Beyond A-Theory and the Block Universe:
A non-circular derivation of "before", change, and local asymmetric time*

Daniel Saudek

Abstract:

This article proposes a "third way" in the philosophy of time beyond A-theory and the block universe, in which time is understood as a purely local phenomenon. It does so by starting with simple metaphysical assumptions about substances and their properties. Based on these assumptions, the notions of "before", of change, and of time as a local quantification of change can be derived non-circularly, i.e. without invoking temporal concepts. I then proceed to prove the irreversibility of local time by showing that the propositional content of the local past cannot be changed, since this would imply a contradiction, whereas that of the future can. Time's familiar asymmetric character, in particular the difference between the fixed past and the open or "branching" future, is therefore a non-illusory but purely local phenomenon. Such a model requires no past-present-future distinction valid for the entire cosmos, and is therefore consistent with special and general relativity. The article furthermore explores the implications of this model for the notion of an evolving universe.

1. Introduction

Ever since the advent of relativity theory, there has been an ongoing discussion on its implications for the philosophy of time. Unresolved questions remain, of which this article focuses on the following: Can a robust distinction between past and future be upheld, or is such a distinction illusory, or at least of no ontological significance? As conscious agents, we experience a clear difference between a determinate past, which can be neither changed nor revisited, and an open, "branching" future which can still be influenced. In everyday life, we tend to assume, as Aristotle did, that the truth values of propositions about the past are fixed, whereas propositions about the future have no truth values.[1] The existence of a mind-independent distinction between the past and the future, and of a global present which constantly changes, so that future events become present ones, which then become past ones, is the central tenet of the A-theory of time. The global present comprises events which are simultaneous, i.e. which happen at the same time. Hence, A-theory requires an ontologically privileged parameter *t* by which all events can be ordered. Only then can equivalence classes

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1 See *De interpretatione*, 19a,1-19b,4; and *Ethica Nicomachea,* 1139b, 6-11.

be construed which define the set of events occurring at any given time *t,* and hence also the set of events occurring now. B-theory, while denying that pastness, presentness and futurity are mind-indepedendent properties of events, likewise holds, at least in its classical formulation, that for all events, there is an objective fact about which events precede which, and which events are simultaneous. In other words, B-theory, like A-theory, assumes an ontologically privileged total ordering of all events. But, as is well known, special relativity theory undermines the notion of such a privileged ordering: it follows from the Lorentz transformations that, if an observer O' moves past another, O, at a fraction β of the speed of light, then the plane of simultaneity for O' has a slope β relative to the plane of simultaneity for O in a Minkowski diagram of flat spacetime.[2] Thus, the temporal ordering of spatially separated events is not absolute, but depends on the frame of reference. Special relativity therefore undermines not only A-theory, but also B-theory.

Can the intuitive view of time be reconciled with spacetime physics? The answers given in the contemporary literature about this question can be broadly divided into three types: "cosmic A-theory", according to which there is a global now, i.e. a past-present-future distinction valid for the entire cosmos; the block universe, according to which there is no such distinction of any mind-independent significance; and a small body of literature promoting a "third way" whereby this distinction is real, but local rather than global.

The first view, which I termed "cosmic A-theory", has the advantage of saving the intuitively obvious features of the passage of time. Its representatives include William L. Craig (2001), Dean W. Zimmerman (2013), and Thomas M. Crisp (2003), to name only a few. Recently, Roberto M. Unger and Lee Smolin (2015) have argued forcefully that a preferred global time is necessary in order to account both for the evolving, changing universe, and for time as experienced by agents. To this end, Smolin proposes giving up the relativity of simultaneity, and looking for experimental evidence of violations of Lorentz-invariance [Unger and Smolin (2015, pp. 414-421 and pp. 491-2)]. Cosmic A-theorists have advanced several ways of defining absolute simultaneity in spite of relativity theory, employing, for example, a neo-Lorentzian interpretation of special relativity [see Craig (2001, ch. 9), cf. also Tooley (1997, pp. 344-354)], or arguing from simultaneity in quantum mechanics, in particular from the collapse of a wave function describing an entangled system of two spatially separated particles, as occurs in Einstein-Podolsky-Rosen (EPR) experiments [see Craig (2001, pp. 223-235), and D. W. Zimmerman (2013, pp. 80-1)]. Here is not the place to discuss these moves in detail. They arguably both fail: the neo-Lorentzian interpretation of special relativity incurs the high—in my view too high—cost of giving up the frame independence of the laws of nature. The argument from EPR experiments to absolute simultaneity leads to what Craig Callender has termed an "irresolvable coordination problem" (2008, p. 13) between the frame of reference in which the experiment is carried out and the assumed privileged frame which, according to proponents of absolute simultaneity, defines the locus of wave function collapse.[3]

2 See any textbook on relativity, e.g. Cheng (2010, pp. 53-4).
3 Cf. J. Lucas' "hyperplane advancing throughout the whole universe of collapse into *eigen*-ness" [Mellor & Lucas (1998, p. 55)].

But cosmic A-theorists have another interesting argument to offer: that from the evolving universe revealed to us by contemporary cosmology. If the universe goes through different stages of its existence, marked by different characteristics, it would at first sight seem that the notion of "the universe at time *t*" is not only viable, but also necessary for scientific cosmology. Indeed, this is one of the key motivations for Unger and Smolin's proposal.[4] The evolving cosmos seems to restore a necessary condition for the truth of A-theory, so that it might seem that we can unproblematically speak of "the universe now" after all.

However, in my view, evolutionary cosmology does not restore an ontologically privileged temporal parameter which could be used to order all events in spacetime, and which is necessary in order to define the global now as the boundary between the past and the future. Accounts of the evolution of the observable universe are given in terms of so-called cosmic time functions, which are constructed on the simplifying assumption that the universe is everywhere homogenous and isotropic. This assumption, which leads to the Robertson-Walker metric, is experimentally confirmed for very large scales. It then emerges that each observer at rest relative to the cosmic fluid—known as a "fundamental observer"—will measure, for the same local time *t* after the Big Bang, the same parameters describing the characteristics of her cosmic vicinity at a very large scale. These parameters include pressure, matter and radiation density, curvature, Hubble's constant, Ω_{matter} and Ω_{Λ}.[5] By putting the observations of fundamental observers together to form an atlas, macroscopic states of the universe, i.e. states defined by the above parameters, can then be correlated to times as measured by fundamental observers. Thus, a total ordering of such states isomorphic to the positive real line is obtained. This finding is of great philosophical interest in its own right, but it only applies to a rough, macroscopic description of large portions of space. Events in spacetime such as collisions between astronomical bodies, football matches, musical performances, and so on, happen at a much smaller scale. Here, special and general relativistic effects come into play: clocks tick at different rates relatively to each other, depending on their state of motion and the gravitational potential in which they are situated. This precludes the possibility of ordering all events occurring in spacetime by a preferred temporal parameter. For this reason, I submit that evolutionary cosmology does not restore the global passage of time advocated by the cosmic A-theorists.

The most well-known alternative is the block-universe view, whereby the distinction between past, present and future is of no ontological significance. This has usually been taken to imply a universal determinism whereby the truth values of propositions about the future are determinate, just like those of propositions about the past, as argued in the by now classical papers by Wim Rietdijk (1966) and Hilary Putnam (1967). We find a similar picture of the future as "just there" in the thought of Arthur Eddington (1920, pp. 46-7). Likewise, Olivier Costa de Beauregard (1981) took the lack of a global present to imply that the future light cone of agents in spacetime is "inscribed" (pp. 429-430) and "written down" (p. 432). On this picture, the content of the future light cone cannot be influenced. More examples could be

4 See e.g. pp. x –xi in the introduction of their book.

5 i.e. the fractional contribution of matter and cosmological constant, respectively, to the total mass-energy of the universe. For a detailed discussion of cosmic time, see Whitrow (1963, ch. 5); Cheng (2010, ch. 9); and Hawking (1969).

cited, but perhaps the most succinct argument to the effect that relativity theory renders a robust notion of the passage of time impossible was put by Kurt Gödel:

> It seems that one obtains an unequivocal proof for the view of those philosophers who, like Parmenides, Kant, and the modern idealists, deny the objectivity of change and consider change as an illusion or an appearance due to our special mode of perception. The argument runs as follows: Change becomes possible only through the lapse of time. The lapse of time, however, 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 … 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 (1990, pp. 202-3)]

The block universe, while compatible with relativity theory, has the obvious disadvantage of failing to account for the asymmetric character of time which is so manifest from everyday experience, in particular the difference between the indeterminate future and the fixed, unchangeable past. Not surprisingly, a squarely static worldview where nothing happens and everything is just "there" seems to have few defenders today, and contemporary proponents of the block universe emphasize that their view does not amount to an altogether unchanging world [see e.g. Skow (2015), cf. also Price (1996, pp. 12-13)].

There is currently only little in the direction of a "third way" which reconciles the experienced features of the passage of time with spacetime physics. Examples include: Steven Savitt's proposal (2011) whereby change is real, but the tensed structure of time is an essentially local phenomenon; the theory of "branching space-time" developed by Nuel Belnap (1992) and then further, for example, by Thomas Müller (2012); Robert J. Russell's (2012) move of understanding past, present, and future as relations between, rather than properties of, events; and James Harrington's theses whereby an Aristotelian theory of time opens the possibility of a non-illusory passage of time independently of a global time (2009), and whereby the proper time measured locally along an individual worldline "just is time" (2007, p. 12).

The approach I will propose falls within the family of "third way" views on which there is a robust local past-future distinction, but no global present. In its Aristotelian outlook, it is particularly close to Harrington's work on the subject. The novel contribution I wish to offer is a rigorous derivation of local time from simple assumptions concerning substances and their causal interactions. I will present the case that temporal notions can be derived operationally and non-circularly from non-temporal ones. Therefore, it is not necessary to presuppose an absolute time which exists independently of interactions between substances. In line with Aristotle, we can thus defend the claim that change gives rise to time, not vice-versa as Gödel assumed. To this end, in section 2, operational definitions of the relation "before", of change, and finally of time itself will be developed. In section 3, an epistemological assumption is made whereby we can infer the truth of some propositions from records contained in substances. Based on this groundwork, I then present, in section 4, a new argument in order to show why the local past is fixed and unchangeable, whereas the local future is open. This yields a branching structure of time as a real phenomenon, albeit a local one which is independent of a global passage of time, thereby providing a fresh approach to understanding the problem of the "arrow" of time, i.e. of time's one-way-street character. Section 5 is devoted to a detailed discussion of objections to this model, as well as comparisons to other related models. Finally, in section 6, the outline of a physically correct model of time beyond A-theory and the block universe will be sketched.

2. Constructing local time

I propose constructing a concept of time in terms of local causal interactions through the following steps: First, a definition of the temporal ordering relation "before" will be developed. I claim that this is possible in a non-circular way. This will allow us to define the notion of change in substances, and in a next step, to introduce a neo-Aristotelian concept of time as a quantification of change through a measuring standard.

2.1 Defining "before" non-circularly

The first step, i.e. defining "before" non-circularly, is based on two simple metaphysical assumptions:

A.1: Substances exist, and they can exist in different states characterized by non-essential intrinsic properties.

Thus, if A is a substance, then there are non-essential intrinsic properties p for A, i.e. intrinsic properties such that A is identical to itself whether or not it possesses p. For any such properties p, *A-with-p* and *A-without-p* will be called "states" of A.

A.2: For any substance A, different states of it exist only if it is subject to causal interactions, either with its environment, or among its own parts.

On this assumption, some non-essential intrinsic properties of substances are due to causal interactions. We can therefore term such properties "records", and substances, as the bearers of these properties, can be thought of as "recorders". I leave open whether substances also have non-essential intrinsic properties which are not records.

In order to see how assumptions (A.1) and (A.2) help us to construct a non-circular definition of "before", consider a simple physical object A being affected causally by its environment in the course of two separate events. With each event, a record on A is associated. Let's call the two records on A "Alice" and "Fred". Notice that, if the event associated with Fred is before that associated with Alice, then a state of A exists with Fred and without Alice, and another state exists with both Fred and Alice, but there is no state with Alice and without Fred. Thus, we find that, in the scenario under consideration, there is an asymmetry *in the existence of states* of A: the situation would be symmetric if there were also a state of A with Alice, but without Fred.

The crucial point in the above example is that an asymmetry in the existence of states of A needs no temporal concepts in order to define it. Rather, we need only to quantify, timelessly, over actually existing states of A in order to determine which of the two events is before the other.

Of course, in practice nothing guarantees that properties of A due to causal interactions will stick. In the above example, Fred could be deleted again, so that we would be left with a state of A with Alice and without Fred, in which case the asymmetry in the existence of states of A breaks down. This situation can be remedied by introducing the notion of an *amended recorder:*

D.1: An amended recorder is a recorder A such that each event affecting it produces a record in A, and does not affect other records in A.

Note that I do not demand that records "stay" or "do not become destroyed" in A. To do so would be to circularly invoke concepts which involve temporal precedence. Instead, I chose a formulation which does without such concepts.

However, the amended recorder needs a further improvement in order to attain a non-circular definition of "before": we need to ensure that each event affecting A is associated with a *unique* record. For if the records produced by two distinct events are not unique, the later one of two events affecting A can produce a property which is already in A, in which case the above asymmetry in the existence of states of the recorder A once again breaks down. An example of this case could be a camera which records two indiscernible pictures of a landscape. Let's call r^* the record produced twice in A in the course of two distinct events. We notice that, even in such cases, there is still an important difference between these events: one of them is associated with the production of r^* in a state *A-with-r**, and the other with the production of r^* in a state *A-without-r**. This difference can, however, only be made out by a recorder which is able to monitor its own states, i.e. to tell in which state, characterized by which records, it exists. Such a recorder will therefore be called an "ideal recorder":

D.2: An ideal recorder is an amended recorder which is able to fully specify its own state.

Thus, for an ideal recorder, there will be two distinct instances of r^* , which could be labeled, for example r^*_a and r^*_b, even if these two records are intrinsically indiscernible. Each event affecting A is therefore associated with a unique record.

It is now possible to define the relation "before" between events. Let x and y be two events associated with the production of two properties, r_x and r_y , in an ideal recorder A. Then,

D.3: x is before y iff there is a state of A with r_x, and a state with r_x and r_y, but no state with r_y and without r_x.

We now have an operational definition of "before" which does without temporal concepts, and which therefore does not need to assume an absolute time, existing independently of substances and events, as ontologically primitive. Of course, readers may wonder whether a definition which involves the concept of an ideal recorder is of much use, since such substances do not in fact exist. My answer to this objection is that there are substances in the world we know which approximate the ideal recorder very well. Such substances can therefore be used for establishing the relation "before" between events in a highly reliable way by applying the criterion in definition (D.3) to them. For example, even simple physical objects like the moon can be used quite well to establish the order of impact events on it, by quantifying timelessly over its states. The human cognitive apparatus saves records within the brain, protecting them from interaction with the environment, and is therefore a particularly good amended recorder. It has the additional ability of being able to monitor its own states, albeit of course imperfectly. This enables us to identify distinct instances of sense impressions which are intrinsically indiscernible, so that we approximate the ideal recorder well. Furthermore, even though in imperfect recorders, some records of events become deleted, it is still possible to carry out a comparison with records contained in other recorders, in order to infer what an ideal recorder would record. On this basis, a relationship of temporal precedence, as defined in (D.3), can be established.

Note also that, even though I defined "before" in terms of a quantification over all states of an ideal recorder, this quantification does not need to be carried out explicitly. This is because every event affecting the ideal recorder A is associated with a unique record, and does not interfere with other records. Hence, given only two states of A, such as A-*with*-r_x (without r_y), and A-*with*-r_x-*and*-r_y, we can be certain that there is no state A-*with*-r_y (without r_x). Thus, we do not need an overview over all states of A in order to verify whether definition (D.3) is satisfied. This is consonant with everyday experience where, having witnessed two events, we can immediately judge which is before which. To form this judgment, we do not have to await the end of our life in order to quantify over all our states.

2.2 Change

Suppose that a substance B is within the causal reach of an ideal, or approximately ideal, recorder A, and that there are two states of B: B-*without*-p and B-*with*-p. These states can affect A, for example by emitting electromagnetic waves, and produce two corresponding records in A, which will be called $r_{B\text{-}without\text{-}p}$ and $r_{B\text{-}with\text{-}p}$. This allows defining the notion of change in a substance:

D.4 A substance B changes iff it acquires or loses a property p, where "B acquires p" iff $r_{B\text{-}without\text{-}p}$ is before $r_{B\text{-}with\text{-}p}$ for A, and "B loses p" iff $r_{B\text{-}with\text{-}p}$ is before $r_{B\text{-}without\text{-}p}$ for A.

Because "before" is defined via the ideal recorder A, and because B is a substance which is not necessarily an ideal recorder, we cannot define the change of B in terms of B alone. This poses no problem, since there is never a danger that A gets the order between the states of B wrong. In other words, whatever A's location or state of motion, A cannot measure a different order from that which would be measured by an ideal recorder whose worldline is immediately next to B's. For this latter order is an invariant, as is known from relativity theory, and so it is the same in A's frame of reference. Because of this, the events which are associated with the production of the records $r_{B\text{-}without\text{-}p}$ and $r_{B\text{-}with\text{-}p}$ in A must likewise occur in the same order.[6] Hence, if "B acquires p" or "B loses p" according to some ideal recorder, then the same is true according to *any* ideal recorder.

2.3 Local time

Since an ideal recorder can mark two instances of a record r^* as distinct, it should be possible to construct a local parameter t based on repeated instances of r^*. I propose doing this in the following way: Let A be an ideal recorder, or a sufficiently good approximation thereof. Suppose that A is in a state with r^*_a and r^*_b. Then, the collection of r^*_a and r^*_b can be thought of as a record in its own right, which will be called r^*_2. A state of A with r^*_2 can be affected in such a way as to produce yet another instance of r^* in it. The collection of r^*_2 and r^* can then be called r^*_3, and so forth. This is a procedure of successive inclusion similar to that used in the standard set-theoretical construction of the natural numbers [see e.g. Holmes (2012, pp. 25-6)] except that we start, not with the empty set, but with a single instance of r^*, whose first successor is r^*_2.

We can then identify the index of r^*_i as the local parameter t measured by A:

D.5: If A is an ideal recorder, or a sufficiently good approximation thereof, then for all r^*_i in A, $i \equiv t$.

The local natural parameter can then be subdivided further by some other repeated change in A, thereby yielding a rational parameter, on the basis of which a real parameter can be constructed, at least in thought, e.g. by the standard procedure of defining real numbers in terms of sets of rational numbers [see e.g. Holmes (2012, pp. 94-6)]. Let's continue to call this refined parameter t. We can then write states of A as A_t, i.e. we can identify them by this local parameter, rather than by the records they contain. By writing *A-with-*r_x simply as Ax, where x is an event and r_x the record in A associated with it, this identification reads:

I.1: $A_t = Ax_1,\ldots,x_n$, for some n.

In other words, A_t contains records of finitely many events.

Writing states of A as A_t also allows assigning records in A to the local parameter t, by defining:

D.6: If a record r is produced in A_t, then $r \equiv r_t$.

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6 At any rate, this is true in a special relativistic context, as can be seen from a simple calculation: Suppose that B changes from green to red, and that, as it does so, it rushes towards A at a very high speed v. Let x be the distance between A and B, according to A's frame of reference, when the process of change starts and when B sends off a message "B is green". Let $\Delta\tau$ be the proper time for the process of change as measured along B's worldline, and let Δt be the time for this process according to A's frame of reference. As is known from special relativity, if $\Delta\tau$ is positive, so is Δt. Let $t=0$, according to A's frame, when the message "B is green" is sent off from B. This message arrives at A at time $t_{green} = x/c$. B is at a distance of $(x - v\cdot\Delta t)$, again according to A's frame, when the message "B is red" is sent off. This message arrives at A at $t_{red} = \Delta t + (x - v\cdot\Delta t)/c$. Thus $t_{red} - t_{green} = (1 - v/c)\cdot\Delta t$. This interval can be an arbitrarily small fraction of Δt, but it can never be negative, and so A receives the two signals in the correct order.

On the basis of what has been developed throughout section 2 so far, I propose a neo-Aristotelian definition of time:

D.7: Time is a local parameter t established through a recorder A on the basis of repeated instances of records of the same type r^* in A, such that t is used to quantify processes of change in substances which can causally affect A.

Registering change in substances and establishing the local parameter t can only be done by a substance A sufficiently close to an ideal recorder. Such a substance can quantify changes either in itself or in other substances. In the latter case, the quantification can be carried out in different ways. The simplest way is to use the temporal indices t of records r_t in A which correspond to changes in A's surroundings. Alternatively, change can be quantified from these indices in combination with additional information, in particular about the distance between A and substances which can affect it.[7] In the limit of small distances or a high speed of propagation of causal influence, the results of both methods of quantification will coincide. This leads to the impression that there is a "world at time t", i.e. that an entire state of the world corresponds to a locally measured time, as was generally thought before the advent of relativity theory [cf. Russell (2012, pp. 263-5)].

Some readers may be concerned that a repeated process is not sufficient to establish a local time standard, but that the process also needs to occur regularly. However, in my view, regularity only becomes an issue when several repeated processes come into play, whose rate with respect to each other may vary. If there is only one such process, then there is no way of quantifying the intervals defined by it, and of comparing their duration. Hence, this process alone is sufficient to define a unit of time.[8]

3. Epistemological realism

In view of deriving the irreversibility of local time in section 3, one more premise is needed: I will assume that from records in a recorder A (which need not necessarily be ideal, or even amended), conclusions can be drawn about the truth of propositions. This is done with the help of rules of inference v, the set of which I will call V. Let R^A denote a set containing records r^A in A. Then, we can assume:

A.3: From the fact that the rules $v \in V$ apply, and from the existence of records $r^A \in R^A$, it follows that some propositions p_R^A are true, the set of which will be called P_R^A.

7 as is done in the Einstein synchronization procedure, described in (Taylor & Wheeler 1992, pp. 37-9).

8 Cf. the similar observations made by Francisco Suárez (1965, sect. IX, 4): "in the same motion, so to speak, of one revolution of the sky, the real duration is the same, for the real being of such motion is the same … although that entire duration, by comparison to an extrinsic time … could last longer or shorter according to the faster or slower passing by of that motion." In the original: "Nam in eodem motu, verbi gratia, unius circulationis caeli, eadem est realis duratio, quia idem est reale esse talis motus … quamquam tota illa duratio per comparationem ad extrinsecum tempus … magis vel minus durare posset iuxta velociorem vel tardiorem transitum illius motus." On the issue of periodicity and regularity, cf. also the discussion in (Janich 1980, pp. 180-9).

R^A will contain finitely many records, since it is a subset of the set containing all records in *A,* which is itself of finite cardinality. On the other hand, *V* could be of countably infinite cardinality, since it may well be that it is not possible to give a finite list of rules for drawing inferences from records to propositions. As far as I can see, $P_R{}^A$ will also be of finite cardinality, since it seems that only finitely many propositions can be inferred from finitely many records. In any case, this point makes no difference for the argument which follows.

An assumption along the lines of A.3 is an essential requirement for scientific and everyday realism, since arguably all our knowledge of the external world is based on records contained in substances [cf. the discussion in Von Weizsäcker (2002, pp. 47- 78)].

4. The asymmetry of the local arrow of time

4.1 The fixed past and the open future

I will now argue that, on the theory of time laid out in section 2, as well as the epistemological assumption of section 3, we can account for familiar features of time such as its linear, unidirectional character, as well as the asymmetry between the fixed past and the open future.

To do so, let's consider an ideal recorder *A* causally interacting with its surroundings, and let's assume, furthermore, that *A* establishes a local parameter *t*, as discussed in section 2.3. Suppose that *A* is in some stage $A_{t\alpha}$, where $t_\alpha > 0$. $A_{t\alpha}$ will in general bear records of causal interactions (cf. identification I.1), and being a substance, it can receive more such records (assumptions A.1 and A.2).

Because *A* counts, records in it are associated with locally measured times *t* (definition D.6). Furthermore, *A* counts on the basis of a repeated process affecting it, and so records in the state $A_{t\alpha}$ which we are considering cannot be associated with numbers *t* greater than t_α. They must therefore be associated with numbers *t* less than t_α, or possibly equal to it (more on this problem below). For each time *t* less than t_α, there is a set $R^A{}_t$ of records in *A*. This set will contain at least one record, namely the one associated with the local time keeping process. It may or may not contain further records $r^A{}_t$. On assumption (A.3), from the existence of the records contained in the set $R^A{}_t$, together with the rules of inference *v* contained in the set *V*, the truth of some propositions associated with these records follows. We can therefore assign the index *t* also to these propositions and call them $p^A{}_t$, and the set containing all of them and only them will be called $P^A{}_t$. If, for some *t* less than t_α, $R^A{}_t$ is empty apart from the record associated with the local time keeping process itself, then, we may stipulate, $P^A{}_t$ will contain information only about the occurrence of time *t*, and nothing else. In any case, all times *t* less than t_α will be associated with sets $P^A{}_t$, since such times have records, whereas all times *t* greater than t_α will not be associated with such sets, since these times have no records. This association of local times with sets of records and sets of propositions has three noteworthy consequences:

First, local time measured by *A* has a linear, as opposed to circular structure. For given two locally measured times *t* and *t'*, even if the records $r^A{}_t$ in $R^A{}_t$ are indiscernible from the records

$r^A{}_{t'}$ in $R^A{}_{t'}$, so that two type-identical sets of propositions $P^A{}_t$ and $P^A{}_{t'}$ follow from them, $P^A{}_t$ and $P^A{}_{t'}$ are nevertheless not identical, because all propositions contained in $P^A{}_{t'}$ involve $A_{t'}$ rather than A_t. In this way, every local time t is assigned a unique set $P^A{}_t$. Thus, even if exactly type-identical interactions take place twice, this does not amount to the recurrence of the propositional content of a past time.

Second, for a state $A_{t\alpha}$ of A, the propositional content associated with a local time t less than t_α, which is given by the set $P^A{}_t$, is fixed and unchangeable. Suppose that we are unhappy with a proposition $(p^A{}_t)*$ contained in $P^A{}_t$, and therefore wish to bring about that not-$(p^A{}_t)*$ is true. This is impossible, because $(p^A{}_t)*$ is implied by true statements: first, the fact of the existence of certain records which are contained in $A_{t\alpha}$ and which are associated with local time t, and second, the rules contained in set V. Hence, $(p^A{}_t)*$ is itself a true statement, and so not-$(p^A{}_t)*$ cannot be true. Nor can we change the propositional content of a local time t less than t_α by attempting to add a proposition to its set $P^A{}_t$. For this set, by assumption, contains all and only the propositions which follow from the rules v in V and the existence of the records contained in $R^A{}_t$, and therefore excludes any other propositions. The notion of adding some proposition, call it $(p^A{}_t)+$, to $P^A{}_t$ therefore likewise entails that $(p^A{}_t)+$ is both true and false. In sum, the local past cannot be changed, because to do so implies a contradiction.

Third, the propositional content of local times t greater than t_α can be influenced. This is because $A_{t\alpha}$ is a state of A, and A, being a substance, can be influenced: it can acquire records through causal interactions, records which in turn generate sets of propositions according to assumption (A.3). However, for $A_{t\alpha}$, the propositional content of a time less than t_α cannot be changed in virtue of the argument in the preceding paragraph. On the other hand, no such argument applies for times greater than t_α, because no records are contained in $A_{t\alpha}$ for such times. Thus, the local future is open: each time t greater than t_α is not associated with a unique P-set, but can be occupied by infinitely many such sets. The propositional content of such times can therefore be thought of as “branching”. In other words, given the basic metaphysical assumption that substances can receive non-essential properties, it is not astonishing that there is a branching set of possibilities which can occur to them. What needs to be explained, rather, is why there are no such branching possibilities for the past as measured locally.

What must be left open at this point is whether t_α itself is occupied by a set of records and a corresponding set of propositions, i.e. whether it is the last point of the local determinate past or the first point of the open future. On the one hand, according to definition (D.6), $A_{t\alpha}$ can receive more records. This opens the possibility of several different states of $A_{t\alpha}$, which could be ordered by the relation “before” according to definition (D.3). On the other hand, this is unsatisfactory, because according to identification (I.1), there ought to be a unique state of A associated with t_α. Dilemmas such as this typically plague thought about the present in the philosophy of time. For if the present is associated with some event content, then it seems that it must have some extension. But if it has extension, then there are earlier and later parts of the present, which contradicts the notion of the present as containing only simultaneous events [cf. Dainton (2010, pp. 95-102)]. In other words, the problem arises from associating an infinitesimal point with event content. Operationally, the simplest solution seems to me to view all events associated with the production of records in $A_{t\alpha}$, as well as these records themselves, as belonging to t_α . As of local time t_α itself, there is then no definite fact as to the precise content of the set of records $R^A{}_{t\alpha}$. This set is, so to speak, still under construction, and therefore, so is the propositional content $P^A{}_{t\alpha}$ of t_α .

But what about substances which are not ideal recorders? Do they have a fixed past and an open future? For substances which approximate ideal recorders well, such as ourselves, the structure of time is the same as for the ideal recorder, but this is complicated by the fact that some records for past local times are deleted, and that even preserved records cannot always be accessed. However, as pointed out in section 2.1, it is still possible to reconstruct what an ideal recorder would record through comparison with other recorders. In this way, the content of *P*-sets for locally past times can be inferred. Defining time via the ideal recorder therefore has the advantage of explaining the features of the passage of time as we experience it: Past local times are associated with definite and unchangeable propositional content, even though we may not always know that content. For future times, on the other hand, there is no definite and unchangeable propositional content.

What has been laid out in this section can shed light on the difficult problem of the unidirectionality and anisotropy of time's arrow, which is subject to so much debate in the philosophy of physics. Why is it that we can move back and forth in space, but not in time, that we can only act "forward" in time and never "backward"? If we understand time operationally in terms of the ideal recorder, it is the principle of non-contradiction which accounts for this asymmetry: since past local times are occupied by *P*-sets, the notion of revisiting a past point at time *t* entails that some statement $(p^A{}_t)*$ both is and is not true. Thus, if time moves anywhere, it can only move forward. I therefore propose that the reason for time's arrow is not to be found in irreversible physical phenomena such as the increasing entropy of isolated systems. While these phenomena accompany time's arrow, they are not its underlying cause. To use Huw Price's words, they belong not to the "genealogy problem" of temporal asymmetry, but to the "taxonomy problem", i.e. the problem of "asymmetries of things *in* time" (1996, p. 17). Nor do we need the physically highly implausible concepts employed by cosmic A-theorists, such as a global now or ontologically privileged hypersurfaces of simultaneity, in order to account for the passage of time. The tensed structure of time, in short, is a real, but only local phenomenon.

4.2 The now

A theory of local time also enables a new approach to the issue of the now, i.e. the question of what the experienced "nowness" of events consists in and whether it is of any ontological significance. It is frequently argued that, since the experienced now cannot be illusory, there must be such a thing as "nowness" for the world as a whole [see e.g. D. W. Zimmerman (2013, pp. 41-52); Unger & Smolin (2015, pp. 481-2)]. I propose, however, that we do not need to choose between an absolute, global now on the one hand, and entirely dismissing the concept of now as illusory on the other. The now associated with a state A_t of a recorder *A* can, for example, be identified with the set of propositions $P^A{}_t$ obtained from the set of records $R^A{}_t$, given a set of rules *V*. The now experienced by us as conscious agents will then be related, but not identical to $P^{A}{}_{t}$: As we in some state A_t are affected by the world, and ourselves affect the world, we conclude the truth of some propositions concerning these interactions on the basis of records contained in the set $R^{A}{}_{t}$. If we do so correctly, these propositions will be a proper subset of $P^{A}{}_{t}$. But $P^{A}{}_{t}$ contains many more propositions since, being imperfect reasoners, we cannot draw all conclusions which can be obtained from $R^{A}{}_{t}$ and V.

Which records $r^{A}{}_{t}$ are produced in A_t is an invariant fact, since the production of these records coincides at the point in spacetime where A_t is located. Hence, given a set V of rules of inference, $P^{A}{}_{t}$ is likewise invariant, and unlike the notion of the global now, does not fall prey to the relativization of temporal concepts brought about by spacetime physics. Thus, the now of A_t, unlike the pre-relativistic notion of "all that is occurring in the entire world now", is by no means illusory but has a *fundamentum in re*, namely the content of $P^{A}{}_{t}$. Like the distinction between past and future, the now too is a real but local phenomenon.

5. Objections and comparisons

Having laid out a proposal for the derivation of "before", of change, of local time and of its asymmetric character, it is now necessary to answer objections to this proposal and to compare it in more detail with other accounts found in the literature. This will, I hope, both corroborate the proposed account and make clearer what it is, and what it is not.

5.1 Charges of circularity

It may be objected that what I have developed in sections 2.1 to 2.3 is manifestly circular. Doesn't all this presuppose a dynamic and thoroughly temporal world? Specifically: Doesn't the notion of different states of substances presuppose a time in which these states exist in temporal succession? Furthermore, are the notions of "causal interaction" and of substances "affecting" each other even conceivable in the absence of time, and isn't time a precondition for such notions?[9]

Similar objections have been raised against Aristotle's definition of time as "number of motion (κίνησις) in respect of 'before' and 'after'": First, it is objected that the notion of κίνησις, far from explaining time, presupposes it, since no κίνησις is possible unless there is an underlying time in which it occurs. Second, the definition circularly employs the temporal concepts of "before" and "after".[10] My definition of time in (D.7) closely follows Aristotle's. I

9 Cf. Kant (1787, AA 57-8). In the translation of Meiklejohn (1855, p. 28), the relevant passage reads: "Time is a necessary representation, lying at the foundation of all our intuitions. With regard to phaenomena in general, we cannot think away time from them, and represent them to ourselves as out of and unconnected with time, but we can quite well represent to ourselves time void of phaenomena. Time is therefore given *a priori*. In it alone is all reality of phaenomena possible. These may all be annihilated in thought, but time itself, as the universal condition of their possibility, cannot be so annulled."

10 Roark (2011, p. 41). Cf. also the objection against a causal theory of time raised in (Whitrow 1963, p. 275): "The basic difficulty confronting the causal theory is that the very essence of time lies in temporal succession … unless the existence of *successive* states of phenomena is tacitly assumed it is impossible for the theory to yield

spoke of "change" rather than "motion", but the definition of change I proposed in (D.4), as the acquisition or loss of an intrinsic property *p*, closely matches the Aristotelian term κίνησις, which comprises the qualitative change of objects (ἀλλοίωσις) and their quantitative increase (αὔξησις) or decrease (φθίσις).[11] On the other hand, change as I defined it, unlike Aristotle's κίνησις, does not include an object's motion through space (ἡ κατὰ τόπον κίνησις), since an object acquires no intrinsic property by such motion.[12]

I submit that a neo-Aristotelian view of time escapes the aforementioned charges of circularity: the notion of a set of states of some substance *B* is not intrinsically temporal, since it can be defined without recourse to temporal notions. Given such a set, it is possible to define an ordering through the relation "before" between the states contained in this set by using an ideal recorder *A*, as discussed in section 2.1. This, in turn, allows us to define change, and in a next step, the quantification of change with the help of a recurring standard change affecting a recorder *A*. Thus, change does not presuppose time, but rather, time can be defined in terms of change.

It may be objected that, even if it is possible to define a set of states of a substance independently of time, it is inconceivable that such states in fact exist in the absence of time, since for any substance *B* and property *p, "B has p"* and *"B does not have p"* cannot both be true *simpliciter*. Instead, they must be true at different times. Hence, there is no change without time. I agree with this, but I do not believe that it stands in the way of a reduction of time to change. Rather, I propose that time, as a number assigned to processes of change, is precisely that respect which makes it possible to speak of a self-identical substance *B* as existing with contradictory intrinsic properties, e.g. in state *B-with-p* at t_1 and *B-without-p* at t_2. We might also say that the possession of contradictory properties by substances "spans" time.

What about the notions of causal interaction and of substances affecting each other causally? Are they intrinsically temporal? This is a complex and much debated issue which to discuss at length is beyond the scope of this article. I will therefore only provide a sketch of an answer here. It seems to me that a strong case can be made, based on two pieces of evidence, that causation is not intrinsically temporal. First, as Stephen Mumford and Rani L. Anjum (2011, ch. 5) have argued, in my view convincingly, causation ought to be thought of as simultaneous rather than diachronic. Mumford and Anjum use the example of colliding billiard balls, where the causation takes place during the contact phase between the balls, not before or after it (pp. 108-9). Such examples intimate that causes do not precede effects, but that the two are simultaneous. To this I would add, secondly, that ordinary causal interactions between macroscopic substances are electromagnetic in character and are mediated by the exchange of photons. This is true of interactions involving contact forces, such as pushing, pulling,

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temporal succession."

11 *Categories,* ch. 14. Cf. also the discussion in [Roark (2011, pp. 63-7)].

12 Presumably, Aristotle took locomotion to be a species of κίνησις because he considered place (τόπος) to be an accident of a substance. This classification may also have to do with the fact that Aristotle understood κίνησις κατὰ τόπον as a type of causal interaction, since in Aristotelian physics a force must act on an object in order for it to move.

breaking, squeezing, and so on, but also for mechanical waves, which involve electromagnetically interacting molecules. But the exchange of photons does not seem to be a temporal process: the spacetime interval between emission and absorption of a photon is zero for any distance traveled, and the very notion of temporal measurement, which requires massive, composite objects, appears to have no meaning at the level of photons. Indeed, as E. J. Zimmerman has argued, time is not a feature of the microscopic world, but a parameter used for the extrinsic description thereof [Zimmerman (1981, see esp. pp. 492 and 496)]. In my view, therefore, the relationship between causation and time is best summarized as follows: the existence of different states of substances gives rise to time, and the electromagnetic interaction[13] is responsible for the existence of these different states. But this interaction is not itself something intrinsically temporal. Hence, the notions of causally affecting and of causal interaction do not presuppose time.

None of all this should be read as a denial of time and change, or as an argument for a Parmenidean, static world. On the picture I propose, change and time are not illusory, but they are derived notions rather than ontologically fundamental ones.

5.2 The proposed causal theory does not rely on causal asymmetry

A further clarification should be added at this point: The view of time laid out in sections 2 to 4 can be called a causal theory of time because, on it, causal interactions between substances account for time. This needs to be distinguished from the claim, often associated with the term "causal theory of time", that some form of asymmetry between causes and effects accounts for temporal asymmetry. Several different models which employ this basic strategy can be found in the literature: for example Hans Reichenbach's mark method [Reichenbach (1958, pp. 135-8), as cited in Grünbaum (1973, p. 180), which see for a discussion], D. H. Mellor's reduction of temporal to causal order (1998, pp. 105-117), or Mathias Frisch's argument (2013) whereby temporal asymmetry can be understood in terms of causal and explanatory models. A related account is that developed by Adolf Grünbaum, where the relationship of temporal betweenness between events is explained in terms of an event's being necessary for the causal connectedness ("*k*-connectedness") of two other events (1973, pp. 193-7).

By contrast, I do not claim that temporal order follows from causal order, or that it is derived from an asymmetric relationship between cause and effect. Rather, I claim that different states of substances exist due to causal interactions, and that time can be constructed on this basis by quantifying, timelessly, over states of a particular type of substance, namely an (approximately) ideal recorder. This leaves open whether such states also stand in an asymmetric relation of causal dependence among each other, and in which way events or states of affairs stand in such relations. These questions are clearly of fundamental philosophical importance, but their resolution, I claim, is not necessary in order to establish a non-circular theory of local time.

5.3 The objection from general relativity

13 Other interactions which are associated with a zero spacetime interval may also come into play, but as far as I can see, interactions which result in intrinsic change of substances are by and large electromagnetic.

It can furthermore be objected that the very notion of causal interaction, on which the present account of local time rests (by assumption A.2), is incompatible with general relativity (GR). This objection can roughly be summarized as follows: The notion of causal interaction relies on the transfer of energy. But statements about the transfer of energy from one system to another are only warranted if an integral conservation law applies, thereby allowing us to keep track of where in space, and by which systems, energy is gained or lost. As Erik Curiel (2011, p. 20) succinctly puts it:

> The fact that it is always the same *amount* of energy that is gained and lost by interacting systems is supposed to preclude the idea that energy can be created or destroyed, and so warrant the inference that energy is actually *transferred* between interacting systems, as required.

Curiel then shows that such transfer accounts cannot be formulated in GR, because only a differential (and hence, in a curved spacetime, covariant) conservation law, but no integral conservation law applies in a general relativistic spacetime (pp. 20-28).

I agree with Curiel that GR imposes constraints on physicalist accounts of causation. However, it cannot be used to undermine all notions of causal interaction. The main reason for this is that GR is fundamentally a metric theory. Very roughly speaking, its fundamental equation, the Einstein Field Equation, tells us how certain measurable quantities, spatial and temporal ones, relate to the quantities contained in the stress-energy tensor. But measurement is itself a type of causal interaction, either among the parts of an object (as in the case of a ticking clock), or of an object with its environment (as in the case of length measurement). Therefore GR, far from ruling out causal interactions, presupposes them, not merely as an essential part of the context of discovery of the theory, but in the sense that terms fundamental to the theory cannot be understood apart from such interactions. This is not to deny the fundamental character of GR as a physical theory, which Curiel rightly draws attention to. As far as we know, everything obeys the quantitative predictions of GR. However, the theory is not metaphysically fundamental, insofar as it is based upon concepts defined independently of the theory itself.

What might be an account of the notion of causal interaction which *is* compatible with GR? It is beyond the scope of this paper to give a fully-fledged account of causation. It suffices to show that accounts are possible which do not depend on integral conservation laws. An example is that given by Mumford and Anjum, for which I already stated my preference in section (5.1). On it, causal interactions are thought of as point-like, so that we do not need to keep track of portions of energy over space and time in order to support a causal claim. To use again the example of two colliding billiard balls—let's call them *a* and *b*—it is "the impact which is causally efficacious, not how ball *a* got to the point of impact" [Mumford and Anjum (2011, p. 108)]. This being so, a necessary condition for the causal claim that *b* acquired energy from *a* is that a differential equation of energy conservation—which in a general relativistic spacetime will have a covariant form—is satisfied at the point of impact, whereas an integral one which ensures that energy is conserved over a spatiotemporal volume is not necessary. It may be objected that the collision event between *a* and *b* cannot be viewed as strictly pointlike, but is itself extended in space and time. However, this event can be analyzed in terms of smaller events involving the emission and absorption of photons by the molecules contained in *a* and *b*, for which it remains true that these events, not what happens before or after them, are causally efficacious. Hence, an account of causation such as Mumford and Anjum's is not undermined by the absence of an integral conservation law in GR.

Suppose, in a next step, that even a differential conservation equation failed to hold. For example, let's imagine that, in a collision between two point-particles *a* and *b,* where *b* is initially at rest, the total momentum miraculously changes, so that *b* flies off with more momentum than *a* had before impact. Clearly, this would preclude the causal claim whereby *b*'s momentum came from *a,* or at least that it did so entirely. But even then we would be justified in applying assumption A.2: *b* acquired its momentum by interacting with its environment, at least in the minimal sense of something distinct from *b* itself, which in this case is the assumed miraculous source of the extra momentum.

In sum, assumption A.2 is in no way undermined by GR. The theory does not rule out the very notion of causal interaction, but only particular types of physicalist accounts thereof.[14]

5.4 Comparison with Janich's protophysics of time

The present account of time is consonant with the operationalist approach of the Erlangen School, and in particular Peter Janich's protophysics of time (1980), in the sense that time is understood in terms of a quantification of change with the help of a repeated standard change. The principal difference lies in the derivation: Janich starts his account of time measurement with change and motion as notions known by example from everyday experience (p. 142), and therefore not in need of further analysis. After a detailed geometric discussion of comparisons between different locomotions (pp. 151-179), Janich then introduces repeated change, also known by example (p. 192) as the basis for quantification of change. From this, Janich provides rigorous, and in my view helpful, definitions of time measuring devices and of their regularity and constancy, based on a distinction between a device itself and a part of it which functions as a time indicator (pp. 194-210). The relations "earlier" and "later", as well as the asymmetry between past and future are, on Janich's account, consequences of time measurement so introduced, and therefore do not stand in need of a further derivation (pp. 214-5).

My proposal, by contrast, is to start with the definition of "before" in terms of changeless notions, and from there on to derive the notions of change and of a repeated standard change as the basis for time measurement, as carried out in sections 2.1-2.3. Also, I have proposed a derivation of the irreversibility of time in section 4 based, not on measurement alone, but on propositions and their truth values. Janich's account of clocks and chronometry is much more detailed than my rather minimalistic proposal of defining time in terms of several instances of a property r^* in an ideal recorder *A*. But the two approaches for time measurement can be combined, for example by defining repeated instances of records of the same type r^* in *A* as records of a time measuring device, as construed by Janich, in *A*'s vicinity.

14 Similarly, Curiel points out that his critique does not apply to all accounts of causation, but only ones whereby "causality is a *physical* relation holding among *physical* entities" and which "take the transfer (and the propagation) of energy to play the most important role in constituting the causal relation" (p. 2). I went further in arguing that even a transfer account is viable, as long as it is based on point-like interactions. But this does not exclude that other accounts of causation, not based on the transfer of energy, may be viable.

5.5 Comparison with the IGUS-model of temporal asymmetry

The physicist James B. Hartle proposes that the asymmetry of time is best understood in terms of IGUSes, i.e. "information gathering and utilizing systems" (2008, p. 1). This approach is consonant with what I have laid out in section 4, where the difference between past and future was explained in terms of records contained in a substance and propositions derived from them. There are, however, important differences: Hartle's account presupposes, first, a time interval in which the IGUS erases old images in its memory and acquires new ones (p. 2), and second, a direction of time defined by the increasing entropy of the universe (pp. 6-8). Hence, a pre-existing spacetime structure in which the IGUS lives is assumed. In Craig Callender's words:

> Is this [the IGUS] enough for passage? I think it probably isn't. Ultimately with IGUS we have a robot instantiating various asymmetric processes and maintaining an asymmetric correlation structure with the outside world… [However] we don't have movement yet, the *whoosh* and the *whiz.* Nothing seems to "crawl up" the IGUS's worldline, thereby making time flow… The memory asymmetry doesn't provide us with our desired feature of *something moving through time.* [Callender (2017, p. 247)]

The account offered in this article, if successful, solves this problem by deriving the notions of "before" and of change themselves in terms of a recorder. Thus, it does not need to presuppose an existing temporal structure in order to explain the temporal asymmetry "experienced", so to speak, by the IGUS. A further difference is that, on Hartle's account, it is in principle possible for a robot to organize its memory in different ways relative to the direction of time, e.g. it could remember its future (pp. 8-9). By contrast, I have proposed (section 4.1) reconstructing the familiar notion of the "past" through records contained in a recorder *A* and the propositions which can be derived from them, and the "future" in terms of *A*'s ability to acquire more records. Hence, on my account, a recorder cannot in principle remember its future.

6. A relativistically correct model of time beyond A-theory and the block universe

If the above proposal for a real but local passage of time succeeds, the conflict between relativity theory and the experienced passage of time, which appears so clearly in the work, for example, of Gödel or of Unger and Smolin, dissolves. Essentially, this is because this proposal views time as quantification of change, where change, as argued, can be defined independently of temporal notions. Only local causal interactions affecting substances and counting recorders are needed for this proposal, whereas the concept of time as a succession of global nows can be altogether dispensed with. Note that such a theory of time makes no statements about fundamental physics, since it is based on concepts which only apply at a relatively macroscopic level, in particular such as relate to substances and their properties, as well as on metaphysical arguments involving propositions. On this theory, it is not surprising that it is hard to account for temporal asymmetry at the level of fundamental physics.

It is now possible to spell out the consequences of such a theory for the philosophy of time:

I submit that the local past along a worldline is fixed, and the future open since, if time is understood operationally in terms of recorders, there is a unique and unchangeable *P*-set for any past time, but infinitely many possibilities for the content of the *P*-set of any future time. Therefore, the most fitting metaphor for this model of local time is not the tree, whose branches separate at the present and represent the possible future courses of events, but rather something like a horsetail, a plant where there is branching from every node above a certain threshold. On this model, the experienced difference between the tenses is not illusory. To account for this, we do not, however, need the classical A-theoretical picture whereby events change their ontological status as time passes, in such a way that future events become present ones, and then past ones. Instead, as far as the ontology of events themselves is concerned, we need only to distinguish between possible and actual ones. That an actual event x is past for some stage $A_{t\alpha}$ of a recorder A means that a real relation between $A_{t\alpha}$ and x holds, namely that the proposition describing x is in one of $A_{t\alpha}$'s *P*-sets. This picture of local time asymmetry matches our everyday experience as conscious agents: at any stage of our existence, we can actualize states of affairs, and can only meaningfully deliberate about actualizing future ones, or possibly present ones, whereas the past cannot be revisited in principle.

However, we cannot apply the predicates past, present, and future to stages of the development of the universe as a whole. Evolutionary cosmology and the notion that the world as a whole undergoes a development from earlier to later stages can in a sense be upheld, at least insofar as these stages can be put into a total and directed order, or B-series, by using cosmic time, which is uniquely suited for an account of the development of the observable universe, as outlined briefly in section 1. However, the evolution of the cosmos does not itself form an A-series, because no frame-independent temporal ordering of all events is available for the construction of equivalence classes, and hence ontologically privileged hypersurfaces of simultaneity or a global present separating the past of the cosmos from its future are rendered impossible.

As for the ontology of time itself, this article made the case that temporal notions such as the relation “before”, time intervals, past, present, and future, are best understood operationally in terms of substances and their records, as well as *P*-sets. On this picture, time is neither understood as in substantivalism, i.e. as a substance existing independently of measuring operations, nor as a merely subjective or illusory phenomenon, but instead, to use an ancient phrase, as an *ens rationis cum fundamento in re*: an entity of reason with a foundation in reality.

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