Did time have a beginning?

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Abstract
By analyzing the meaning of time I argue, without endorsing operationalism, that time is necessarily related to physical systems which can serve as clocks. This leads to a version of relationism about time which entails that there is no time 'before' the universe. Three notions of metaphysical 'time' (associated, respectively, with time as a mathematical concept, substantivalism and modal relationism) which might support the idea of time 'before' the universe are discussed. I argue that there are no good reasons to believe that metaphysical 'time' can be identified with what we ordinarily call time. I also briefly review and criticize the idea of time 'before' the big bang associated with some recent speculative models in modern cosmology, and I argue that *if* the big bang model is a (roughly) correct description of our universe, then the best current answer to the question in the title is that time did have a beginning.

1. Introduction
According to the standard big bang model of cosmology, time began together with the universe in a singularity approximately 14 billion years ago. In this framework the popular question concerning what was before this 'big bang' is considered as meaningless as asking for what is north of the North Pole (see e.g. Hawking 1989, p. 69). However, not everybody agrees with this verdict. Various speculative scenarios in recent theoretical cosmology, associated with string theory or some versions of inflation, appear to indicate that the big bang singularity can be bypassed and thus that one may meaningfully ask what happened before the bang. Also philosophers have questioned the implications that big bang cosmology may have for time's beginning. For instance, Smith (1998, p. 135) argues that "...a correct, non-verificationist, philosophical part of physics implies that [...] there is time before the big bang, [and] that past and future time are infinite...". Lucas (1999, p.15) provides another, if more agnostic, example: "The mere fact that the universe had a beginning does not of itself constitute a beginning of time too. Time may have begun then, or may have begun earlier, or may have been beginning-less".

But what are the presuppositions behind this debate of whether there is a 'north pole' for time? The scientific part of the question obviously depends on whether the standard big bang cosmological model is at least roughly correct – i.e. that the universe is expanding from a hotter and denser state in the past. While this may be questioned, I shall here leave such doubts aside. In both physics and philosophy the key presupposition in the debate concerns what exactly time is taken to be – and in particular what the *meaning* of time is. For instance, if time means something over and above what it means in specific cosmological models, then there might not be problems in contemplating earlier times than the big bang. If the opposite is true the time concept of these models must be taken into account in order to answer the question of time's beginning.

Broadly speaking, there are three ways to have time before the big bang. For the purposes of this paper I have already excluded the first which is to assert that, current evidence to the contrary, the big bang model could be false and thus it could be that there was no earlier hotter and denser state in the past, no big bang, and no corresponding beginning of time. The second way is to hold that the model of standard cosmology could be embedded in a larger cosmological model, e.g. a cyclic model of big bangs and big crunches, which allows for time before the big bang (by using the time concept of the larger model). The third way is to argue that the time concept of the big bang model (or some larger model) leaves unchanged a more fundamental, or metaphysical, time concept which may be invoked before the bang.

I shall in this paper consider three versions of metaphysical time – all of which may be argued to have some initial intuitive plausibility. The first is to conceive of time in mathematical terms as being isomorphic to, or essentially characterized by, the real number line or some other mathematical structure, e.g. part of a four dimensional differentiable manifold. The second version, often related to the first, is container (or substantival) time which holds that time is like a container which exists independently of the content of the universe (and, in some versions, even independently of the universe itself). Thirdly, one might invoke counterfactuals to argue that even if our actual world (and time) began with the big bang event at a specific time in the past, it might have begun earlier – and thus there are possible worlds in which there is time before the big bang. This 'counterfactual time' might then give meaning to (metaphysical) time before the big bang.

In the following, I first (section 2) defend the view – which should not be confused with operationalism – that in both ordinary practical language and scientific language the meaning of time is necessarily bound up with physical systems which can serve as clocks.[1] This investigation of the meaning of time is followed in section 3 by a brief analysis and critique of Newton's absolute time concept. In section 4 I argue that none of the metaphysical time concepts mentioned above give a satisfactory account of time. In section 5 I briefly review and criticize the time concept associated with some speculative cosmological models (e.g. associated with string theory) which attempt to extend the big bang model and allow for time before the big bang. Finally, in section 6, I briefly sum up my conclusions.

2. The meaning of time

It has been known at least since St. Augustine that it is hard, if not impossible, to give a *reductive* definition of time in terms of other concepts that are themselves independent of time (see e.g. Gale 1968, pp. 3-4). For instance, operationalism, 'time is what a clock measures', is ruled out as a reductive definition, since one cannot specify what a clock (or a measurement) means without invoking temporal notions. Also it seems difficult to provide a meaning of time via a referential theory of meaning, assuming e.g. that 'time

[1] While the present work provides a systematic treatment and defence of this relation between time and clocks, it is discussed elsewhere as well. In Rugh and Zinkernagel (2008) we examine (a slightly different formulation of) the time-clock relation in connection with a detailed critical discussion of the physical assumptions involved in setting up the standard model of cosmology. In Zinkernagel (2008) the time-clock relation, in conjunction with a relation between clocks and causality, is used in an argument against Hume's scepticism about the future validity of causal laws and tomorrow's sunrise

is (or means) whatever it corresponds to in reality', since one cannot point to or specify what this referent might be (or at least, as I shall discuss below, one cannot do this unless the referent somehow involves clocks).

The difficulties in providing a meaning (or definition) of time point to the common intuition that time is a fundamental, e.g. irreducible, concept. Nevertheless, even if we cannot define time, it is clearly the case that we use and understand the concept without problems in most situations in both ordinary practical language and physics. It seems to me that for time – and possibly also for other fundamental concepts – the only viable alternative to operationalism and referential theories of meaning is some version of Wittgenstein's idea of meaning as use. Of course, 'meaning' is a contentious notion in contemporary philosophy. Without in any way pretending to give a complete theory of meaning, I here assume that a (fundamental) concept is meaningful only insofar as we know something about how the concept may and may not be used.[2] In particular, we need to know something about the concept's relations to other concepts.

Consider the following examples from ordinary practical language in which we are concerned with – as far as possible – unambiguous communication: "The football match lasts 90 minutes"; "The elections took place three years ago"; and "She graduated before she was married". Despite the changes in our conception of time brought about by modern physics (in particular, the theories of relativity), these statements have natural analogues in the language of physics, for instance: "The life-time of the particle is 15 minutes"; "The solar system was formed 4.5 billion years ago"; and "The detector was ready before the electron was emitted". The meaning of these expressions – and a multitude of other expressions involving time in ordinary language and physics – is usually non-ambiguous since the 'time of the event' or the 'amount of time' can be identified by referring to some physical system which serves as a clock. Thus, for instance, "three years ago" can be understood in terms of the earth having completed three revolutions around the sun. An unambiguous meaning to such temporal expressions can also be achieved by reference to what may be called 'counterfactual clocks', that is, possible but not actual physical systems which serves as clocks – this is, for instance, one way to justify how we can unambiguously speak of years also before the formation of the solar system.[3] In fact, it is not clear that the expressions involving temporal notions mentioned above would have a well-defined meaning at all if such means of referring were not presupposed. For instance, how should "3 years" be understood in a sentence like "3 years passed, yet no physical process took place (or, counterfactually, could have taken place) at all"? If reference to physical (clock) processes is not presupposed then how is such a statement to be distinguished from a similar one involving 4, 5 or any other number of years (see also section 4)?

As mentioned above clocks cannot (reductively) define time since any analysis of what a clock is and does will at some point involve temporal notions. This suggests that the following *time-clock relation* – implicitly or explicitly – underlies our use of the time concept:

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[2] Cf. also Weissman (1968, p. 56): "Indeed, if anyone is able to use the word correctly, in all sorts of contexts and on the right sort of occasion, he knows 'what time is' and no formula in the world can make him wiser".

[3] As we shall discuss further below, the relevant modality here is physical – that is, a physical system serving as a clock (e.g. the Earth revolving around the Sun) is possible if its existence is allowed by physical laws.

There is a logical (or conceptually necessary) relation between 'time' and 'a physical system which can serve as a clock' in the sense that we cannot – in a well-defined way – use either of these concepts without referring to (or presupposing) the other.

I emphasize that this is not an attempt to analyze the time concept in terms of something more fundamental but rather a thesis saying that time and physical systems which can serve as clocks cannot be defined independently of one another. Although formulated as a relation between concepts, the time-clock relation reaches beyond the conceptual level (hence the term 'logical relation').[4] For instance, the relation is also meant to capture the idea that the use of the time concept *refers* to (possible or actual) existing clocks – and in this sense the use of the time concept presupposes both the existence and the concept of clocks (see also below).

What physical systems can serve as clocks? Broadly speaking, any physical system undergoing change.[5] A change in a physical system, however, may correspond to just one process – like a single glass falling from the table to the floor – and although such a 'clock' may provide an unambiguous meaning to statements such as "before/after the glass shattered" or "the time it took the glass to fall", its usefulness is clearly limited. Indeed, depending on the temporal statement in question, more than mere change may be required of the physical system. For typical duration statements, a physical system can serve as a clock if it undergoes a (more or less) regular, constant or repetitive, process, which determines (more or less) equal time intervals.[6] The qualification 'more or less' is included here since, as has been known throughout clock-making history, some clocks are more regular than others. However, this insight obviously makes sense only if we can somehow compare a specific clock with a more regular one, and/or if we can give theoretical reasons as to why a specific clock is irregular (see section 3). Since clocks involve physical change, the time-clock relation leads to a version of relationism about time in the tradition of Aristotle and Leibniz (although the relationism implied here is non-reductive and differs somewhat from what Aristotle and Leibniz defended, see Rugh and Zinkernagel (2008, section 2.2)).

The main question addressed in this paper is whether there was time (whether time existed) before the big bang. It is therefore necessary to know what 'time exists' (and 'time does not exist') means. In our context, this question is clearly most interesting if it is presupposed that time *does* exist after the big bang. Thus, various traditional senses of 'time does not exist' – e.g. associated with Kant's idea of the ideality of time, or McTaggart's denial of time's existence – seem irrelevant here (see however below).

If it is true that our use of temporal notions is of necessity bound up with reference to (actual or counterfactual) clocks – or, more precisely, reference to possible

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[4] The notion of logical relations between concepts, which may be seen as a kind of implicit definitions, is inspired by P. Zinkernagel (1962).

[5] Since my interest here is in the time concept employed in ordinary practical language and physics, I shall (almost) disregard psychological, poetic or religious uses of the term. As concerns our psychological notion of time (associated with changes in mental states) I here assume that mental changes are somehow correlated with physical changes.

[6] Note that the concepts 'constant or regular process', and of course 'equal time intervals' refer to time – illustrating again that the concepts of 'time' and 'clocks' are interrelated but not reducible to one or the other. One may speak also of 'order' – as opposed to 'metric' – clocks which can only determine earlier/simultaneous/later relations, and in this sense the clocks need not necessarily be capable of determining equal time intervals. The clocks of ordinary life also include some kind of counter (e.g. a clock dial) to register the increments of time. I am here only interested in the first (core) component of a clock, namely the physical process in the clock's interior (see also below and Rugh and Zinkernagel 2008).

physical systems which can function as clocks – and if it is true that no (clock-independent) referent for time can be specified then it would seem that both the *meaning* of (the concept) time and the *existence* of time depend on clocks. This idea of an ontological reading of the time-clock relation is reinforced by the fact that it is difficult to say what 'time exists' means, since existence in ordinary language and physics is usually understood as existence *in* space and time. By contrast, actual (or counterfactual) clocks do (or could) exist in space and time, so time's existence can plausibly be understood as being dependent on the existence (or possible existence) of clocks. On this account, the question of whether there was time 'before' the big bang translates into the question of whether clocks (physical systems undergoing change) existed or could have existed 'before' the big bang. In sections 4 and 5 I argue for a negative answer to this question.

In what follows I shall consider two related types of objections to the time-clock relation and, in conjunction with big bang cosmology, the implication that time had a beginning. The first type of objection holds that the (necessity of the) time-clock relation is implausible as it stands. One such objection is that the time-clock relation appears to lie close to an unsustainable operationalist (or verificationist) account of time. For instance, as hinted in the introduction, Smith (1998) suspects that arguments purporting to show that time began with the big bang rest on flawed verificationist theories of meaning. But the time-clock relation is not an expression of operationalism ('time is what a clock measures') since clocks cannot define time. Moreover, the time-clock relation departs from the operationalist doctrine in at least three important ways: (i) both within Newtonian and modern physics, the time-clock relation provides meaning to a kind of absolute time via ideal, or perfectly regular, clocks (see section 3). One cannot, of course, measure on such clocks since they do not exist; (ii) the time-clock relation allows (to a certain extent, see sections 4 and 5) reference to counterfactual clocks – whether perfectly or imperfectly regular; and (iii) the time-clock relation is satisfied if reference can be made to some physical process (the 'core' of a clock), or a succession of such processes. It does not rely on any counter mechanism that could transform this (or these) physical process(es) into a real functioning clock by actually 'measuring' time.

Another objection of the first type attempts to undermine the idea that the time-clock relation – and hence the necessary relation between time and change – is the right conclusion to draw from an analysis of how we (learn to) use temporal concepts. For instance, Le Poidevin argues:

> It is clearly true that we acquire temporal concepts in a context of change. [...] What is not at all obvious is that temporal concepts are therefore inextricably linked with the idea of change. We can, after all, abstract the idea of a time from the particular events that occurred at that time. [...] ...if I can imagine a time without being obliged to think of it as being filled by the very events that did happen then, why can I not think of it as filled by *no events at all?* (Le Poidevin 2003, p. 21)

This argument proceeds from the idea that, counterfactually, other events (and other changes) than the actual ones might have occurred in a period of time to the idea that perhaps no events occurred at all. However, by speaking of time as being "filled" with events, Le Poidevin assumes that time is like a container for (possible and actual) events. This takes us to the second type of objection which holds that whatever the conceptual and/or epistemic relation between (physical) time and clocks might be, such a relation cannot exclude (metaphysical) time before the big bang – e.g. because (metaphysical) time *does* have a referent, such as the container, which is independent of clocks.

In general, this second type of objection asserts that whereas the *conceptual* reading of the time-clock relation might be plausible (so that e.g. one cannot possess the time concept without possessing the clock concept and vice versa), the inference to an *ontological* reading (time cannot exist without clocks and vice versa) is unwarranted. A version of this objection can be found in Teichmann (1993). From an analysis of our use of the time concept, closely in spirit to the one presented in this manuscript, Teichmann argues in favour of a constitutive connection between time and clocks since the paradigmatic circumstances for ascribing temporal duration to some process are, or at least include, circumstances in which a (true) clock would give a reading of the duration in question. Nevertheless, Teichmann maintains that temporal duration can be meaningfully ascribed also to situations in which no clock (and no clock readings) could exist – as it may be physically impossible for the clock to do its job. For example, even if no clock can exist in the vicinity of some particularly violent explosion, it is surely reasonable to assert that the explosion took a definite amount of time.

However, I think Teichmann assumes a clock concept which is unnecessarily restrictive. As indicated above, no real functioning clock seems to be needed in order to give duration statements an unambiguous meaning. Indeed, the time-clock relation suggested above easily accommodates Teichmann's example of a violent explosion since such an explosion is in itself a physical process which may be seen as the 'core' of a physical system which can function as a clock.[7] On my view, then, the fact (if it is a fact) that temporal concepts can be applied in situations (such as violent explosions) where real functioning clocks cannot work does not imply that temporal concepts can also be applied in much more extreme situations – such as 'before' the universe came into existence – where no processes in physical systems can take place at all. In any case, I take it that any account of time which implies that (metaphysical) time can exist independently of clocks (or, rather, independently of possible physical system which can function as clocks), ought to explain what this existence amounts to.[8]

In the following sections I shall review and criticize three possible accounts of metaphysical time: mathematical time, container time, and counterfactual time. My main complaint about these accounts starts with the observation that the logical, or conceptually necessary, relation between time and clocks (change) is extracted from ordinary practical language and scientific language – and that it encapsulates the use of our 'ordinary' time concept. If metaphysical time is something else (which can be

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[7] For instance, it makes sense to say 'the amount of time given by the explosion' or speak of 'before or after the explosion'.

[8] In an influential paper, Shoemaker (1969) argued that time without change is possible, that is, that one can think of situations (e.g. a total freeze of some fantasy world) where the time concept can be meaningfully applied without referring to any change. Shoemaker's argument may perhaps be seen as another instance of the second type of objection to the time-clock relation (since duration statements in Shoemaker's fantasy world appear to be specified in terms of clocks, cf. 1969, p. 370). However, although I cannot here argue the point in detail, I think Shoemaker's argument fails as no satisfactory account is given of what time, and specific time intervals like a year, means 'during' a putative total freeze in his fantasy world. Candidates would include "time is what a clock would have measured had the world not been frozen". But since, by hypothesis, no clock can operate 'during' a total freeze, the only option for explicating this counterfactual definition seems to be to appeal to other (nearby) possible worlds in which no total freeze (but only, say, an almost total freeze) is taking place. However, as will be discussed in the section on 'counterfactual time' below, it is questionable whether times in different possible worlds can be identified (and thus, it is questionable whether one can say that time has passed 'during' a total freeze).

independent of clocks) – we need an account of what the relation to our ordinary concept of time is. I will suggest that a satisfactory version of such an account cannot be (or, at least, has not yet been) given, and that, therefore, there are no good reasons to identify 'metaphysical time' with time.

3. Newtonian time

As a preliminary to the various possibilities of a metaphysical time it is helpful to consider Newton's idea of absolute time which apparently allows for time before the universe. For instance, Craig writes:

> ...the fact that physical time (and space) had a beginning in the Big Bang does not automatically carry with it the conclusion that time itself began, given the distinction drawn by Newton between absolute time, God's time, and our physical measures of time. It is quite easy to conceive of God's existing temporally prior to the Big Bang in a metaphysical time, perhaps busy creating angelic realms. (Craig 2001, p. 20)

Whether it is "quite easy" to conceive of such heavenly activities prior to the big bang, however, depends on what exactly is to be understood by absolute time, and – in particular – what its relation to our usual notion of (physical) time is supposed to be. In *Mathematical Principles of Natural Philosophy* from 1687, Newton put forward his famous distinction between true and apparent time:

> Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year. (Newton 1729, p. 6)

At first sight, Newton's absolute time stands in stark contrast to the time-clock relation formulated in the section above. But how precisely should this absolute time be understood? Worse still, is this absolute time at all intelligible? It is very hard, if not impossible, to specify the meaning of 'flow' (or 'equable flow') without relation to anything external (see also Whitrow 1980, p. 33). Indeed, 'equable flow' involves ideas like steady or uniform motion, which more than suggests a reference to the motion of a physical system, and which makes little sense without a specification of 'steady/equable with respect to what?'. This problem indicates that it might be more advisable for a Newtonian to reject the flowing of time e.g. by opting for a 'B-theory' of time according to which there is no 'moving now'.[9] But even if one were to dispose of time's flowing, there is still the question of what should be understood by absolute time.

Newton's identification of absolute time and mathematical time could indicate that we should somehow understand absolute time in a purely formal way – for instance as being essentially characterized by the real line or some more complex mathematical structure. Another option, also entertained by Newton, is to conceive of time (and space) as some sort of container in which physical objects and events can be placed. As

[9] Alternatively, or additionally, one may try to reinterpret 'time's flowing'. For instance, Earman (1989, p. 7-8) holds that time's flow should be read as absolute simultaneity, absolute duration, and there being an intrinsic (e.g. independent of clocks) temporal metric.

already announced, however, I shall attempt (in the next section) to argue that neither mathematical time nor container time provides a satisfactory account of time.

As Craig mentions, a third possibility for understanding absolute time is to identify it with 'God's time'. However, while Newton's assertion in the General Scholium that "He [God] constitutes duration [absolute time]" may perhaps satisfy some theological needs, it is far from clear what precisely it means. This makes it hard to judge what, if any, relation 'God's time' bears to our usual concept of time. By contrast, the notions of mathematical time and container time both have some initial intuitive relation to our usual concept of time (and our use of this concept). Indeed, we can and do count time, and we can and do speak of how events are located *in* time. But, as far as I can see, there are no comparable intuitive grounds for relating 'God's time' to our time, so I shall in the following leave out this possibility for a metaphysical time.

Before turning to the arguments against mathematical and container time, it will be instructive to ask whether such arguments – if convincing – will render Newton's absolute time useless in practice as e.g. Whitrow (1980, p. 34) suggests. Not necessarily. As noted above, 'equable flow' suggests 'uniform movement' and this notion is specified in Newton's first law of motion and refers precisely to the motion of physical systems (a freely moving particle may serve as an ideal clock). Now, as Newton himself notes in the Scholium, there might not be any real systems in uniform motion (e.g. due to friction and the universality of gravitational attraction) – hence uniform motion is an idealization. But just as Newton's 'common time' refers to real physical systems which can be used as clocks, so his absolute time can be seen to refer to idealized physical systems which can be used as perfect clocks, such as a free particle in uniform motion.

This understanding of absolute time is supported by the fact that the closest practical realization within Newtonian physics of absolute time is *ephemeris* time – the time calculated from the observed positions of the moon and the planets assuming that Newton's laws are exactly valid. In this way the solar system as a whole is used as a clock.[10] As Barbour (1999, p. 107) notes, an important fact about ephemeris time is that "...it exists only because the solar system is well isolated as a dynamical system from the rest of the universe". This implies that if one were tempted to make an exact identification of absolute time with ephemeris time one would have to make the idealization involved in treating the solar system as *completely* isolated from the rest of the universe.[11] If sufficiently is known about the sources of non-ideality of a clock (e.g. if we know about how the rest of the universe affects the motions of the solar system in the ephemeris clock, or know about the irregularities involved in the sideral clock given by the earth's rotation), theoretical considerations can in principle be used to extract, or abstract, an absolute time from any clock. This same idea is what allows us to say that even the best atomic clocks are slightly inaccurate – because we know something about what uncertainties and errors are involved.

As Grünbaum (1977, p. 310) notes, on Newton's view clocks *at best* provide epistemic access to time intervals, and clocks play no ontologically constitutive role for

[10] Both free particle motion and ephemeris time are connected to the idea of an implicit definition of (absolute) time via laws. As discussed in detail in Rugh and Zinkernagel 2008, section 2.1, such implicit definitions of time via laws – as illustrated by ephemeris time – make essential reference to physical systems which can function as clocks and hence an implicit definition of time via laws is in conformity with the time-clock relation.

[11] In practice, there are more idealizations involved in the identification – e.g. connected to general relativistic corrections and limited observational accuracy of the positions of the solar system bodies, see e.g. Audoin and Guinot 2001, p.46 ff. (ephemeris time actually served as the official astronomical time standard in the 1960s before the advent of atomic clocks).

such intervals. I would add that, unless we construe absolute time as just sketched (i.e. conceptually dependent on ideal clocks), it might as well be that clocks *at worst* bear no relation to absolute time at all. In other words my claim is that either we understand Newton's absolute time as what an idealized clock would measure or we cannot – if my arguments against mathematical and container time below are successful – ascribe it a well-defined meaning or use. In particular, we can give no compelling reasons to call 'absolute time' time if it cannot be related to our usual notion of time (i.e. via the relation between real and ideal clocks). By contrast, if Newtonian absolute time is understood as suggested here then this time does refer to clocks and thus conforms to the time-clock relation from section 2.

4. Metaphysical time

In this section I shall analyze three metaphysical time concepts which – at first sight – allow for a time before the big bang: mathematical time, container time and counterfactual time.

Mathematical time

The idea of a mathematical time which might be independent of physical states of affairs derives its appeal from the fact that time is often represented mathematically. Some authors, for instance Kant, have thought that the representation is of a specific form, for example that time is isomorphic to the real number line (see e.g. the critique of Kant's argument in Newton-Smith 1980, p. 101). After the advent of the theories of relativity, the mathematical representation of time is usually given as part of a four-dimensional manifold or as part of such a manifold and a metric tensor (see e.g. Hoefer 1996).

The proponent of mathematical time as a metaphysical time which is before the big bang will presumably hold that that the representation (to which time is isomorphic) somehow 'goes beyond' the representation of time used in the big bang model of cosmology. As we shall see in section 5, the time concept in the classical big bang model may be represented by the positive part of the real number line (under the assumption that the universe expands forever), where the big bang corresponds to $t = 0$. Thus, a time concept extending beyond that of the big bang model could be represented, for instance, by the whole real line (including negative numbers).[12] However, Newton-Smith has issued a sound warning about using such ideas in arguments for time's non-beginning or for time 'before' a first event:

> We often label moments at which events occur by elements of some number system. [...] As the number sequence itself can be further extrapolated we are seduced into thinking that there must be times corresponding to these numbers. However, the extrapolation within the representing system does not guarantee that those extrapolated elements of the system have referents. (Newton-Smith 1980, p. 102)

But why, precisely, should the isomorphism between time and, say, the real number line be resisted? In other words, how should we decide what the best or correct representation of time is? To answer these questions, we will have to look a bit closer

[12] Note that there are mathematically trivial ways of changing a representation from that of the positive real line to that of the whole real line, e.g. by using the transformation $t \rightarrow \log(t)$. Such transformations, however, cannot in any relevant sense be used to address times 'before' the big bang.

on the relation between time and mathematics (see also the discussion in Whitrow 1980, chapter 4).

The fact that our usual notion of time can be associated with a formal (mathematical) structure originates in time being related to physical systems, e.g. as when we count the number of sunrises, rotations of wrist watch hands, or vibrations in a cesium atom. As mentioned in section 2, it is this association to physical systems which is used to give unambiguous meaning to statements involving time, e.g. statements about how long time an event lasts or how events are temporally related. By itself this situation undercuts the idea that time is essential characterized by a mathematical structure.[13] Furthermore, the meaning of time can be underdetermined by a formal mathematical structure. For instance, while we may represent time mathematically as the real line we cannot, given just the real line, know that we are talking about time. Indeed, spatial dimensions (as well as a host of other physical quantities) can also be represented by the real line.[14] It would seem that there must – therefore – be more to time than just mathematics (and hence time cannot be essentially characterized by a mathematical structure). What should this "more" be if not something physical?

Within the context of the general theory of relativity, the representation of time (as part of a manifold or a manifold plus a metric tensor) is indeed associated with more than just mathematical notions. Thus, these representations of time are usually understood within a substantivalist picture according to which time is part of a space-time 'container' in which physical objects and processes are (or may be) embedded in accordance with physical laws. Once a 'container' for physical objects and processes is introduced, we have left a purely mathematical notion of time, and the notion of mathematical time thus drifts into 'container time' (see below).

The idea of time as isomorphic to (at least a segment of) the real line is a cornerstone of modern science. In particular, the laws of nature (e.g. equations of motion) in both classical, relativistic, and quantum physics are formulated in terms of a continuous 'time' parameter. However, the all pervasive use of mathematics in physics should not obscure the fact that mathematical models (e.g. sets of differential equations) and concepts are not automatically endowed with physical meaning. Specifically, as I shall discuss further in section 5, to interpret the t parameter of a supposed cosmologically relevant mathematical model as *time*, it must be possible to establish a correlation between t and a physical system which can serve as a clock, and, moreover, the physical conditions for setting up the model must be satisfied.

For the proponent of mathematical time 'before' the big bang, it remains an option to hold that even if time is correlated with clocks in some intervals of the real line, it might still be the case that one could extrapolate the time concept into other intervals (where no clocks were available – e.g. before the universe). This option will be analyzed and criticized in section 5 below.

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[13] Cf. also the algebraist Cayley in his Presidential Address to the British Association in 1883 (quoted from Withrow 1980, p. 176): "It appears to me that we do not have in Mathematics the notion of time until we bring it there"

[14] Underdetermination type arguments have also been put forth within the context of the general theory of relativity: As noted e.g. by Hoefer (1996, p. 11) there is nothing inherent in a mathematical manifold which distinguishes space and time (and so it is unclear how the pure manifold could somehow be the 'representator' of time). Grünbaum (1977, p. 356-357) has argued that the formal properties of the $g_{\mu\nu}$ (gravitational) field in general relativity are insufficient to determine that this $g_{\mu\nu}$ field is *also* the metric tensor of space-time (rather, Grünbaum suggests, this role is only secured by making reference to the behaviour of external metrical standards like rods and clocks).

Container time

According to the doctrine known as substantivalism, time (and space) is a kind of container in which physical objects and events are placed. This container would still exist even in the absence of physical objects and events. In the context of Newtonian physics the universal history unfolds within the (space-)time container so even if there is a beginning of the universe (a moment at which physical objects and events appear) this will not imply a beginning of time.[15] The one-dimensional container then provides a referent for time – with individual times somehow corresponding to 'slots' in the container.

There are at least two questions, however, which should be addressed in order to determine whether container time is a satisfactory account of time which distinguishes it from mathematical time and allows time before the big bang: (i) can the (time) *container* be characterized in non-mathematical terms?; and (ii) can the *existence* of the container be characterized in non-mathematical terms?

As concerns (i) it seems that many, if not most, of the properties the substantivalist could ascribe to the container are indeed mathematical (topological) – such as 'being one-dimensional', 'being linear' or 'being continuous'. This is in line with Kant's mathematical conception of time:

> We represent the time-sequence by a line progressing to infinity, in which the manifold constitutes a series of one dimension only; and we reason from the properties of this line to all the properties of time with this one exception, that while the parts of the line are simultaneous the parts of time are always successive (Kant 1965, A33).

The "one exception" is of little help to the substantivalist (who wants to defend non-mathematical properties of the container) since it is in need of further explication insofar as both 'simultaneity' and 'succession' are usually taken to be themselves temporal notions.[16] However, as suggested above, there is at least one property of the container which is non-mathematical – namely that of being (possibly or actually) occupied by physical objects and events. But if this is the distinctive non-mathematical property of the container then this distinctive property clearly depends on (actual or possible) physical objects and events. In that case it becomes difficult to separate the substantivalist position from that of the relationist who insists that time must be understood in relation to physical objects and events (the reference to *possible* physical objects and events means that the relationism will have to be of a modal type – see below).[17]

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[15] By contrast, within the context of general relativity, modern substantivalists may well agree, insofar as they assign the metric tensor a role in representing (space and) time, that there can be no time 'before' the universe (before the big bang). This is so since physically interesting space-times (metric tensors) are confined to those – like the one underlying big bang cosmology – which satisfy Einstein's equations, and since the metric of the big bang model cannot be extrapolated back (there is no container) 'before' the beginning of the universe; see e.g. Earman 1977 and below. I shall not here take issue with this kind of substantivalism (see however the discussion in Rugh and Zinkernagel 2008, section 2).

[16] Kant's theory of time – which is not substantivalist – is too complex to be considered here in any detail. I should note, however, that Kant's central claim that "time is nothing but the inner sense [...and] the formal a priori condition of all appearances" cannot allow for time before the universe (even though this is a presupposition of both horns of Kant's first antinomy, see e.g. Newton-Smith p. 101) *if* we assume that minds (and their accompanying bodies) appeared *after* the universe came into existence – since, on Kant's account, there cannot be time without minds (and hence not *before* minds).

[17] It is a matter of debate whether relationism is compatible with an empty universe without any actual physical objects or events (or whether, rather, such a universe would make substantivalism and

With respect to (ii), concerning the postulated *existence* of the container, the question is in what sense it is supposed to exist (independently of physical objects and events)? In both ordinary practical language and physics, existence is usually taken to be existence *in* space and time. Clearly the container does not exist in this sense as it is supposed to *constitute* (space and) time. Existence as a mental phenomenon will not do either. For this would violate the minimal realist assumption that physical objects and events (in the container) exist objectively – i.e. in space and time *and* independently of mental state of affairs (as noted earlier, I assume that minds and their accompanying bodies appeared after the universe came into existence).[18] It therefore seems difficult to describe the 'mode of existence' of the container in non-Platonist (non-mathematical) terms.

This brief discussion suggests that container time either collapses into a version of mathematical time, or that it makes essential reference to (possible or actual) physical objects and events – and thus it cannot be said to exist independently of these objects and events. In the first case, we again need an account of how container (mathematical) time is related to our usual notion of time. In the latter case, container time cannot be used to contemplate time before the big bang since there cannot be (possible or actual) physical objects and events without the universe. Or, at least, container time cannot be so used unless the modality involved in the reference to 'possible' physical objects and events is understood as non-physical (see next subsection).

Just as it is often useful to speak of time in mathematical terms, my argument in this subsection is not that it is wrong to speak of events and things as being *in* time. All I question is the inference from the fact that we can and do speak of physical things and events in time to the conclusion that container time can be characterized as being independent of such things and events.

Counterfactual time

An attractive feature of relationist positions – such as the one defended in this paper – which tie time to (physical) change is that it makes the question of the beginning of time more tractable. Thus, if time is dependent on change, and there is no change 'before' the universe, then there is no time 'before' the universe. Modal relationism threatens this attractive feature since if time merely depends on the possibility of change then it *might* be reasonable to contemplate time before the universe. In fact, some authors take it to be straightforward that counterfactuals license talk about time before the universe. Thus, for instance, Smith writes:[19]

> For example, some mathematical proposition's property of *being true for a year* does not require that the earth revolve once around the sun; it entails merely that the proposition is true for an interval of time that would be occupied by the earth revolving once around the sun, if there were to exist such an earth and sun. Such counterfactuals enable us to talk

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relationism indistinguishable, cf. e.g Earman 1989, p. 135). In the context of big bang cosmology we can sidestep this question since – as noted in footnote 15 above – there is no container 'before' the beginning (and thus there is no empty universe waiting to be populated 'before' the big bang).

[18] Again, this assumption might be denied on dualistic and/or theological grounds, e.g. by holding that minds (or some supreme mind) are independent of bodies and eternal. But this would – at least – require a convincing account of how minds and/or God exist, and how this existence relates to our usual notion of time.

[19] A similar idea about time before a first event was formulated already by Locke in 1689 – see e.g. Van Fraassen (1970, p. 27). Another example of using counterfactuals to address time before the big bang can be found in Lucas (1999, p. 15).

> about hours, years, etc., prior to the big bang, even if there exist only abstract objects [such as sets or numbers] before the big bang. The truth-makers of these counterfactuals are some possible worlds that are the most similar in the relevant respects to the actual world. (Smith 1998, p. 112)

The notions of an "interval of time that would be *occupied by* the earth...", and that of existence of "abstract objects before the big bang" suggest that Smith is holding a container (and a mathematical) conception of time. But – assuming that my arguments against purely mathematical and/or container-like notions of time above are successful – the interesting point here is whether the addition of a modal relationist component allows us to speak of time before the universe.

One way to understand the counterfactual construction is that even if the universe began with a specific event, e.g. a flash of light, at some point, it might counterfactually have begun at a different point, and in this sense there are possible worlds in which there is time (and events) before our actual universe comes into being. The first thing to note is that the mere *possibility* of time 'before' the universe hardly qualifies as establishing the *actuality* of time before the universe, cf. also Newton-Smith (1980, p. 45 and 104). This point can be strengthened by taking a closer look on what kind of modality is involved in positing counterfactual objects (e.g. the earth) and events (e.g. the earth revolving once around the sun) before the big bang.

If physically possible is taken to mean, roughly, what is compatible with known physical laws, then the modality cannot be physical. Indeed, insofar as the known physical laws (including general relativistic laws with the big bang model as a special case) predict or 'retrodict' that the universe had a beginning, it is physically impossible to have objects and events, and therefore time, 'before' the big bang (since there cannot be physical objects and events without the universe). A related way to see that the modality cannot be physical is to note that since the physical laws break down at the spacetime singularity (infinite curvature), we cannot even address what would be physically possible 'before' the big bang (see however section 5). Presumably, then, the modality should be construed as metaphysical – i.e. we are somehow to compare our actual world with other metaphysically possible worlds. Consider two examples of such possible worlds:

(i) A possible world where the big bang occurred earlier. Suppose that I am right that we can exclude the Newtonian idea of the universe being situated in an absolute (container) time which is independent of the universe and its (possible) content. In that case the term 'earlier' must be understood as something like 'in this possible world longer time than in the actual world passes between the big bang and the appearance of the first philosopher' – say 16 billion years instead of the current estimate for our world of 14 billion years.[20] However, just as in our world, in this possible world there cannot be time before the big bang (of this world). And, presumably, the proponent of counterfactual time is not merely making the rather trivial claim that the age of the universe might have been different from what it is, but is instead claiming that there is time before the big bang – regardless of precisely how long time has

[20] This is even a physically possible world since no laws necessarily have to be changed: a rough estimate of the age of the universe is given by the present value of the inverse Hubble parameter (see e.g. Peacock 1999 p. 127). This parameter is a measure of the rate of the universal expansion, and its value is determined observationally. The value of the Hubble parameter can be taken to be part of the (contingent) boundary or initial conditions for the physical laws in our universe, and it takes no great leap of imagination to think of this value as being different from what it actually is.

elapsed since this bang. In any case, although 16 are greater than 14, there seems to be no good reasons to think that (parts of) the 16 billion year universe is *earlier* than our actual universe, and hence no good reasons to think that this possible world is suitable to make pre-bang counterfactuals true.

(ii) A possible world where the big bang never happened, for instance a world which is described by the steady-state model according to which there is no beginning of the universe (see e.g. Narlikar 2002, p. 318 ff). In this possible world, it would be pointless to ask the question of whether there was time before the big bang – because there was no such bang. But, conversely, could the conceptual possibility of a world without beginning allow us to speak of (actual) time before the big bang in our world? A central problem has to do with the meaning of "similar in the relevant respects" when evaluating claims (such as Smith's) about truth-makers for counterfactuals. For instance, on Lewis' theory of counterfactuals an important aspect of judging the similarity of possible worlds to the actual world is the extent to which they are governed by the same laws and the extent to which the facts of the two worlds agree up to a given time (Lewis 1986, p. 75). But since both the laws of the worlds are different (e.g. steady-state cosmology requires modifications of general relativity), and the temporal regions 'spanned' by these worlds are different, these 'similarity measures' do not point to the worlds being "most similar" as Smith's idea requires. In fact, since it is the very notion of time which is in question, it is not clear that (at least the latter of) these 'similarity measures' are even adequate to carry out the cross-world comparison, and hence determine the truth of the counterfactual in question.

It seems to me that the correct thing to say about either of these cases is that each possible world has its own time (Van Fraassen (1970, p. 99) makes a similar point on behalf of Leibniz's relationism), but that none of the possible worlds give us any right to talk about time before the big bang in our actual universe. Thus, it is one thing that we can easily imagine possible worlds without a beginning or with an 'earlier' bang – where earlier is to be understood as above. But it is quite another to affirm, as Smith does in the above quote, that these imagined worlds provide truth-makers to counterfactuals which enable talk of time before the big bang.

5. Time of a larger cosmological model

As mentioned earlier I assume throughout this paper that the present empirical evidence provides a good case for the big bang model being roughly correct (implying that the present universe has evolved from a hotter and denser state in the past). But if the big bang model is supported by the evidence, it would seem that larger (more encompassing) models could also be supported by the same evidence. For instance, Le Poidevin argues in his discussion of the (possible) beginning of time, that

> [t]he obvious similarity of the Big Bang and Big Crunch suggests that the Big Bang may itself have been the result of the collapse of an earlier universe. [...] Any evidence for the Big Bang will not therefore tell us whether or not it was truly the first event, or merely one of a never-ending series of such events. (Le Poidevin 2003, p. 76)

In fact, the current evidence suggests that we live in an ever expanding universe without a big crunch, so there is a sense in which the similarity between the bang and the crunch can be questioned. Nevertheless, this does not invalidate Le Poidevin's point when seen as an instance of the general thesis of underdetermination of theories by data. That is, if the standard big bang model is supported by the evidence, then so – it seems – is any larger model which coincides with the big bang for the past 14 billion years or so. However, there are reasons to resist the thesis of underdetermination in this case.

The first point to note is that it is questionable whether an embedding of the big bang model in a larger model will allow one to 'go through' the big bang singularity (in the cyclic model mentioned by Le Poidevin) and hence speak of time on the 'other side'. Thus, Earman has remarked:

> In the case of the spatially closed Friedmann universe, there are formal solutions to the differential equations governing the temporal behavior of the radius R of the universe which, if taken literally, would allow one to picture the universe as oscillating between the singular points where R=0 [...]. But here as elsewhere, one can be misled by taking a picture too literally, for [...] these mathematical solutions are purely formal. ...the "singular points" at which $R = 0$ can be represented only by sophisticated mathematical techniques [...]. Second, although continuity considerations can be used to help characterize certain aspects of singularities, they do not seem to provide a means of carrying us "through" the singularities and into "other" space-time regions on the "other side" of the singularities. (Earman 1977, p. 130)

Earman's analysis apparently takes place under the assumption that cosmic time is an aspect of some combination of a four dimensional manifold and the metric tensor (1977, p. 129 and p. 131) – and hence it assumes a mathematical and/or substantival (container) notion of time. On my view, it is necessary to ask not only whether the mathematical time (*t*) concept of the big bang model can be "carried through" the singularity – but also how the *t* concept of the larger model is related to our usual (physical) notion of time. To address this question it will be helpful first to ask the simpler question: How is the *t* concept of the big bang model related to our usual notion of time?

Time in the big bang model

In the framework of big bang cosmology, time is taken to be a parameter (*t*) in the Friedmann-Lemaître-Robertson-Walker (FLRW) model – which is a particular solution of the general relativistic field equations given certain assumptions of the matter-energy distribution in the universe.[21] As it stands, however, the FLRW model is just a mathematical model containing a parameter *t*. The identification of the *t* parameter with time is usually made in big bang cosmology by associating *t* with the time measured on a *standard clock* at rest in the co-moving frame (the reference frame at rest with respect to the universal expansion). In Rugh and Zinkernagel 2008 it is argued that a standard (metric) clock in cosmology is any physical process (or physical system undergoing change) which can be correlated with specific *t* intervals and thus identify specific epochs in cosmic history. In conformity with the time-clock relation, the association of *t* with standard clocks is necessary for the FLRW model to be a *physical* (even if idealized) model of the universe involving time, and not just a mathematical model involving *t*. For instance, the main empirical evidence in support of the standard model of cosmology – the Hubble law, the light nuclei abundances in the universe, and the

[21] This subsection is based on Rugh and Zinkernagel (2008).

microwave background radiation – are all interpreted (or associated with the model) via some standard clock.[22]

As we shall see below, it is instructive to ask how far back in t the $t \leftrightarrow$ time interpretation can be made within the big bang model. At first sight, it might be thought that even if it is granted that time is conceptually related to clocks, such clocks need not always be available (this would be a denial of the ontological reading of the time-clock relation mentioned in section 2). If this is so then early times could have physical significance in virtue of later clocks – even if no clocks are (or could be) available at these early times. For example, the $t \leftrightarrow$ time interpretation in the FLRW model receives empirical support at present, e.g. via the Hubble law. Once this interpretation is established one may then imagine to extrapolate the physical interpretation of t as far back as the mathematics allow, i.e. arbitrarily close to $t = 0$ or maybe even further back if one, pace Earman (1977), finds a way to 'go through' the singularity. Thus, the fact that the laws of nature governing the model (the FLRW metric, and more generally, Einstein's field equations) have empirical support – and cosmological relevance – in some t parameter range would be used to give meaning to time (via these laws) in other t intervals.

However, since the procedure involves the extrapolation of a physical conception of time by virtue of the FLRW model, it seems reasonable to require that the physical foundations for setting up the FLRW model are themselves not invalidated along this backward extrapolation. It is widely agreed that the FLRW model cannot be extrapolated below Planck scales and, accordingly, that the $t \leftrightarrow$ time interpretation cannot be made in the context of this model for t values below 10^{-43} seconds. The Planck scale limitation is inferred from the expectation that the space-time metric (because of quantum effects) fluctuates increasingly as the Planck scale is approached, and thus the (classical) time concept is gradually rendered invalid. This illustrates that a physical condition, namely that quantum effects may be neglected, can imply a limitation for the $t \leftrightarrow$ time interpretation. Indeed, except for the space-time singularity itself, there are no internal contradictions in the *mathematics* of the FLRW model (or classical general relativity) which suggests that this model should become invalid at some point, e.g. at the Planck scale. In Rugh and Zinkernagel (2008, section 3), it is argued that (at least some core elements of) rods and clocks are necessary for setting up the reference frame of FLRW cosmology – and hence that the, at least physically possible, existence of rods and clocks provides a *further* physical condition for extrapolating the FLRW model backwards in time, and not just in t. In particular, the notions of rods and clocks (and physical change) become highly suspect at the Planck scale (see also below).[23] There are thus good reasons to doubt that the $t \leftrightarrow$ time interpretation can be made all the way back to $t = 0$ (let alone further back!).

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[22] The Hubble law supports the idea of the expansion of the universe through a relation between the t parameter and the cosmic scale factor (which, for a closed Friedmann model, is equal to the radius of the universe). The change in the scale factor (the clock), in turn, is given physical significance via redshifted light (i.e. frequency changes in electromagnetic radiation monitors the expansion). The light nuclei abundances in the universe are compatible with a hot primordial origin of these elements when seen in the light of a relation between t and temperature (thus, temperature here acts as a clock). Similarly, the microwave background radiation is thought to be a consequence of a drop in temperature at an early time allowing for a decoupling between matter and radiation.

[23] In fact, the necessity of (possible) rods and clocks for setting up the FLRW model suggests that it might not even be possible to extrapolate the $t \leftrightarrow$ time interpretation all the way back to the Planck scale (unless speculative physics is invoked): current theories (the standard model of particle physics) indicate that the physical conditions no longer allow for (metric) rods and clocks when the FLRW model is extrapolated

Beyond the big bang model

In the beginning of this section I referred to a simple cyclic model (crunch, bang, crunch, etc.) which might allow time 'before' the big bang – *if* there is a way to extrapolate *both* the mathematical *t* parameter *and* the *t* ↔ time interpretation right through the big bang singularity. As we have seen, there are no good reasons to think that this can be done. But there are other speculative ideas in modern cosmology which propose to modify the big bang model in its very early stages so as to make the big bang model part of a larger model in which time might be beginning-less. These ideas – which I can here only comment on briefly – concern modifications of the big bang model either due to quantum gravity effects or due to inflation (or both).

As examples of the first class, some string theory inspired cosmologists have proposed that the Planck time limitation may indicate that the classical big bang singularity can be by-passed, and times earlier than the big bang thus meaningfully addressed.[24] Various problems confront such projects however. First, any version of quantum gravity is bound to change the notions of space and time, and – since no satisfactory theory of quantum gravity exists as yet – it is still far from clear what these changes will eventually amount to. For instance, it is unclear that any notion of time in preliminary theories of quantum gravity can even be identified (cf. the problem of time in quantum gravity, see e.g. Butterfield and Isham 2001). For this reason, it is not known whether or how the *t* concept of the FLRW model – let alone the standard clocks ensuring the *t* ↔ time interpretation – can be 'carried through', or even 'into', a quantum gravity 'epoch' where physics, and physical change, as we know it is supposed to break down. In particular, as mentioned above, the classical FLRW model is *not* valid when quantum gravity effects become important, and so the time concept of this model cannot be used to describe a quantum gravity 'epoch'.

Another example of a more encompassing model which might allow for time before the big bang has been suggested by some adherents of cosmological inflation. In general, inflation implies that the FLRW model is to be replaced by an exponential expanding phase, for instance (depending on the specific inflation model) when the FLRW model is extrapolated back to $t = 10^{-34}$ seconds. According to some of these models, e.g. the so-called chaotic inflation scenario, our universe is supposed to be just one inflating bubble in an infinitely bigger and older 'multiverse' – with each component expanding differently and having different physical laws, see e.g. Linde (2004, p. 430 ff). However, for this to provide time before the big bang an account is needed of how the time concept of the multiverse is related to the *t* parameter and time concept of the FLRW model – and, at least to my knowledge, such an account is still lacking.[25] Intuitively, the idea is that while 'our' part of the multiverse had a big bang approximately 14 billion years ago, other parts may have had their bang much earlier. But this idea faces a problem similar to that considered for counterfactual time above: just as it cannot be guaranteed that the time concepts of two (metaphysically) possible worlds are comparable – in the sense that it is meaningful to say that one part is earlier

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back to 10^{11} seconds, corresponding to the so-called Higgs transition before which the universe might become scale invariant (Rugh and Zinkernagel 2008, section 5).

[24] According to these ideas, the big bang is identified with the beginning of the expansion at the Planck scale. For a popular overview of pre-big bang cosmology (and the so-called ekpyrotic scenario – which is a modern string theory inspired version of the cyclic model) see e.g. Veneziano (2004).

[25] Providing such an account is not made easier by the fact that chaotic inflation relies on Planck scale physics (cf. e.g. Peacock p. 336-337) – and the scenario may therefore be susceptible also to the problems mentioned above concerning time in quantum gravity.

or later than another – so it cannot be guaranteed that the time concepts of two different parts of the multiverse are comparable. Perhaps the two time concepts can be made comparable by stipulating the two parts of the multiverse to be embedded in some 'grand' time container (in which the whole multiverse is encompassed). But given the difficulties of making non-mathematical sense of container time, this multiverse time should presumably be correlated with (physically) possible or actual processes somewhere within the multiverse. And insofar as each part of the multiverse is governed by different laws, these parts physically allow for different processes and will in this sense have different time concepts (e.g. different time scales).[26] How then should a 'super-cosmic' time for the multiverse as a whole be specified? Note that the situation stands in striking contrast to the underlying assumption in standard big bang cosmology according to which all standard clocks co-moving with the universal expansion obey the same laws and will agree on the same cosmic time parameter.

The insistence on a physical, and not just mathematical, basis for the time concept thus seems to exclude (at least presently) a license to talk about time before the big bang in the context of some more encompassing model. This conclusion is underscored by the fact that both quantum gravity and inflation-based multiverse ideas are highly speculative and so far without any empirical support.

6. Conclusion

In this manuscript I have argued that our usual notion of time – used in ordinary practical language and physics – is of necessity related to physical systems which can serve as clocks. With this in mind I have analyzed three notions of metaphysical time and concluded as follows: Time cannot *just* be mathematics, e.g. because time is underdetermined by formal mathematical structures. Time cannot be an independently existing container for objects and events, e.g. because the characteristics of a time-container will be either purely mathematical or conceptually dependent on objects and events. Modal relationism allows reference to counterfactual clocks but these clocks must be physically possible. Hence counterfactual clocks cannot be posited without (or 'before') the universe, and cannot therefore give meaning to 'counterfactual time' 'before' the big bang.

As concerns the theories of modern cosmology, I have argued that the time concept employed in the standard big bang model conforms to the necessary relation between time and clocks. By contrast, the 'time' concept employed in certain speculative (and more encompassing) cosmological models which might allow for time before the big bang does not seem to conform to this relation. Therefore, the 'time' concept of these models cannot, at least so far, be related to our ordinary notion of time.

I should emphasize that I take it to be perfectly reasonable and meaningful to speak of time both in mathematical, container, and counterfactual terms. Indeed, we often do speak of time in this way, for instance, when we *represent* time mathematically in physics, when we remember what happened *in* a given year, or when we consider what events *might have happened* if things had been different. What I do not think is that any of these metaphysical time notions (including any combination of them) can give a satisfactory account of time *independently* of physical systems which can serve as clocks. If this is true, then – if the big bang model is a roughly correct description of

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[26] In a similar manner, Svend E. Rugh has (in private communication) emphasized the difficulties in extrapolating physical concepts from our universe to other parts of the multiverse.

our universe at large scales – the current best answer we have to the question of whether time had a beginning is affirmative.

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