender, for example, in his book *What Makes Time Special?*, introduces a simple toy model of an information gathering and utilizing system (or "IGUS"), in order to show how creatures like us, living in a world where there is no real passage of time, might nonetheless come to have an experience of flowing time (Callender, 2017, Chap. 11). IGUS comes equipped with a perceptual apparatus that takes visual images of the environment, and a series of $n + 1$ memory registers $P_0, P_1, \ldots, P_n$, each of which stores a “snapshot” of the environment at a different time. New images are taken at fixed time intervals, and are stored in the initial register P_0. As the perceptual apparatus periodically gathers new information, P_0 is updated accordingly, and previously acquired information is successively passed down the chain of memory registers. With this initial setup (plus a few further enhancements), Callender tries to show that IGUS will come to experience temporal passage, and develop something akin to our common-sense notion of time.

Callender’s account of how IGUS (and by extension, we humans) might come to have an experience of the flow of time is flawed for the same reason as that pointed out by Popper above: it implicitly presupposes what it purportedly denies. The fact that IGUS periodically takes new images and updates its memory registers *ipso facto* implies that there is a real succession of events—namely, the taking of new images and updating of IGUS’s registers—and hence an objective passage of time. This point has been brought out clearly by Savitt in his review of Callender’s book:

> IGUS’s initial sensory buffer, P_0, is updated periodically and its contents passed down to a chain of other buffers in turn. That is, P_0 receives one image after another; it receives images successively. To one who thinks that succession is the key or essential feature of passage, this says that IGUS operates in a world in which time, in fact, passes [...] If time did not pass in this sense and IGUS’s buffers never updated, then I fail to see how IGUS would develop a theory of passage. (Savitt, 2018)

I suggest that this particular instance is illustrative of a general rule: any attempt to explain even the mere *appearance* of the passage of time in a world where there is no real passage cannot do so without implicitly assuming some form of real passage in the first place.[4] Insofar as we have an experience of change and passage, there must be a real passage of time in the world, since nothing else could produce even the illusion of something so peculiar and *sui generis*.

Another reason why the B-theory of time is implausible is that it cannot explain why we experience events gradually and successively, in a strict serial order, even though the events themselves are supposed to have a “timeless” existence according to the theory. As pointed out by John D. Norton, a consequence of the B-theory that is rarely spelled out explicitly by its proponents is that our brain somehow “delivers news of the moments of time in small, serially ordered doses to consciousness. [...] Nothing in the objective facts of the world requires that the news of the moments must be delivered in this rigid, serial regimen” (Norton, 2010, p. 26). He further argues:

> Most significantly, the delivery of the doses is perfect. There are no revealing dislocations of serial order of the moments. While there may be minor dislocations, there are none of the types that would definitely establish the illusory character of passage. We do not, for example, suddenly have an experience of

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[4] This is what Arthur has called the “notorious sticking point” for static views of reality, namely: “how to account for the appearance of passage or temporal becoming without presupposing the becoming of the appearance” (Arthur, 2019, p. 14). See also the similar argument given by Abner Shimony (1998, pp. 164–65).

> next year thrown in with our experience of today; and then one of last year; and then another from the present. (Norton, 2010, p. 27)

To my knowledge, no B-theorist has provided a non-question-begging explanation of this fact. Again, here is Callender:

> On long time scales Norton is of course correct that we don't experience dislocations of day or year. Is *this* so hard to explain? It's no more mysterious than the fact that an IGUS taking successive pictures sees the pictures successively. The perceptual system can only weld together percepts based on stimuli that have arrived. The stimuli come in succession, the successive updating then happens after a fixed interval, and the order of all these events is invariant because IGUS is an entirely timelike worldline. [...] Unless one thinks the experiences are utterly detached from our cognitive architecture, it's hard to see how huge disorder dislocations could happen. (Callender, 2017, p. 237, emphasis in original)

It seems to me that Callender misses the point of Norton's argument. First of all, as we noted above, it makes no sense to speak of "IGUS taking successive pictures," stimuli coming "in succession," or the "successive updating" of IGUS's memory registers unless one begs the question and reads our common-sense idea of temporal becoming into the B-theory. If one accepts the block universe view, then—switching back from talk of IGUS to ourselves—our body must instead be pictured as a spatiotemporally extended piece of matter lying on a timelike wordline. Why, then, don't we experience every event on our worldline all at once? Why don't we experience distantly separated events on our worldline in a haphazard way? There is no distinguished *now* in the block universe, so there is no reason why we should experience a certain event on our worldline as happening now rather than some other event, or why we shouldn't experience every event on our worldline as happening all at once. Our experienced *now*, precisely because it lacks an objective counterpart, might as well randomly jump around our worldline or even embrace it entirely, and it wouldn't make the slightest difference as far as the objective world is concerned.

In short, why should our experience of reality unfold gradually and successively, in a serial order? There is absolutely no reason in the objective physical world why this should be the case, if one adheres to the B-theory. It is the B-theory, not Norton, that makes our experiences "utterly detached from our cognitive architecture," because it is the B-theory that leaves our experience of the gradual unfolding of reality hanging in the air, without any why or wherefore in the nature of things. If, on the other hand, we suppose that the passage of time is real, then it is no wonder that we experience the gradual unfolding of reality in the way we do.

To sum up, the B-theory of time is untenable for two reasons: (1) it is unable to explain our experience of the passage of time without implicitly assuming the kind of real becoming that it purportedly denies; and (2) it cannot explain why we experience events gradually and successively, even though the events themselves are supposed to have a "timeless" existence according to the theory. Why, then, do so many philosophers and physicists endorse the theory? What is the alleged evidence in favor it? For one, as we noted above, there is the awkward fact that the passage of time does not appear in our current physical theories. Faced with this unsettling situation, thinkers of a certain disposition are tempted to brush the passage of time away into the “mind” or “consciousness,” a convenient receptacle for placing entities and phenomena that elude straightforward physical explanation. But this is not so much an explanation as a mere brushing aside of the problem. Our response to the above situation is simply that current physics still has not uncovered everything there is to know about nature. We might reasonably expect that in the future, physics will uncover a mechanism or feature of the world responsible for giving rise to the passage of time. Indeed, as we noted above, there are some speculative candidates for such a mechanism that have been proposed. Another, more significant factor that has lured numerous thinkers into the block universe view is the (alleged) incompatibility of an objective passage of time with the theory of relativity. To this we shall now turn.

3 The passage of time in relativity theory

In this section we explore why relativity theory has often been considered inhospitable to our common-sense conception of time and its passage, and look at one of the proposed approaches for reconciling relativity with an objective passage of time. We begin by reviewing how the relativity of simultaneity entailed by special relativity (henceforth *SR*) rules out the existence of an objective, global *now* (Section 3.1). We then move to the setting of general relativity (henceforth *GR*) and take up the notion of “cosmic time” (Section 3.2), which can be defined in the standard FLRW models of relativistic cosmology. While some writers have suggested that cosmic time enables us to recover the objective and global passage of time that had disappeared in special relativity, I argue that it is not up to the task. Finally, we will review Savitt and Arthur’s causal diamond theory, which drops the assumption that the flow of time must be global, re-conceiving it as a local phenomenon compatible with relativity (Section 3.3).

3.1 Special relativity

Based on our common-sense conception of time, there are at least two features that we expect the *present* or *now* to possess:

(1) The *now* is *global*, i.e., extends indefinitely through all of space.
(2) The *now* is *objective* in the sense that it does not depend on any observer or group of observers. In particular, the *now* is shared by everyone, unlike notions like “here,” “left,” or “right,” which depend on an observer’s spatial position and/or orientation.[5]

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[5] Of course, one might point out that the *now* depends on an observer’s temporal location, just as the *here* depends on an observer’s spatial location. But what distinguishes the *now* from the *here* (according to common sense) is that it makes perfect sense to say that only one of these temporal locations is the *true now*—there is only one moment that is actually taking place *now*, which is *this* very moment in which you happen to be reading this sentence—whereas it hardly makes sense to say that there is a single true *here*.

It is a straightforward consequence of SR that the *now* cannot possess both of these properties together. A fundamental result of SR is the *relativity of simultaneity*, which states that whether or not two spacelike separated events are simultaneous depends on the choice of reference frame. Thus, two events that are simultaneous according to one observer (reference frame) are not simultaneous according to another observer (reference frame) in relative motion with the first. If we agree that a certain spacetime point p is *now*, and if we further assume that the *now* is a global slice of spacetime—a global spacelike hypersurface—as stipulated in (1), then the relativity of simultaneity implies that different observers will in general disagree as to which events are simultaneous with p, and hence which events constitute the *now*. But this goes against the objectivity of the *now* stipulated in (2).

Thus, insofar as the passage of time is construed as the successive updating or coming into being of an objective, global *now*, there cannot be any passage of time according to SR. This same argument constitutes the first step of Gödel's dialectic against the idea that time really passes. As he puts it succinctly:

> The existence of an objective lapse of time [...] means (or, at least, is equivalent to the fact) that reality consists of an infinity of layers of "now" which come into existence successively. But, if simultaneity is something relative in the sense just explained, reality cannot be split up into such layers in an objectively determined way. 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, pp. 202–3)

The setting for SR is flat, Minkowski spacetime, which corresponds to an idealized world where there is no matter to cause spacetime to curve. What happens when we move to the more general and realistic setting of curved spacetime, which is the purview of GR? Let us turn to this issue next.

3.2 Cosmic time

The second step of Gödel's dialectic consists in recognizing that the above argument against an objective passage of time, which relied on the relativity of simultaneity in SR, does not straightforwardly carry over into GR. The reason for this is that in the standard models of relativistic cosmology, generally held to be the best approximations to the large-scale structure of spacetime, one can define in a natural way a *unique* global foliation of spacetime—a decomposition of spacetime into a 1-dimensional *cosmic time* and a family of 3-dimensional global spacelike hypersurfaces, each representing the state of the universe at a certain "instant" of the cosmic time. Let's take a look at how this is done.

When I say that the *now* is objective and shared by everyone, I am referring to this unique, distinguished *now* embodied in our common-sense conception of time.

The standard models of modern cosmology are known as the Friedmann–Lemaître–Robertson–Walker (FLRW) spacetimes, named after the physicists who devised the underlying metric. These models rely on two simplifying assumptions:[6]

Weyl's Principle The worldlines of galaxies ("fundamental observers") form a bundle of non-intersecting timelike geodesics orthogonal to a family of spacelike hypersurfaces. (Narlikar, 2002, p. 107)

Cosmological Principle On large scales, the universe is spatially isotropic and spatially homogeneous.

Let's look at Weyl's principle first. Weyl's principle amounts to a specification of a distinguished family of worldlines, namely, those of galaxies—also called "fundamental observers" in this context—for representing the matter in the universe. The importance of this principle lies in the fact that one can use it to set up a so-called *comoving frame of reference*, in which the fundamental observers, the galaxies, carry the constant spatial coordinates and hence are always at "rest." The frame is called "comoving" because it follows the motion of matter; it is, in effect, the "rest frame" of the universe.

Since the galaxies are at rest in the comoving frame, we can use the three spatial coordinates $x^i (i = 1, 2, 3)$ to label a galaxy wordline in the bundle specified by Weyl's principle. We can further use the time coordinate x^0 to specify a spacelike hypersurface among the family of hypersurfaces mentioned in the principle. The requirement that the galaxy worldlines are orthogonal to the family of hypersurfaces implies that the metric components $g_{0i} = 0$. If we choose $g_{00} = 1$ so that the time coordinate x^0 corresponds to the proper time recorded by the galaxies, we can write the metric in the special form

$$ds^2 = c^2 dt^2 - g_{ij} dx^i dx^j \qquad (i, j = 1, 2, 3) \tag{1}$$

where $x^0 = ct$. The form of this metric indicates that we have globally decomposed spacetime into a 3-dimensional space and 1-dimensional time. The time coordinate $x^0 = ct$ is called the *cosmic time*, and is the proper time recorded by any galaxy. Finally, we can invoke our second assumption, the isotropy and homogeneity of the universe, to further simplify the spatial component g_{ij} of the metric in (1).[7] This gives us the FLRW metric, which represents a constant curvature space that evolves in (cosmic) time. A point that deserves notice here is that it is Weyl's Principle that does all the work in decomposing spacetime into space and time; the Cosmological Principle is only invoked in order to cast the spatial component of the metric (1) into

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[6] The discussion below closely follows the presentation given in Narlikar (2002, Sec. 3.5) and Rugh and Zinkernagel (2011).

[7] More precisely, only the isotropy condition is necessary, because isotropy at every point (or even just two points) *implies* homogeneity (Peacock, 1999, pp. 65–66).

a form that represents a constant curvature space. In fact, as pointed out by Svend E. Rugh & Henrik Zinkernagel, the Cosmological Principle is conceptually parasitic upon Weyl's Principle (Rugh & Zinkernagel, 2011).

What we have done using Weyl's principle is introduce a preferred foliation of spacetime by specifying a distinguished class of observers, the fundamental observers. The symmetry among observers that had prevailed in SR is broken by the existence of these "privileged" observers that follow the motion of matter. In this way, when one moves to the setting of relativistic cosmology, one can in a certain sense *recover* the objective and global passage of time that had disappeared in SR, by introducing a preferred foliation and cosmic time. It is on the basis of this cosmic time that we are able to say, for example, that the Big Bang took place 13.8 billion years ago.

The idea that we can recover an objective and global passage of time when we move to the setting of cosmology was voiced as early as 1936, by the physicist and astronomer James Jeans:

> Einstein tried to extend the theory of relativity so that it should cover the facts of astronomy and of gravitation in particular [...] It was natural to try in the first instance to retain the symmetry between space and time which had figured so prominently in the simpler physical theory [SR], but this was soon found to be impossible. If the theory of relativity was to be enlarged so as to cover the facts of astronomy, then the symmetry between space and time which had hitherto prevailed must be discarded. Thus time regained a real objective existence, although only on the astronomical scale, and with reference to astronomical phenomena. (Jeans, 1936, pp. 21–22)

It is against this view of Jeans that Gödel directs his attack in the third and final step of his dialectic, using his newly discovered "rotating universe" solution to the Einstein field equations (Gödel, 1949b, p. 204). In fact, as Gödel himself makes clear, it was his desire to rebut Jeans' argument and confirm the idealistic conception of time—which he drew from Kant—that led him to search for rotating solutions in the first place (Gödel, 1949c, p. 274). We will return to Gödel's argument in the following section (Section 4); here let us focus a bit more on the idea of cosmic time.

The question we are interested in is whether cosmic time provides us with the means for formulating our common-sense conception of temporal passage in the context of relativity theory. This question must be answered in the negative: as has been argued by Craig Bourne (2004) and Callender (2017), we cannot identify the cosmic time of FLRW spacetimes with the "flowing time" that we experience in our everyday lives.

First, as Jeans acknowledges in the passage quoted above, cosmic time can only be defined on astronomical scales, with reference to astronomical phenomena (i.e., galaxies). Such a notion of time is so divorced from the scales of our normal everyday experiences that it is hard to see how it can be identified with the "flowing time" we are all familiar with. Second, as we saw above, the notion of cosmic time is conditioned on Weyl's Principle, which, however, does not strictly hold in our actual universe. The principle requires that the worldlines of galaxies do not intersect—this is necessary in order to prevent the same spacetime point from having different (incompatible) coordinates in the comoving frame (Narlikar, 2002, p. 108). But actual galaxies collide. Therefore, instead of considering the actual worldlines of galaxies, one takes as the fundamental worldlines of Weyl's Principle the "average worldlines" associated with the average motion of galaxies, in order to "smooth out" any crossings (Rugh & Zinkernagel, 2011, p. 419). The problem is that an element of arbitrariness enters into this averaging procedure, casting doubt on the purported "objectivity" of cosmic time.[8] The reasonable conclusion to draw from this is that cosmic time is only a useful parameter that we can define in the standard cosmological models; there is no reason to believe that it represents something like the "true" time of the universe.

Gödel too recognizes the arbitrary nature of cosmic time. In a footnote he writes:

> Another circumstance invalidating Jean's argument is that the procedure described above gives only an approximate definition of absolute time. No doubt it is possible to refine the procedure so as to obtain a precise definition, but perhaps only by introducing more or less arbitrary elements [...] It is doubtful whether there exists a precise definition which has so great merits that there would be sufficient reason to consider exactly the time thus obtained as the true one. (Gödel, 1949b, p. 204fn)

Nonetheless, Gödel's main counterargument against Jeans relies on the existence of a cosmological model (solution to the Einstein field equations) for which a global time cannot be defined at all—namely, the Gödel universe. Before turning to the Gödel universe in Section 4, I want to address the question of how we can re-conceive the passage of time in a way compatible with relativity. This brings us to Savitt and Arthur's causal diamond theory.

3.3 The causal diamond theory

How can we make sense of the passage of time in the setting of relativity theory? One approach—the one I find most promising—is to abandon the assumption that the *now* must be global, and to re-construe the passage of time as a purely local phenomenon. The basic idea behind this approach is that the notion of a global time, flowing uniformly throughout the entire universe, is the result of an illegitimate extrapolation of our local, limited experience. Nothing in our experience tells us that the passage of time is a global phenomenon, or that the *now* extends indefinitely through all of space. By abandoning these unwarranted assumptions we can re-conceive temporal becoming in a way consistent with relativity.

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[8] While a similar point is made by Callender (2017), he seems to hold that cosmic time presupposes not only Weyl's Principle but also the Cosmological Principle. For example he writes: "FLRW time [i.e., cosmic time in the FLRW models] depends on elaborate averaging ... At most spatial scales the universe is not even close to being isotropic and homogeneous ... The standard model irons out these differences, as is only proper in a model. Yet why on earth should fundamental time, if it exists, march to that particular averaged scale?" (Callender, 2017, p. 75). But as we saw above, cosmic time does not depend on the Cosmological Principle, so Callender's argument here misses the mark. Nonetheless, his general point—that cosmic time depends on elaborate averaging procedures—holds.

Various versions of local becoming have been proposed in the literature.[9] The approach I find most compelling is the *causal diamond theory* put forward by Savitt (2009, 2015) and Arthur (2006, 2019). On their view, the present is to be modelled in terms of a local structure called a *causal diamond*, also known as an *Alexandrov interval*, named after the Russian mathematician Alexandr Danilovich Alexandrov.

The definition of a causal diamond is as follows (Savitt, 2015). Let $\mathcal{M}$ be a strongly causal spacetime with a time orientation defined.[10]

Definition 1 Given two points $p, q \in \mathcal{M}$, if there is a smooth, future-directed timelike curve from p to q, then p is said to *(chronologically) precede* q, and we write $p \prec q$.

Definition 2 The set $I^+(p) := \{x \in \mathcal{M} \mid p \prec x\}$ is called the *chronological future* of p. The set $I^-(p) := \{x \in \mathcal{M} \mid x \prec p\}$ is called the *chronological past* of p.

Definition 3 Given two points $p, q \in \mathcal{M}$ with $p \prec q$, the set $ALEX(p, q) := I^+(p) \cap I^-(q)$ is called the *causal diamond* of p and q.

Intuitively, the causal diamond of p and q, $ALEX(p, q)$, is the set of all events that can causally influence an event lying on a timelike curve connecting p and q (excluding the endpoints), and also *be influenced* by some other event on that same curve. Hence the name *causal* diamond. Since $ALEX(p, q)$ is the intersection of the interior of the future light cone of p and interior of the past light cone of q, it has a diamond-shape, as pictured in Fig. 1. Causal diamonds are *local* structures in that they occupy only a small region of spacetime. Furthermore, they have the desirable property of being *objective* in the sense of being independent of the choice of coordinate frame (and hence observer-independent). This makes them suitable candidates for modelling an objective passage of time.

Savitt and Arthur's causal diamond approach takes its cue from the observation that our experienced *now* is not instantaneous, but has a certain temporal breadth (in the literature this kind of extended *now* is often referred to as the *specious present*). Let us represent this temporal interval as a timelike curve from point p to q. Then we can let $ALEX(p, q)$ represent the "present" for this interval. One such present is defined for every worldline, and the flow of time is expressed as the succession of these presents along their respective worldlines. For the sake of brevity, let us call a present represented by $ALEX(p, q)$ a *diamond present*.

The advantage of modelling the passage of time in terms of diamond presents is that we can recover some of the features of our common-sense conception of time as "approximations." For example, suppose the interval from p to q is 1 s, which is a

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[9] Apart from the causal diamond theory to be discussed below, see Stein (1968, 1991), Clifton and Hogarth (1995), Dieks (2006), and Rovelli (2019) .

[10] The condition that $\mathcal{M}$ be *strongly causal* means that $\mathcal{M}$ does not contain closed or almost-closed timelike curves (see Minguzzi & Sánchez (2008, Sec. 3.6) for a precise definition); this rules out spacetimes like the Gödel universe. As we will see later, our definition of a causal diamond will need to be slightly modified in order to extend it spacetimes that contain CTCs.

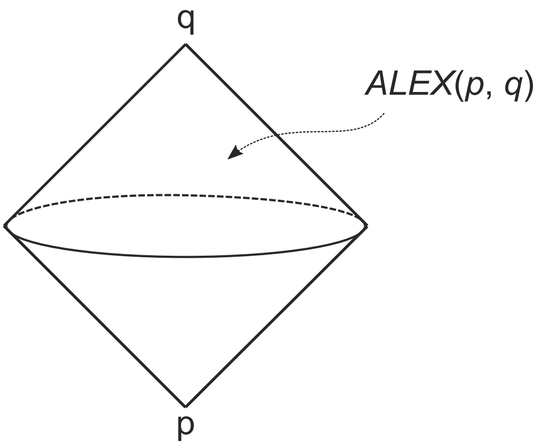

Fig. 1 A causal diamond $ALEX(p, q)$, defined for spacetime points p and q

reasonable value for the duration of the "specious" or psychological present (Savitt, 2009, p. 356). Then, assuming that the speed of light is 3×10^8 m/s, the diamond present $ALEX(p, q)$ has a spatial extent of the order of 10^8 m, roughly ten times the earth's diameter. This is such an enormous stretch of space compared with the length scales of our own bodies and everyday objects, that it is no wonder we usually think of the present as extending indefinitely throughout the entire universe. Furthermore, since the velocities of our everyday motions are small compared with the velocity of light, the diamond presents of human observers virtually overlap, allowing us to explain why we developed the idea that we all share a common *now*.

As Arthur points out, however, it is important to note that while the diamond present may accommodate whatever is present to human consciousness, it *need not* be indexed to the specious or psychological present of a human observer (Arthur, 2019, p. 168). Otherwise—if we were to make the definition of the diamond present relative to the psychological present of humans—we would undermine the objectivity (observer-independence) of the diamond present, which is supposed to be one of the main virtues of the causal diamond theory. The diamond present is defined with respect to a section of any timelike curve, regardless of whether the curve represents the trajectory of some sentient observer. We can thus speak of the passage of time in a universe where there are no human or other sentient beings.

A further fact that makes causal diamonds an appealing candidate for modelling the passage of time is that they are physically well-motivated structures that have a wide range of applications in theoretical physics. In addition to the examples listed in (Savitt, 2015), one should mention the theorem due to David Malament (1977), which states that for spacetimes that satisfy certain causality conditions (namely, past and future distinguishing spacetimes), the spacetime's causal structure (the structure of $\prec$ relations among events) taken as a primitive is sufficient to determine the spacetime's topology, differential structure, and metric structure up to a scale factor. This result is the inspiration behind the causal set approach to quantum gravity, which seeks to recover the geometry of spacetime from causal relations among discrete events (Dowker, 2013). In particular, since the information about the local scale is contained in the *volume* of causal diamonds, all the information about the geometry of spacetime can be thought of as being "encoded" in the causal diamonds (Gibbons & Solodukhin, 2007).

So far we have looked at how Savitt and Arthur's causal diamond theory reconceives the passage of time as a purely local phenomenon, in a way consistent with relativity. In the following section we will turn to Gödel's argument for the ideality of time, and see how the causal diamond approach can be employed to counter this argument.

4 Gödel's argument for the ideality of time

No philosophy of time that takes the results of modern physics seriously can ignore Gödel's argument for the ideality of time. As we noted in the introduction, Gödel's argument is based on his discovery of a "rotating universe" solution to the Einstein field equations, commonly known as the Gödel universe. We will begin by taking a brief look at some of the curious properties of this model, without going into the technical details (Section 4.1).[11] Then we will turn to Gödel's argument, which (as we saw in the introduction) consists of two steps. We will first take up the second step, the *modal step* or *modal argument*, and defend it against the consensus view that finds it wanting (Section 4.2). Finally we will turn to the first step, which aims to show that there can be no objective passage of time in the Gödel universe. We will show, on the contrary, that the Gödel universe is compatible with objective becoming as long as the latter is construed locally, along the lines of the causal diamond approach sketched in the previous section (Section 4.3).

4.1 The Gödel universe

Gödel's cosmological model describes a homogeneous universe in which matter is in a state of uniform, rigid rotation. A striking feature of this universe is that it contains CTCs, everywhere-timelike curves that return to their starting point. In fact, a CTC exists *everywhere* in the Gödel universe: Given any two points p and q in the Gödel universe, there is a smooth CTC containing p and q (Malament, 2012, pp. 207–8). In particular, if $p \prec q$, then starting at q, one can travel along the CTC in the future direction and arrive at p, which lies in the chronological past of q. In this sense, the Gödel universe permits time travel into the past. We can visualize this time travel in terms of the "tilting" of the light cones depicted in Fig. 2. As illustrated in the figure, the light cone structure becomes "tilted" as one moves farther away from the center of rotational symmetry. There is a critical distance from the center beyond which the light cones begin pointing "downward," below the central light cone's hyperplane of simultaneity. An observer departing point q in the figure can therefore reach point p (which lies in the observer's past) by moving far enough outward from the center and following these downward-pointing light cones.

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[11] See (Malament, 2012, Sec. 3.1) for an excellent technical exposition of the Gödel universe.

The existence of CTCs immediately implies that the Gödel universe does not admit a *global time function* of the sort that exists in the standard cosmological models (Gödel, 1949a, p. 191). A global time function on a given spacetime $\mathcal{M}$ is a smooth function $t : \mathcal{M} \mapsto \mathbb{R}$ that is strictly increasing along every future-directed causal (timelike or lightlike) curve. The absence of a global time function means that there is no consistent time order of events for the whole universe—hence there cannot be a global passage of time. Alternatively, one could reach the same conclusion by noting that the Gödel universe does not admit any *Cauchy surfaces*, i.e., spacelike hypersurfaces that intersect every inextendible smooth timelike curve exactly once. A Cauchy surface is a reasonable model for a global *now*, so to say that the Gödel universe does not admit any Cauchy surfaces means that one cannot define a global *now* in this spacetime.

From the undefinability of a global time, Gödel concludes that there cannot be an objective lapse of time in the Gödel universe (Gödel, 1949b, p. 205). This result constitutes the first step of his argument for the ideality of time. We will see below that this conclusion is unwarranted. Before that, however, let us turn to the second step of Gödel's argument, the modal step.

4.2 Gödel's modal argument

For the sake of argument, let us grant for the moment that there can be no objective passage of time in the Gödel universe. It is generally agreed that the Gödel universe is not a valid model of our actual universe. It is a non-expanding solution, so it does not yield the redshift for distant galaxies that we actually observe. It is therefore only

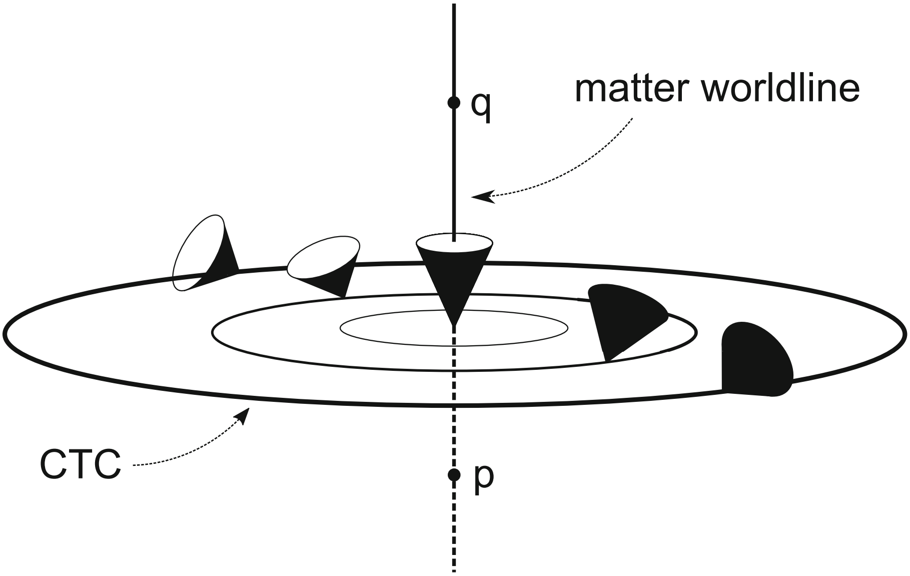

Fig. 2 Visualization of the Gödel universe (with one dimension suppressed). The light cones become tilted as one goes farther away from the center, enabling time travel into the past

a *physically possible* model. The question, then, is: what bearings could a merely physically possible model have for our understanding of time in the actual universe? In response to this question, Gödel puts forward a *modal* argument that aims to show that the mere fact that a universe lacking an objective passage of time is permitted by the laws of GR implies that there is no objective passage in our actual universe either. He writes:

> The mere compatibility with the laws of nature of worlds in which there is no distinguished absolute time, and [in which], therefore, no objective lapse of time can exist, throws some light on the meaning of time 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. (Gödel, 1949b, pp. 206–7)

The basic line of thought here seems to be as follows.[12] We are given that the Gödel universe is a solution to the Einstein field equations. In this sense it can be said to be "compatible with the laws of nature." In other words, exactly the same laws of nature can be said to be at work in our actual universe and the Gödel universe. The only difference that separates our universe from the Gödel universe lies in the distribution and motion of matter—namely, matter in the Gödel universe is in a state of uniform, rigid rotation, whereas (we assume) the same is not true for our universe. It follows that if time really passes in our universe, then it must do so by virtue of the specific distribution and motion of matter. Yet it seems strange to claim that the passage of time should depend on such a *contingent* factor as the distribution and motion of matter. It seems more natural to think that if time really passes in our universe, it does so by virtue of some law of nature.[13]

Most philosophers who have commented on Gödel's modal argument are unconvinced by it (Stein, 1970; Savitt, 1994; Earman, 1995; Dorato, 2002; Belot, 2005; Smeenk & Wüthrich, 2011).[14] The skepticism is summed up by John Earman:

> Gödel's essentialist intuitions here are not easy to fathom. There seems to be no lurking contradiction or anything philosophically unsatisfactory in saying

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[12] An alternative kind of "modal argument" has also been suggested by Yourgrau (1999, pp. 47–48) and articulated by Savitt (1994). I set this argument aside here because, as pointed out by Gordon Belot (2005, p. 270fn), it is based on a passage where Gödel is dealing with an entirely different topic from the one we are concerned with here, namely, the implications of the existence of CTCs for the passage of time in the Gödel universe. Furthermore, I don't see how one could justify in a non-question-begging way one of the premises of the argument as presented by Savitt, namely, that hypothetical inhabitants of the Gödel universe would have an experience of temporal passage just like ours (see Dorato (2002) for further discussion).

[13] Gödel explicitly makes this point in one of his working drafts for the article quoted above: "A lapse of time [...] would have to be founded, one should think, in the laws of nature" (Gödel, 1946/49, p. 238).

[14] One of the few commentators who wholly embrace Gödel's argument for the ideality of time, including the second modal step, is Yourgrau (1999). See also (Manchak, 2016) for a sympathetic reconstruction of the modal argument along different lines from the one I present here.

> in the same breath: "Space in the actual world is open, but if the mass density were a little greater, space would be closed," or "Time in the actual universe goes on forever into the future, but if the mass density were greater the universe would eventually recollapse and time would come to an end." Why then is there a lurking contradiction or something philosophically unsatisfactory in saying: "Time in our universe lapses, but if the distribution and motion of matter were different, there would be no consistent time order and so time would not lapse"? (Earman, 1995, p. 198)

In what follows I will defend Gödel's modal argument against Earman's objection by adducing a line of thought which (to my knowledge) has not been addressed in the literature. It may or may not be along the lines of what Gödel actually had in mind, but in either case it is an argument that I find quite compelling.

The difference between Earman's two examples (the openness of space and endlessness of time) on the one hand and the passage of time on the other is that the openness of space and endlessness of time in the actual universe can be fully explained by the mass density of our universe, together with the laws of GR; whereas the distribution and motion of matter (together with the laws of GR) do not constitute an explanation of why time passes in our universe. The distribution and motion of matter, together with the laws of GR, may ensure that our universe has a *geometry hospitable to the passage of time* (e.g. that it admits a global time function or preferred foliation of spacetime), but this by itself does not amount to an explanation of why time passes in our universe (assuming that it does). The underlying difference here is that the openness of space and endlessness of time are *geometric* features of space and time, respectively, which are susceptible to explanation by GR, whereas temporal passage is a non-geometric feature of time, regarding which GR remains silent.

The mere possibility of the Gödel universe, however, rules out any alternative explanation of the passage of time, since, as we saw above, the only difference between the actual universe and the Gödel universe lies in the distribution and motion of matter, and so there is no other factor that could be responsible for giving rise to a (putative) lapse of time in the actual universe. As long as we assume that, apart from the distribution and motion of matter, the same laws and conditions prevail in the actual universe and Gödel universe, there is no possible explanation for why time should pass in the former but not the latter. Therefore, to say that time passes in the actual world, but would not pass if the distribution and motion of matter were different, makes the passage of time in the actual universe something utterly mysterious. A view that admits the reality of temporal passage, and yet claims that time would not lapse if the distribution and motion of matter were different, while not an outright contradiction, "can hardly be considered as satisfactory" because it denies the possibility of giving a rational explanation of the passage of time.[15]

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[15] Of course, one might suppose that there is some yet unknown law that causes time to flow whenever a given spacetime satisfies the necessary geometric features. But we can't just *postulate* such a law; at present there are simply no reasons for supposing such a law to exist.

I believe these considerations compel us to embrace Gödel's modal argument: if there is no objective passage of time in the Gödel universe, then neither is there in our actual universe. In the next section I want to show that the antecedent of this conditional does not hold.

4.3 Local becoming in the Gödel universe

We saw above (Section 4.1) that there cannot be a global passage of time in the Gödel universe because it does not admit a global time function or any Cauchy surfaces. What deserves notice, however, is that the Gödel universe is *temporally orientable*, i.e., among the two lobes of the light cone structure at every point in the spacetime, one can choose one of the lobes to represent the "future" direction of time, and the other lobe the "past" direction, consistently throughout the entire spacetime. In other words, one can define a local direction of time in a consistent way throughout the entire universe.[16] This suggests that although the Gödel universe does not admit a *global* passage of time, we can still make sense of a *local* passage of time in this universe.

My proposal is that we can model a local passage of time in the Gödel universe by extending the causal diamond approach outlined in the previous section (Section 3) to *totally vicious* spacetimes, i.e., spacetimes like the Gödel universe that have CTCs everywhere. The most straightforward way of doing so, one might think, is to simply define a diamond present on *every* timelike curve, including CTCs. In fact, this is precisely the approach suggested by Savitt (2005, pp. 419–20). However, as pointed out by Phill Dowe (2017, p. 193), this does not work, because in a universe where there are CTCs everywhere, any given diamond present will embrace the entire spacetime. To see why, consider a causal diamond defined with respect to two points p and q (where $p \prec q$) in a totally vicious spacetime. Given an arbitrary point x in the spacetime, there is a CTC containing both p and x, and a CTC containing both q and x. Since every point on a CTC lies both in the chronological future and chronological past of itself and every other point on the CTC, it follows that $p \prec x$ and $x \prec q$. Hence, x is contained in $ALEX(p, q)$, the causal diamond of p and q. But x was chosen arbitrarily, so this means that the entire spacetime is contained in $ALEX(p, q)$.

In his reply to Dowe, Savitt acknowledges that his original proposal of defining diamond presents on CTCs fails (Savitt, 2017, p. 200). In its stead, he suggests a "revised version" of the same strategy, pointing to a remark in Robert Wald's *General Relativity* (Wald, 1984, p. 263) that for any point p in any spacetime $\mathcal{M}$, there is a neighborhood O of p such that O, considered as a spacetime in its own right, is *globally hyperbolic*, i.e., admits a Cauchy surface. What Savitt doesn't mention, however, is that one can take causal diamonds as these globally hyperbolic neighborhoods. Let's see how this is done.

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[16] As an example of a spacetime that is *not* temporally orientable, consider defining a direction of time on a Möbius strip: transport the "arrow" of time continuously along the strip, and it will have reversed its direction when it returns to its original position (Maudlin, 2012, pp. 156–57). Hence we cannot define a direction of time consistently on the entire strip.

Given any spacetime $\mathcal{M}$ and any point $p \in \mathcal{M}$, one can define an arbitrarily small *geodesically convex neighborhood* (or simply *convex neighborhood*) of p, i.e., a neighborhood C such that for any pair of points $q, r \in C$, there is a unique geodesic connecting q and r that stays entirely within C (Minguzzi & Sánchez, 2008, Sec. 2.3). Convex neighborhoods are geometrically well-behaved in that their causal structure is the same as Minkowski spacetime (Minguzzi & Sánchez, 2008, Prop. 2.10). Now let us restrict our causal diamonds to those defined on some convex neighborhood. A causal diamond thus restricted, considered as a spacetime in its own right, can be shown to be globally hyperbolic (Minguzzi & Sánchez, 2008, Sec. 2.3). In particular, it will not contain any CTCs. Let us call a causal diamond restricted to a convex neighborhood a *diamond neighborhood*. Diamond neighborhoods are suitable structures for modelling the *nows* in any spacetime, even those that are totally vicious: because they are globally hyperbolic, there is no worry that they will embrace the entire spacetime, or an entire CTC (which would also be problematic). Thus, I suggest that we can model a local passage of time in any totally vicious spacetime (including the Gödel universe) by taking the *nows* to be represented by diamond neighborhoods, defined on every worldline (including CTCs). As before, the flow of time can then be expressed as the succession of these *nows* along their respective worldlines.

5 Concluding remarks

Let us take stock of our discussion so far. In Section 2 we saw that in order to account for our experience of temporal passage, we have no choice but to assume that the passage of time is an objective feature of reality, rather than a subjective appearance or illusion. However, the theory of relativity is often regarded as inhospitable to our common-sense conception of time and its passage. In Section 3 we explored the reasons behind this common view, and reviewed Savitt and Arthur's causal diamond theory, which seeks to re-conceive the passage of time as a purely local phenomenon compatible with relativity. Finally, in Section 4 we took up Gödel's argument for the ideality of time. We defended the second modal step of Gödel's argument against the consensus view and rejected the first step, showing that we can make sense of a local passage of time in the Gödel universe by extending the causal diamond approach outlined in Section 3.

A question that may arise at this point is: why should we think that the *now* is adequately modeled as a causal diamond (or diamond neighborhood) rather than some other local structure? As we noted in Section 3, there are three features that make causal diamonds appealing candidates for representing the *now*: (1) they are objective (coordinate-independent), making them suitable structures for modelling an objective passage of time; (2) they are capable of reproducing some of the features of our common-sense conception of time as "approximations"; and (3) they are physically well-motivated structures that have a wide range of applications in theoretical physics. But are these reasons strong enough for us to maintain that the *now* should be represented as a causal diamond? My view, which probably deviates somewhat from that of Savitt and Arthur, is that causal diamonds are only one candidate (albeit an attractive one) for modelling the *now*—this does not rule out other potential ways of conceiving the *now*. The point I want to stress is not whether the *now* should be thought of as a causal diamond, but rather *the very fact that one can define a local passage of time within the setting of relativity theory*, even in spacetimes that are as pathological as the Gödel universe.

Of course, this still leaves us with the questions: What is the *now*? What mechanism or feature of the universe is responsible for giving rise to our experience of temporal passage? I am inclined to think that questions like these are ultimately to be settled by physics rather than philosophy. This does not mean, however, that philosophy has no choice but to wait on the sidelines while physics does its work. On the contrary, I believe that philosophical speculation has the potential to lead us to new and interesting physical discoveries, just as Gödel was driven to discover his rotating universe model by his philosophical interest in the ideality of time.

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Declarations

Competing interests I have no competing interests to disclose.

References

Arthur, R. (2006). Minkowski spacetime and the dimensions of the present. In D. Dieks (Ed.), *The ontology of spacetime*. Elsevier.

Arthur, R. (2019). The reality of time flow: Local becoming in modern physics. Springer.

Belot, G. (2005). Dust, time and symmetry. *The British Journal for the Philosophy of Science*, *56*(2), 255–91.

Boltzmann, L. (1964). *Lectures on gas theory* (trans: Brush, S.G.) Dover. [1896–1898].

Bourne, C. (2004). Becoming inflated. *The British Journal for the Philosophy of Science*, *55*(1), 107–19.

Callender, C. (2017). *What makes time special?* Oxford University Press.

Clifton, R., & Hogarth, M. (1995). The definability of objective becoming in Minkowski spacetime. *Synthese*, *103*(3), 355–87.

Craig, W. L. (1990). What Place, then, for a creator?: Hawking on god and creation. *The British Journal for the Philosophy of Science*, *41*(4), 473–91.

Davies, P. (1995). *About time: Einstein's unfinished revolution*. Simon & Schuster.

Dieks, D. (2006). Becoming, relativity and locality. In D. Dieks (Ed.), *The ontology of spacetime*. Elsevier.

Dorato, M. (2002). On becoming, cosmic time and rotating universes. In C. Callender (Ed.), *Time, reality and experience*. Cambridge University Press.

Dowe, P. (2017). A and b theories of closed time. *Manuscrito*, *40*(1), 183–96.

Dowker, F. (2013). Introduction to causal sets and their phenomenology. *General Relativity and Gravitation*, *45*, 1651–67.

Dowker, F. (2014). The birth of spacetime atoms as the passage of time. *Annals of the New York Academy of Sciences*, *1326*, 18–25.

Earman, J. (1995). *Bangs, crunches, whimpers, and shrieks: Singularities and acausalities in relativistic spacetimes*. Oxford University Press.

Gibbons, G. W., & Solodukhin, S. N. (2007). The geometry of small causal diamonds. *Physics Letters B*, *649*(4), 317–324.

Gödel, K. (1946/49). Some observations about the relationship between theory of relativity and kantian philosophy. In: (Gödel, 1995).

Gödel, K. (1949a). An example of a new type of cosmological solutions of Einstein's field equations of gravitation. *Reviews of Modern Physics*, *21*, 447–50. Reprinted in (Gödel, 1990).

Gödel, K. (1949b). A remark about the relationship between relativity theory and idealistic philosophy. Albert Einstein: Philosopher-Scientist. ed. Paul Arthur Schilpp. Open Court. Reprinted in (Gödel, 1990).

Gödel, K. (1949c). Lecture on rotating universes. In (Gödel, 1995).

Gödel, K. (1990). In S. Feferman, et al. (Eds.), *Collected works, Vol. II: Publications 19381974*. Oxford University Press.

Gödel, K. (1995). In S. Feferman, et al. (Eds.), *Collected works, Vol. III: Unpublished essays and lectures*. Oxford University Press.

Jeans, J. (1936). Man and the universe. In *Scientific Progress*. George Allen & Unwin Ltd.

Lucas, J. R. (1999). A century of time. In J. Butterfield (Ed.), *The arguments of time*. Oxford University Press.

Malament, D. B. (1977). The class of continuous timelike curves determines the topology of spacetime. *Journal of Mathematical Physics*, *18*, 1399–1404.

Malament, D. B. (2012). *Topics in the foundations of general relativity and Newtonian gravitation theory*. University of Chicago Press.

Manchak, J. B. (2016). On Gödel and the ideality of time. *Philosophy of Science*, *83*(5), 1050–58.

Maudlin, T. (2007). On the passing of time. In *The metaphysics within physics*. Oxford University Press.

Maudlin, T. (2012). *Philosophy of physics: Space and time*. Princeton University Press.

McTaggart, J. E. (1908). The unreality of time. *Mind: A Quarterly Review of Psychology and Philosophy*, *17*(68), 457–74.

Minguzzi, E., & Sánchez, M. (2008). The causal hierachy of spacetimes. In D. V. Alekseevsky, & H. Baum (Eds.), *Recent developments in pseudo-Riemannian geometry*. European Mathematical Society. arXiv:gr-qc/0609119.

Muller, R. A. (2016). *Now: The physics of time*. W. W. Norton & Co.

Muller, R. A., & Maguire, S. (2016). Now, and the flow of time. arXiv:1606.07975.

Narlikar, J. V. (2002). *An introduction to cosmology*, 3rd edn. Cambridge University Press.

Norton, J. D. (2010). Time really passes. *Humana.Mente: Journal of Philosophical Studies*, *13*, 23–34.

Peacock, J. A. (1999). *Cosmological physics*. Cambridge University Press.

Popper, K. (2002). *Unended quest: An intellectual autobiography*. Routledge.

Prigogine, I. (1980). *From being to becoming: Time and complexity in the physical sciences*. W. H. Freeman & Co.

Putnam, H. (1967). Time and physical geometry. *The Journal of Philosophy*, *64*(8), 240–47.

Putnam, H. (2008). Reply to Mauro Dorato. *European Journal of Analytic Philosophy*, *4*(2), 71–73.

Reichenbach, H. (1999). In M. Reichenbach (Ed.), *The direction of time*. Dover. [1956].

Rietdijk, C. W. (1966). A rigorous proof of determinism derived from the special theory of relativity. *Philosophy of Science*, *33*, 341–44.

Rovelli, C. (2019). Neither presentism nor eternalism. *Foundations of Physics*, *49*, 1325–35.

Rugh, S. E., & Zinkernagel, H. (2011). Weyl's principle, cosmic, time, and quantum fundamentalism. In D, Dieks, et al. (Eds.), *Explanation, prediction, and confirmation*. Springer. arXiv:1006.5848.

Savitt, S. F. (1994). The replacement of time. *Australasian Journal of Philosophy*, *72*(4), 463–74.

Savitt, S. F. (2005). Time travel and becoming. *The Monist*, *88*(3), 413–22.

Savitt, S. F. (2009). The transient nows. In W.C. Myrvold & J. Christian (Eds.), *Quantum reality, relativistic causality, and closing the epistemic circle: Essays in Honour of Abner Shimony*. Springer.

Savitt, S. F. (2015). I ♡◇ s. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *50*, 19–24.

Savitt, S. F. (2017). Closed time and local time: A reply to Dowe. *Manuscrito*, *40*(1), 197–207.

Savitt, S. F. (2018). Review of Craig callender, what makes time special? *BJPS review of books*. http://www.thebsps.org/reviewofbooks/craig-callender-what-makes-time-special/. Accessed 5 Oct 2021.

Shimony, A. (1998). Implications of transience for spacetime structure. In S. A. Huggett, et al. (Eds.), *The geometric universe: Science, geometry, and the work of Roger Penrose*. Oxford University Press.
Smeenk, C., & Wüthrich, C. (2011). Time travel and time machines. In C. Callender (Ed.), *The Oxford Handbook of Philosophy of Time*. Oxford University Press.
Smolin, L., & Verde, C. (2021). The quantum mechanics of the present. arXiv:2104.09945.
Sorkin, R. (2006). Geometry from order: Causal sets. *Einstein Online*, *02*, 1007.
Stein, H. (1968). On Einstein-Minkowski spacetime. *The Journal of Philosophy*, *65*(1), 5–23.
Stein, H. (1970). On the paradoxical time-structures of Gödel. *Philosophy of Science*, *37*(4), 589–601.
Stein, H. (1991). On relativity theory and the openness of the future. *Philosophy of Science*, *58*(2), 147–67.
Wald, R. M. (1984). *General relativity*. University of Chicago Press.
Weyl, H. (2009). *Philosophie der Mathematik und Naturwissenschaft*. 8. Auflage. Oldenbourg. [1966].
Yourgrau, P. (1999). *Gödel meets Einstein: Time travel in the Gödel universe*. Open Court.