A Dynamical Perspective on the Direction of Time

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Abstract

It is standardly believed that the generally time-reversal symmetric fundamental laws of physics themselves cannot explain the apparent asymmetry of time. In particular, it is believed that CP violation is of no help. In this paper, I want to push back against a quick dismissal of CP violation as a potential source for the arrow of time and argue that it should be taken more seriously for conceptualising time in physics. After briefly reviewing the general debate on the direction of time, I recall that CP violation is a key feature of our best physical theory which also has large-scale explanatory import regarding the matter–antimatter asymmetry of the universe. I then investigate how CP violation may help to explain the directionality of time. I argue that accounts à la Maudlin that posit an intrinsic fundamental direction of time are not convincing and instead propose to utilize recent results from work on the dynamical approach to relativity theory: if matter field symmetries are more fundamental than spatiotemporal symmetries, the established (fundamental) directionality of the former may explain the (derivative) directionality of the latter.

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1 Introduction

The problem of the arrow (or direction) of time basically arises from the following two observations: on the one hand, time and the ordering of events in time seem to be directed. Typically, reversing the ordering of events in time yields either a very different process, or a process that is not observed to happen at all. Learning is a very different process than forgetting. Recovering from a disease is a very different process than contracting a disease. An egg falls to the ground and smashes, but a smashed egg does not spontaneously jump up to reassemble in my trembling hand. Such examples demonstrate why we belief that directionality is essential to time.

On the other hand, however, it is standardly argued that this observed directionality in, for example, higher-level physics (like thermodynamics) cannot be explained by fundamental physics, since at the level of fundamental physics all processes are supposedly undirected: they do not distinguish between a future direction and a past direction, but are time-reversal invariant. So if a process is allowed by some fundamental law—that is the process is a solution of the respective equations—the time-reversed process is as well.

In other words, fundamental physics seems to suggest that there is no fundamental difference between temporal and spatial dimensions—between the reordering of events from left to right and from the past to the future. But if there is no directedness of time at the level of fundamental physics, why should there be one in those parts of physics that are allegedly derivative on these fundamental dynamics?

> So we have a puzzle at least, a paradox at worst: if there is no fundamental directedness in fundamental physics, how does it come to be present in other areas of physics? (Wallace, 2011, p. 262)

This is the problem of the arrow of time.

Now, it is well-known that there are exceptions to the second observation: some fundamental processes do exhibit some form of time-reversal asymmetry. Tim Maudlin therefore attacks the very starting point of the debate:

> the laws of physics as we have them ... are not Time Reversal Invariant. The discovery that physical processes are not ... indifferent to the direction of time is important and well known: it is the discovery of the violation of so-called CP invariance, as observed in the decay of the neutral K meson ... In short, the fundamental laws of physics, as we have them, do require a temporal orientation on the space-time manifold. So the argument ... collapses at the first step. (Maudlin, 2007, pp. 117–118)

Maudlin's later plea for a fundamental arrow of time does not draw on this critique and is supposed to hold 'even apart from the (actual) lack of time reversal invariance of the laws of nature' (Maudlin, 2007, p. 134), but the existence of CP-violating dynamics is arguably meant to motivate his account further. The idea is that such phenomena imply 'that the laws themselves require an intrinsic asymmetry in time directions, and hence that space-time itself, in order to support such laws, must come equipped with an orientation' (Maudlin, 2007, p. 120).

According to the standard view, however, such CP-violating processes are regarded as of no use for explaining the directedness of time (for example, Price (2011); North (2011); Loew (2018)). In particular, many do acknowledge that there is some empirical evidence for a time asymmetry in certain particle physics processes, but then argue that this is a macroscopically irrelevant effect of specific 'exotic ... particles' (Loew, 2018, p. 484), namely neutral K mesons, that are no constituents of ordinary material objects. Hence, the verdict is that CP violation is irrelevant for the problem of time's directedness.[1]

In this paper I shall push back against such quick dismissals of CP violation as a potential source of explanation for the arrow of time and argue that CP violation should be taken more seriously for conceptualising time in physics. Here is why in a nutshell. There are essentially two arguments for the irrelevance claim that CP violation cannot play any role in explaining the directedness of time: (1) as a tiny effect at the level of subatomic particles it is unclear how CP violation can be responsible for large scale macroscopic behaviour, and (2) CP violation does only affect a few specific subatomic particles that do not constitute ordinary matter (that is, they are 'exotic').

In its generality, the first argument, which I dub the 'scale objection',[2] is hardly convincing without further elaboration. It is fair to assume that it is entirely uncontroversial that there are plenty of large-scale effects that can be traced back to the behaviour of subatomic particles. There are versions of this argument that have more force, but can be sidestepped, as I shall argue.

The central idea of the second argument, which I dub the 'universality objection', seems convincing at first: if CP violation is an effect of very specific exotic particles only, how should it affect ordinary material objects and their processes (in time) at all? Accordingly, why should CP violation have anything to do with time? My reply, in short, is that CP violation does not only affect exotic particles. CP violating processes are the result of a central aspect of our best theory of fundamental particle physics that ultimately affects all ordinary matter, as I shall argue. Thus, the second argument is based on a false premise.

Here is the plan of this paper in more detail. First, I briefly review the extant proposals for dealing with the problem of the arrow of time in section 2. Although I tend to agree with critics of the standard view (due to Albert and Loewer), I argue that alternative accounts à la Maudlin (2007), which posit an intrinsic fundamental direction of time, are not fully convincing either (sections 3 and 4). Instead, I shall propose my own account that utilizes CP violation and

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[1] Maudlin (2007, p. 136) puts the worry as follows: 'The passage of time is ubiquitous and manifest. Violation of CP is rare and subtle. If the orientation of time's passage were just the orientation that the Weak Interaction is attuned to, wouldn't we have trouble explaining how we can be so surely and easily aware of the direction of the passage of time?'

[2] See, for example, Price (2011). Roberts (2022, pp. 189–190) calls it the 'weak signal objection'.

recent results from work on the dynamical approach to relativity theory. In preparation, I briefly review some basics of fundamental particle physics in section 5 and give five reasons why CP violation is not just some minor exotic effect, but a fundamental aspect of our best physical theory that deserves more attention. In sections 6 and 7 I then argue that it is especially a refined understanding of Brown and Pooley's dynamical approach which makes more explicit why CP violation is relevant for the problem of time's directedness. I end with a short conclusion.

2 Extant Solutions to the Problem of the Arrow of Time

So how to explain the temporal arrows that we observe, for example, in higher-level physics? Broadly speaking, we can group the various solutions into reductive and non-reductive accounts. Non-reductionists want to explain the higher-level asymmetry by accepting a fundamental or primitive arrow of time. Reductionists, on the other hand, try to explain the arrow of time in terms of something else, for example, fundamentally asymmetric dynamics or certain asymmetric boundary conditions. The most important reductive account—and arguably the dominant view on the direction of time at least in the philosophy of physics—is due to David Albert and Barry Loewer.[3] They employ an asymmetric boundary condition that Albert (2000) dubs 'the past hypothesis'.[4] The idea is to take the directionality of time as derivative of contingent facts about how matter is distributed in spacetime. The motivating conviction is again the widely shared belief that our best fundamental physics does not provide a direction of time, that is, that our best fundamental physics is time-symmetric. Neither the fundamental dynamics, nor spacetime provide a temporal asymmetry, that is, a distinction between the future direction and the past direction. As a result, one needs to draw on other resources when explaining time-asymmetric higher-level behaviour, or so they argue.

To better understand this rationale, take the most prominent arrow of time in higher-level physics, the second law of thermodynamics: entropy tends to increase towards the future but not towards the past. This is often called the 'entropic arrow' or the 'thermodynamic asymmetry'. To explain it, it seems, one would have to turn to what underwrites thermodynamics, namely, statistical mechanics. According to statistical mechanics and its typicality arguments,[5] the entropy of a system increases towards the future because this behaviour is more typical for the system, that is, given a macrostate most of the compatible microstates evolve towards higher

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[3] Based on Boltzmann (1897). A related proposal is due to Reichenbach (1956); see Fernandes (2022).

[4] More recently, Albert and Loewer defend this proposal in terms of what they call 'The Mentaculus' (Loewer, 2012, 2020).

[5] Typicality is a standard way to make sense of statistical mechanics. The concept is based on the fact that statistical mechanics analyses a given macrostate of a system in terms of a set of many different microstates. 'Intuitively speaking, something is typical if it happens in the vast majority of cases' (Frigg and Werndl, 2012, p. 917). So, a system's evolution from one macrostate to another macrostate (say, from non-equilibrium to equilibrium) is typical, if most of the corresponding microstates evolve that way. See also Loew (2018, p. 485, fn. 4). Notably, Albert and Loewer themselves seek to capture the statistical characteristics not via typicality, but by assuming a suitable statistical postulate.

entropy. But a problem arises: typicality alone is not sufficient to explain the thermodynamic asymmetry. This is because typicality arguments are independent of the temporal direction: 'having evolved from a state of higher entropy in the past ... is ... as typical for a system as evolving into a state of higher entropy in the future' (Loew, 2018, p. 486). Typicality arguments are symmetric. Hence, they cannot establish an asymmetry. So, to explain asymmetric behaviour, we need something else: we need something that distinguishes the two equally typical scenarios 'having evolved from a state of higher entropy in the past' and 'evolving into a state of higher entropy in the future'. This can be done by an asymmetric boundary condition, that is, by fixing that entropy was lower in the past—either by posit or by some independent explanation.[6] The past hypothesis is such a posit (arguably without further explanation).[7] By help of this posit we can then say, for example, that the directionality of time is nothing but the direction in which the entropy of the universe increases.

The main reason to pursue an alternative to this view—be it a different reductive account or a non-reductive account—is a dissatisfaction with the explanation offered by Albert and Loewer. Essentially, the verdict is that their explanation is empty, insufficient and/or ad hoc—at least if the past hypothesis itself is not backed up by an explanation:

> in order for this to work the constraint must itself be specifiable independently of what will result from the operation of the laws. A homely example: we want to explain the occurrence of an earthquake in terms of the preceding state of the underlying geology and the dynamics that governs them. This works fine so long as the precedent state is described in terms like pressures and fissures and plate movements and so on, terms that can be plugged into the laws to determine how the system will evolve. It does not work as an explanation if the only characterization one provides of the underlying geology is 'in a state such as to lead to an earthquake in the near future'. Explaining the occurrence of the earthquake in these terms is clearly empty. (Maudlin, 2007, p. 132)

I do share this concern. The remaining options are then to either (1) provide an independent explanation for the past hypothesis or (2) to do without it. Given that all attempts at explaining why the universe started out from a low-entropy state are highly speculative (see footnote 7), I shall assume for the rest of the paper that the past hypothesis is out of the picture for

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[6] For example, some theory about the early universe could explain why entropy was lower in the past.

[7] It is controversial whether the past hypothesis requires further explanation. Price (2004) demands an independent explanation, Callender (2004) argues that such initial conditions do not require further explanation (see also Voggenauer (2023a)). For Loewer, assuming the past hypothesis is sufficiently justified by the fact that it fulfils the criteria for a best-system law of nature (Loewer, 2021, p. 1083). Voggenauer (2023b), on the other hand, implicitly criticizes this assessment when discussing the merits of local assumptions over global assumptions. Besides all this, there are, in fact, (highly speculative) candidate explanations available. For example, explanations from inflation, anthropic reasoning or the Weyl hypothesis are discussed in the literature (Ainsworth, 2008, p. 159). I thank an anonymous reviewer for pushing me to clarify this. In general, disagreement about what kinds of explanations are permissible (for example, Read and Le Bihan (2021, Sect. 6))—or, similarly, when to stop demanding an explanation—is at the heart of such debates.

explaining the arrow of time, that is, that we have to do without it (at least we have good reason to carefully explore the second option). By design, non-reductive accounts opt for this and propose to implement a fundamental directionality that is intrinsic to spacetime. But note that also a different reductive explanation (that is, without reference to the past hypothesis but to something else) is still on the table—my own proposal will be of this type.

Before I discuss specifically Maudlin's non-reductive proposal in more detail below, let me briefly mention another non-reductive account that argues for a fundamental temporal asymmetry intrinsic to spacetime on the basis of general relativity, namely the 'cosmological approach' due to Castagnino et al. (2003) and Castagnino and Lombardi (2009); see also Bartels and Wohlfarth (2014) and Voggenauer (2023a). The general challenge for the cosmological approach to the arrow of time is that a fundamentally asymmetric feature of spacetime itself is not apparent in relativity theory. The Einstein field equations are time-symmetric, so, generally, relativity theory does not yield a distinction between future light-cones and past light-cones. More precisely, the problem is that the time-symmetric Einstein field equations have both time-symmetric and time-antisymmetric solutions (representing temporally non-oriented and oriented spacetimes, respectively). Now, the proposal is to restrict the Einstein field equations by adding a matter field. In other words, empty worlds without matter are dismissed. As a result, (almost) all solutions are time-asymmetric (the symmetric solutions are of measure zero). Accordingly, the restricted equations describe worlds with a temporal orientation. Worlds without matter fields will generally not have the feature of being temporally oriented. It is important to note that the proposal does not introduce an asymmetry by hand (unlike what some suspect to be the case for the past hypothesis, for example). Rather, the appropriate restrictions are a by-product of introducing a matter field. So restricting the solution space of the Einstein field equations can be justified by the fact that spacetimes without matter fields (or other dynamical variables in addition to the scale factor) do not describe physical universes (Voggenauer, 2023a). Arguably, this is what makes the approach attractive.[8]

Tim Maudlin takes a different path. As the quotation above demonstrates, Maudlin urges the proponent of the standard approach to explain why entropy was lower in the past. Why is it, Maudlin asks, that typicality arguments only work correctly in one direction of time? Maudlin's own answer involves two key aspects. First, Maudlin (2007) proposes to posit a primitive, fundamental and intrinsic time direction—which is mathematically represented by an

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[8] Note that there are therefore two striking similarities to my own proposal in section 7: (1) since the g-field is arguably only reducible to matter field dynamics for globally-hyperbolic solutions (Salimkhani, 2023, pp. 114–117; pp. 171–172), my approach implicitly assumes a restricted solution space of general relativity; (2) in my approach, whether or not the spacetime metric of some world has the feature of being oriented, depends on the actual matter field content of that world. There is a also a striking difference, though: for there to be a time asymmetry, my proposal requires that the world contains specifically CP-violating matter fields. This is not the case for the cosmological approach, which seems to work with any (classical) matter field. However, my account will offer an explanation for why all matter participates at CP violation. In addition, since the cosmological approach is purely classical (including matter fields), there is a sense in which my proposal offers a generally compatible explanation in terms of more fundamental posits: the cosmological approach considers the classical 'placeholder' matter of general relativity, while my approach considers the more fundamental constituent matter fields.

orientation of the spacetime manifold. Second, he proposes to introduce a 'production relation' between states. The explanatory role of the second posit is that, according to Maudlin, the atypicality of the backward evolution of microstates is a result of there being a 'fact about which states produce which' (Maudlin, 2007, p. 134). So, the production relation is supposed to explain why the backward evolution is atypical: the backward evolution runs counter to the actual production relation. The intrinsic time direction is supposed to support this explanation as follows: the assumption of an intrinsic direction of time gives rise to these facts about which states produce which: 'earlier states produce later states' (Maudlin, 2007, p. 134). So, even given time-symmetric fundamental laws 'we would have reason to accept an intrinsic asymmetry in time itself' (Maudlin, 2007, pp. 134–135). Together, this is supposed to explain the thermodynamic asymmetry without invoking the past hypothesis.

However, Maudlin has been criticized for not spelling out his proposal in more detail (for example, Loewer (2012) and Loew (2018)). According to Christian Loew, it remains unclear how the intrinsic direction of time gives rise to such a production relation and how the production relation helps to explain, for example, the thermodynamic asymmetry (Loew, 2018, p. 487). Moreover, Loew wants Maudlin to be more specific about the nature of his primitive direction of time that is represented by an orientation of the spacetime manifold. Loew (2018) therefore attempts to present a metaphysical solution to these issues. Building on Maudlin's proposal, Loew aims to 'examine[] whether we get a better explanation of the thermodynamic asymmetry if we posit an intrinsic direction of time in addition to time-asymmetric boundary conditions' (Loew, 2018, p. 483). Amongst others, Loew aims to explicate how we may understand the posit of an intrinsic directionality of time such that it connects to the production relation. He argues that the intrinsic directionality of time is best understood in analogy with grounding—that is, an asymmetric, extra-modal type of determination relation that gives rise to relative fundamentality (Loew, 2018, p. 488).[9] The idea is, roughly, that as an asymmetric grounding-type determination, the intrinsic directionality of time trumps the potentially symmetric necessitation relation of the laws. This entails that the earlier states are metaphysically more fundamental than the later states (that exist in virtue of them), and underwrites a notion of production. In this way, we can think of Loew's proposal as offering a metaphysical account of Maudlin's production relation and, hence, the thermodynamic asymmetry.

In short, my criticism of Loew's approach is that it is heavily metaphysical without sufficiently connecting to physics. In a sense, such a metaphysical explanation puts the cart before the horse: when seeking to explain some fundamental structure of the physical world, we usually inform our metaphysical inferences by consulting our best theories of fundamental physics, not the other way around. We seek a metaphysical account that is based on a physical explanation. In particular, one might wonder whether there is any further sense in which physics could underwrite the apparent directionality of time. Otherwise, the worry goes, Loew's metaphysics-heavy

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[9] For a nice introduction to the grounding concept in the context of philosophy of physics see McKenzie (2022).

explanation—which is arguably based, first and foremost, on our everyday conception of time as asymmetric—is poorly justified or even in danger of contradicting physics.[10] Also, how does the proposed relative fundamentality of earlier states (or the absolute fundamentality of the initial state) fare with other notions of fundamentality? For example, one might contest that the producer is metaphysically more fundamental (in the grounding sense) than the product. In sum, it seems advisable to be metaphysically more neutral than Loew, that is, to shift the explanatory burden from metaphysics back to physics. Or, to put it less critically: Are there other (additional) ways to justify the posit of a fundamental arrow of time or is it possible to explain the arrow of time reductively (again, without reference to the past hypothesis)? In fact, Maudlin himself does give a supplementary justification for positing a fundamental arrow of time. I shall now briefly present this justification and then turn to my own proposal of reductively explaining the arrow of time.

3 Engraving Topology

As mentioned, Maudlin (2007) does offer some remarks on what positing a direction of time could mean precisely, namely positing that the fundamental manifold has an orientation (Maudlin, 2007, p. 118). However, Loew (2018) is right to call for a more explicit proposal that is linked to the production relation. Such a proposal can be found in Maudlin's subsequent work on topology (see Maudlin (2011, 2014, 2015a,b)). Maudlin can be read as backing up his primitivist account of the direction of time by a particular understanding of topology. To put it the other way round, Maudlin's taking seriously the possibility of an intrinsic directionality of time may be understood best in light of his 'line-based topology'.

Line-based topology is a non-standard axiomatization of topology based on fundamental line elements instead of the standard topology's fundamental open sets. At first, this is just a reconceptualization of standard topology. The interesting feature, however, is that the fundamental line elements have to be conceptualized as fundamentally directed line elements ('one-way streets') to be able to reproduce all topologies of standard open-set topology one by one. Just using (non-directed) line elements reproduces too few topologies.[11] As soon as we conceptualize the line elements as directed, however, we can solve this problem (Maudlin, 2011, 2015b). In this way, Maudlin argues, directed line-based topology reveals that most standard topologies actually have an intrinsic directionality that is hidden in the standard formulation

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[10] The problem of the arrow of time is certainly an interesting case study for studying the interplay between science and metaphysics (see also Emery (2023)).

[11] Non-directed line-based topology is highly restrictive and will give significantly less topologies than standard topology and directed line-based topology do (Maudlin, 2011, 2015b). Take a set of 2 points $\{a, b\}$. Standard topology will give 4 different topologies built from these 2 points—(1) the empty set and the full set are open sets; (2) all sets are open sets; (3) all sets but $\{a\}$ are open; (4) all sets but $\{b\}$ are open. Non-directed line-based topology, however, will only give 2 different topologies—either a discrete topology with every set ($\{\}$, $\{a\}$, $\{b\}$ and $\{a, b\}$) being open, or an indiscrete topology with only $\{\}$ and $\{a, b\}$ being open sets. Similarly, for 5 points we get around 7,000 standard topologies, but only 52 undirected line-based topologies (Maudlin, 2011, p. 200).

(Maudlin, 2011, 2015b).

Obviously, it is here where one can link the topological insights to time. The essence of a line is a linear order among spacetime points or events at spacetime points. The question is then, what physical structure could generate a directed linear order among events. Maudlin (2015a) takes it that the 'before and after' relation conveys this linear order. Hence, for him, the fundamental directedness of directed line-based topology should be interpreted as a fundamental time-directedness. On this view, the directionality of time is a good candidate for a fundamental structure of the world, because it is indispensable for correctly conceptualising topology, as can be seen when translating standard topology into line-based topology.

Now, taking Maudlin's proposal of a fundamentally directed topology in terms of time-directed line elements physically seriously has further implications. It excludes unphysical worldlines from the start—which Maudlin takes as a feature (Maudlin, 2011, p. 212; 2015b); after all, when using the standard four-dimensional manifold one has to exclude these worldlines as unphysical anyways. Theories like special relativity and general relativity which are often said to have 'spatialized' time—time is just another dimension—start from some ready-made open set topology that manifestly treats time as just another dimension—it locally looks Euclidean. But why, asks Maudlin (2015b), should a four-dimensional manifold that locally looks like Euclidean space be the correct space to represent spacetime? Maudlin argues that directed line-based topology interpreted as a time-directed line-based topology makes obvious why this is misleading: the standard four-dimensional manifold allows for many lines that do not correspond to anything physical. The geometry of this four-dimensional space is too rich, most of it is not needed to represent physically possible worldlines—again, this is why physics practice has to exclude such lines (like space-like worldlines) as 'unphysical' after the fact (Maudlin, 2015a).

Thus, by imposing this physicality constraint, Maudlin essentially engraves a directionality into the topology and identifies this topological directionality with time. Since we typically do not try to further explain topological structure, but just start from some fundamental manifold, this is a forceful option. Indeed, what physical structure should ever be able to explain or ground topological structure? The manifold is usually viewed to be a good candidate for a fundamental entity.[12] So, at least to a certain extent, Maudlin may be able to counter Loew's critique.

It is not obvious, however, that this non-reductive account of the directionality of time is without problems. In particular, it must be explained in more detail how its mathematical and metaphysical motivation connects to physics. Arguably, one also needs to investigate how a topological orientation translates to picking out a preferred time direction.[13] It seems that Maudlin would still need something like Loew's proposal.

And, anyways, why is the engraving topology account better than simply excluding certain mathematical excess structure as unphysical after the fact, or than obtaining a directionality from

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[12] This connects to a recent debate on how to dynamically account for topological structure (see Norton (2008) and, against this, Menon (2019) and Linnemann and Salimkhani (2021)).

[13] This is similar to Loew's first worry regarding Maudlin (2007).

introducing a matter field, for example? Ultimately, it again seems that this strategy amounts to inscribing the desired feature into the fundamental ontology without further arguments from physics. Now, one could argue that this is completely fine as long as such posits are consistent with science. Still, one might want to pursue a less prescriptive and more natural explanation based on the dynamical laws of physics (and a dynamical understanding of them).

4 No Time Feelers Either

More importantly, however, we might contest that what Maudlin offers is actually providing an (appropriate) explanation in the first place. Essentially, the worry is that an intrinsic directionality of spacetime is isolated from having any bearing on material bodies. Now, Maudlin does seem to attempt to provide such a connection to the matter dynamics in terms of his production relation, but it arguably still remains unclear how the topological asymmetry (relating to spacetime) can give rise to the production relation (relating to matter). What comes closest to assuming the role of connecting both sectors (spacetime and matter) is his claim that CP-violating laws (relating to matter) imply 'that space-time itself, in order to support such laws, must come equipped with an orientation' (Maudlin, 2007, p. 120).[14] So, firstly, the explanatory role of CP-violating laws would actually be more prominent than Maudlin admits (which is grist to my mill)—recall that his account is supposed to work without challenging the standard lore that all fundamental laws are time-symmetric (see above). But, secondly, why does spacetime need 'to support such laws' if spacetime and the dynamics of matter are ontologically independent, self-standing structures? Why should we believe that 'space-time itself, in order to support such laws, must come equipped with an orientation'? I will come back to this issue in section 6.

For now, I take it that Maudlin's proposal may seem appropriate and handy for our (mathematical) description of directed material processes, but the material processes themselves do not seem to have access to the posited directionality of spacetime: matter particles do not have time feelers—at least, one would need to argue for this option. To solve this problem, the asymmetry in (space)time needs to be accompanied by or grounded in an asymmetry in the matter content.

Famously, Harvey Brown (2005) draws attention to a similar issue.[15] Concerning the so-called geometrical–dynamical debate in the philosophy of spacetime he asks: '[w]hat is geometry doing here—codifying the behaviour of free bodies in elegant mathematical language or actually explaining it' (Brown, 2005, pp. 23–24)? The proponent of the geometrical approach opts for the latter. Spacetime is taken as fundamental and as explanatory of free body motion. Taking spacetime as explanatory in this sense seems to amount to taking the geodesics as 'ruts or grooves in space-time which somehow guide the free particles along their way' (Brown,

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[14] It seems relevant to recall that Maudlin takes laws as fundamental (Maudlin, 2007, p. 106).

[15] The following presentation uses Salimkhani (2023, pp. 59–60).

2005, p. 24). This is arguably reminiscent of Hermann Weyl's 'Führungsfeld' (guiding field).[16] Advocating a similar view as Weyl, Nerlich (1976) argues that particle motion is explained by the 'shape' of spacetime, because a particle has no other way of 'knowing' how to move, '[i]t has no antennae to tell it where other objects are' (Nerlich, 1976, p. 264; as cited in Brown (2005, p. 24)). Brown concedes that 'there is a *prima facie* mystery as to why objects with no antennae should move in an orchestrated fashion. That is precisely the pre-established harmony, or miracle' (Brown, 2005, p. 24). Still, Brown, pushes back:

> it is a spurious notion of explanation that is being offered here. If free particles have no antennae, then they have no space-time feelers either. How are we to understand the coupling between the particles and the postulated geometrical space-time structure? (Brown, 2005, p. 24)

Brown later supports his claim that test particles do not 'read' the spacetime geometry by the fact that their geodesic motion is only approximate in general relativity (Brown, 2005, p. 24).[17]

In the case of special relativity, Brown concludes that spacetime geometry is merely a 'codification' of free body motion—essentially, because he deems the geometrical explanation not only obscure, but also redundant:

> At the heart of the whole business is the question whether the space-time explanation of inertia is not an exercise in redundancy . . . It is non-trivial of course that inertia can be given a geometrical description . . . But what is at issue is the arrow of explanation. The notion of explanation that Nerlich offers is like introducing two cogs into a machine which only engage with each other. It is simply more natural and economical—better philosophy, in short—to consider absolute space-time structure as a codification of certain key aspects of the behaviour of particles (and/or fields). (Brown, 2005, pp. 24–25)

As already put forward above, this issue reappears with respect to the directionality of time. Even if there is an intrinsic directionality of spacetime, how is it supposed to be explanatory of the temporal behaviour of material bodies? How would they 'know' about the direction, given that they certainly do not have time feelers either? It seems that any intrinsic temporal asymmetry of spacetime needs to be either accompanied by or grounded in an appropriate asymmetry in the dynamical behaviour of matter fields.

As discussed above, Maudlin himself does make use of this interdependence of spacetime and matter fields to boost the plausibility of his own account: for him, the existence of

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[16] See Weyl (1970, VI).

[17] Essentially, this is because the geodesic principle follows from the dynamics. '[I]t is not enough that the test particle be force-free' (Brown, 2005, p. 141). For example, 'spinning bodies for which tidal gravitational forces act on its elementary pieces deviate from geodesic behaviour. What this fact should clarify . . . is that it is not simply in the nature of force-free bodies to move in a fashion consistent with the geodesic principle. It is not an essential property of localized bodies that they run along the ruts of space-time determined by the affine connection, when no other dynamical influences are at play' (Brown, 2005, p. 141).

CP-violating phenomena (which originate in time-asymmetric dynamical laws) implies that spacetime requires an orientation to be able to support such time-asymmetric laws. This draws attention to the fact that there is still an option left for further exploration: providing a reductive account of Maudlin's primitive arrow of time. In the following, I intend to exploit that option and show—*pace* the received view—that CP violation in fundamental particle physics is a wrongfully neglected candidate for explaining the arrow of time.

5 CP Violation

To get started, recall that in particle physics C, P, and T are discrete symmetry transformations. C denotes charge conjugation, which essentially means that a particle is transformed to its antiparticle. More specifically, an incoming particle X with 3-momentum $\vec{p}$ and spin vector $\vec{S}$, transforms under C to its complex conjugate $\bar{\mathrm{X}}$ as follows: $\mathrm{C}\,|\mathrm{X};\vec{p},\vec{S}\rangle_{\mathrm{in}} = |\bar{\mathrm{X}};\vec{p},\vec{S}\rangle_{\mathrm{in}}$. The parity transformation P flips the orientation of the three spatial coordinates, such that $\mathrm{P}\,|\mathrm{X};\vec{p},\vec{S}\rangle_{\mathrm{in}} = |\mathrm{X};-\vec{p},\vec{S}\rangle_{\mathrm{in}}$. And time reversal transformation T can be understood as flipping the time direction. There is a long debate on how to conceptualize time reversal transformations precisely (see Albert (2000), Callender (2000), Earman (2002), Peterson (2015), Roberts (2017; 2022), and López (2019; 2021)). In this paper I refer to the standard conception of particle physics where a state transforms under T as follows: $\mathrm{T}\,|\mathrm{X};\vec{p},\vec{S}\rangle_{\mathrm{in}} = |\mathrm{X};-\vec{p},-\vec{S}\rangle_{\mathrm{out}}$. Note that T also changes an incoming to an outgoing state. One can also combine the transformations, for example to charge conjugation parity transformation, short: CP transformation, which yields $\mathrm{CP}\,|\mathrm{X};\vec{p},\vec{S}\rangle_{\mathrm{in}} = |\bar{\mathrm{X}};-\vec{p},\vec{S}\rangle_{\mathrm{in}}$. In all standard quantum field theories the combined transformation CPT, which yields $\mathrm{CPT}\,|\mathrm{X};\vec{p},\vec{S}\rangle_{\mathrm{in}} = |\bar{\mathrm{X}};\vec{p},-\vec{S}\rangle_{\mathrm{out}}$, is an invariant symmetry transformation, that is, the result is identified with the original state: $|\bar{\mathrm{X}};\vec{p},-\vec{S}\rangle_{\mathrm{out}} \equiv |\mathrm{X};\vec{p},\vec{S}\rangle_{\mathrm{in}}$. Notably, applying each transformation twice to some particle state does not change the state, that is, $\mathrm{C}^2 = \mathrm{P}^2 = \mathrm{T}^2 = 1$, up to a phase.[18]

Now, the question is whether physical processes are invariant under these transformations. For example, if all physical processes were invariant under parity, then physics would not distinguish between left- and right-handedness. While most processes are invariant under these transformations, some involving the weak force are not. For example, a positively-charged pion—which is composed of an up quark and an anti-down quark ($\mathrm{u}\bar{\mathrm{d}}$)—always decays to an

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[18] This presentation follows standard textbooks, but is somewhat imprecise. On this definition, each state would transform back to itself. Thus CPT would be the identity operator. This, however, is false, since the identity transformation is unitary, whereas CPT is antiunitary. As a result, my presentation is not entirely accurate. CPT does generally preserve unitary evolution, but not necessarily each individual state. Time reversal symmetry means that T commutes with the Hamiltonian. This is equivalent to saying that the solution space of the Schrödinger equation is preserved and to postulating that, under T, the unitary propagator $U(t)$ transforms to its adjoint, $TU(t)T^{-1} = U^*(t) = U(-t)$. This holds analogously for CPT symmetry: to say that laws are CPT invariant is to say that there exists a CPT operator that transforms the timelike translations $U(t)$ to their inverse $U(-t) = U^*$. In terms of the S-matrix, this means that S transforms to S^*. See, for example, Haag (1996), the presentation in Swanson (2019), and Roberts (2022). I thank an anonymous reviewer for kindly correcting me on this.

anti-muon and a left-handed neutrino ($\pi^+ \longrightarrow \mu^+ + \nu_\mathrm{L}$).[19] This violates parity symmetry. So there are physical processes that distinguish between left- and right-handedness.

Similarly, neutral K-meson decay is observed to violate CP symmetry.[20] The decay rates of the CP-transformed and the original process are slightly different. Notably, via the CPT theorem, which essentially follows from Lorentz invariance and roughly states that any standard quantum field theory preserves CPT symmetry, CP violation implies T violation. So, on the face of it, there are physical processes that distinguish between orientations in time.

Typically, however, the relevance of CP violation in kaon decays for the directionality of time is questioned (for example, Price (2011), Loew (2018)). This is for two reasons: (i) the effect is tiny—call this the scale objection—and (ii) apparently a feature of specific particles only, namely neutral K-mesons, that do not constitute ordinary material objects—call this the universality objection. Essentially, the reasoning is that to explain a phenomenon as large and universal as the asymmetry of time, the explanans has to be large and universal as well.

In the following, I intend to push back against such verdicts.[21] Here are five reasons why CP violation cannot be so quickly dismissed as a curious and minuscule empirical observation that has no bearing on the arrow of time. The first three arguments address the universality objection, the last two the scale objection.

First, addressing the universality objection, CP violation is not observed only for neutral kaons. Since 2001 at the latest, it has been known that CP violation is not merely an effect in the kaon sector. CP violation has also been observed in several B-meson decays and other processes involving the weak force. Moreover, direct T violation was observed independently of the assumption of the CPT theorem in 2012 by the BABAR Collaboration.

The universality objection can be challenged further, which provides the second reason: CP violation is not only experimentally observed, but is sufficiently well understood theoretically. In particular, we know that it is a key feature of our best theory of fundamental particle physics, the Standard Model. Here is why. According to the Standard Model (and our experimental data, of course), there are three quark families. This empirical fact has an important implication for what is called quark mixing.[22] For three quark families, quark mixing is described by a complex 3×3 matrix—the CKM matrix. The CKM matrix necessarily contains an irreducible complex phase (Halzen and Martin, 1984, p. 289). It is this complex phase which gives rise to CP-violating processes. CP violation (and, hence, T violation) is a consequence of the fact that there is an irreducible complex phase in the CKM matrix of the Standard Model. In other

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[19] The primary decay mode is a leptonic decay into an anti-muon and a muon neutrino, that is, $\pi^+ \longrightarrow \mu^+ + \nu_\mu$. The decay into the lighter positron and an electron neutrino $\pi^+ \longrightarrow e^+ + \nu_e$ would offer a larger phase space, but is strongly helicity suppressed.

[20] A neutral K-meson is composed of a linear superposition of down and strange quarks, namely $d\bar{s} - \bar{d}s$.

[21] An independent and quite direct argument in support of universality is presented by Roberts (2022, pp. 171–174): 'Demanding an empirical basis for temporal symmetry thus leads to the result that time reversal symmetry violation establishes an arrow of time itself' (Roberts, 2022, p. 174).

[22] Quark mixing is essentially a result of the quarks having non-vanishing mass due to the Higgs mechanism, such that the quark mass eigenstates are generally different from quark interaction eigenstates.

words, CP violation (and, hence, T violation) is a direct consequence of there being (at least) three interacting quark families with non-vanishing mass. If there were only two quark families (as it was also assumed historically, prior Kobayashi and Masukawa, based on the empirical data available at that time by Cabibbo), the corresponding 2×2 quark mixing matrix would be real rather than complex. Accordingly, there would be no complex quark mixing phase and, hence, no CP (or T) violation. This shows that CP violation is a fundamental aspect of our world in a very robust sense: the third quark family is here to stay.

Third, the universality objection is most strongly contested by our understanding of vacuum fluctuations in quantum field theory and, more concretely, by our theory of hadron constitution: while a hadron's quantum numbers are determined by the so-called valence quarks, these valence quarks carry just one half of the hadron's total momentum. This is because every hadron also consists of, most importantly, gluons and so-called sea quarks. Sea quarks are virtual quark–anti-quark pairs ($q\bar{q}$) that are continuously created and destroyed.[23] They are created when a gluon splits, and destroyed when two sea quarks annihilate to produce a gluon. Via this sea of quarks and gluons, essentially all ordinary matter participates at CP violation in the quark sector. Similarly, due to vacuum fluctuations even 'empty' spacetime is not isolated from such processes.

Let me now turn to the scale objection. First, in its generality, the scale objection is hardly convincing without further elaboration. It is fair to assume that it is entirely uncontroversial that there are plenty of large-scale effects that can be traced back to the behaviour and properties of elementary and subatomic particles—take the temperature of a gas, for example. This is precisely what reductive explanations or part–whole explanations are usually about. After all, already the CP-violating meson decays are traced back to their constituent quarks.

However, there are versions of this argument that have more force. The phenomenon of decoherence, which screens off quantum effects from the classically describable world, or the robustness of higher-level physics against certain changes in the underlying micro-structure are indicative of how the relevance of CP violation might be confined to the level of subatomic particles. To avoid the problem of spelling out how CP violation cuts across the different levels from the scale of fundamental particles to the macroscopic scale, I shall therefore ultimately not propose to directly ground directed large-scale processes (like cases of smashed eggs that never reassemble) in CP violation, but argue how CP violation grounds a spatiotemporal orientation that can be used to align other, arguably independent arrows of time with it.[24] That CP- and T-violating processes are directed (that is, violate time reversal invariance) does not mean that only one direction of the process is observed—both are, but they occur at different rates. So, *prima facie*, it is unclear how CP and T violation should be able to directly connect to processes that only occur in one direction, as in cases of smashed eggs. Sidestepping this issue will also

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[23] Sea quarks may still hadronize to on-shell baryons or mesons.

[24] Arguably, this addresses the universality objection as well: if CP violation grounds a spatiotemporal orientation, this is automatically relevant for all objects in spacetime.

help to connect lawlike asymmetries, like CP and T violation, to an asymmetry of spacetime structure (but see Price (1996, Ch. 1)), as I argue below.[25]

Still, and here is the second reason against the scale objection, unlike parity violation, CP violation does have well-known large-scale explanatory significance: CP violation is crucial for explaining the matter–antimatter asymmetry of the universe (Sakharov, 1967). Arguably, this emphasizes the relevance of CP violation. In particular, it directly runs against the scale objection and can even be used to itself establish a global time direction for the universe. In this paper I shall not opt for this global time direction, since I take the evolution of the matter–antimatter abundance not as a fundamental arrow of time itself, but merely as an observable consequence that is derivative on the more fundamental CP-based arrow of time.

There remains an important and well-known caveat, though, that might reinforce some version of the scale objection: we know that the CP-violating phase in the CKM matrix of the Standard Model does not suffice to explain the observed matter–antimatter asymmetry (Sakharov, 1967). This is precisely why physicists are searching for additional CP-violating phases in extensions to the Standard Model. Theoretically, there are several candidate sectors where such additional CP-violating phases are expected: most importantly in the neutrino sector[26] and in supersymmetric extensions of the Standard Model.[27] So the fact that the CKM phase does not suffice to explain the matter–antimatter asymmetry should not be understood as a problem *per se* for CP-based explanations.

To summarize, CP violation—and hence T violation—is not merely a peculiar feature of some exotic particles, but an integral and irreducible part of our best physical theory that affects, amongst others, (processes in) all baryonic, that is, ordinary matter and is needed to explain the matter–antimatter asymmetry.

6 The Dynamical–Geometrical Debate Revisited

Nevertheless, the question remains how exactly CP and T violation become relevant to the directionality of time. In particular, it is important to remember that these symmetry violations do not yield an arrow of time in the sense that such processes would only occur in one direction (as in cases of smashed eggs that do not reassemble). CP and T violating processes do occur in both directions, but one direction is preferred, that is, the process and its reverse occur at different rates. Accordingly, it seems that such asymmetries cannot directly ground directed processes as in cases of smashed eggs. In addition, the behaviour of, say, an ideal gas seems to be independent of whether or not the constituents of the gas have CP and T violating properties or not. At least, these observations suggest some caution with regard to directly linking CP

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[25] An alternative route to connect the two is proposed in Roberts (2022).

[26] The observation of neutrino oscillation indicates that neutrinos are massive, such that mixing occurs. As there are (at least) three neutrino families, the mixing matrix will generally contain a non-trivial complex phase as well.

[27] Theoretically one would also expect CP violation for the strong force, however, this has been experimentally excluded, which is known as the strong CP problem.

violation and the thermodynamic arrow of time. Therefore, I shall propose a different route that connects CP violation in the dynamics of fundamental matter fields to an orientation of spacetime itself. This has the additional advantage of also addressing the pressing issue of how dynamical asymmetries connect to asymmetries of spacetime structure.

Recall that also Maudlin claims that the existence of CP-violating phenomena implies that spacetime itself requires an orientation to be able to support such time-asymmetric laws. Such a claim can arguably draw on the well-known principles by John Earman which state that dynamical and spatiotemporal symmetries need to match in any given theory T. Here are Earman's principles (see Earman (1989, p. 46)):

(SP1) any dynamical symmetry of T is a spacetime symmetry of T, and

(SP2) any spacetime symmetry of T is a dynamical symmetry of T.

Any violation of these principles would either result in spacetime's having undetectable structure (violation of (SP1)),[28] or a situation where the dynamics can measure geometrical structure that does not exist (violation of (SP2)).[29] Granted that violating these principles is problematic and that one should demand that they hold,[30] the question is why they should hold—Maudlin does not provide an explanation, but merely posits that given certain time-asymmetric laws also spacetime needs to be oriented. Why (SP1) and (SP2) should hold is precisely what the recent geometrical–dynamical debate in the philosophy of spacetime is about. While the standard geometrical approach holds that the spacetime metric somehow explains the dynamical symmetries, the dynamical approach by Harvey Brown and Oliver Pooley opposes this view.

Centrally, Brown and Pooley[31] argue that the property of a field to act as the spacetime metric that is surveyed by material rods and clocks is not an intrinsic property of that field—as the standard geometrical view seems to claim. Rather, this chronogeometricity is said to be a property that a metric field only has in virtue of the dynamical symmetry properties of those matter fields that make up the material rods and clocks. Only if the dynamical symmetry properties of the matter fields coincide with the symmetry properties of a candidate metric field, does a metric field have chronogeometricity such that it is 'the' metric field.

In the case of special relativity, the proponent of the dynamical approach therefore advocates a form of relationalism: the coincidence of the symmetry properties of the Minkowski metric and the matter field dynamics is explained by the fact that the Minkowski metric is ontologically reducible to the Lorentzian symmetry properties of the matter field dynamics.

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[28] If SP1 is violated, then the dynamics has certain symmetries that are not symmetries of spacetime as well. In other words, spacetime has more structure than the dynamics. This means that there are spacetime structures that are undetectable by the dynamics.

[29] If SP2 is violated, then spacetime has certain symmetries that are not dynamical symmetries. In other words, the dynamics has more structure than spacetime. This means that the dynamics can measure spacetime structures that do not exist.

[30] Myrvold (2019) takes it that (SP1) and (SP2) are analytic. For a critical response see Roberts (2022, Sect. 4.5), who argues that (SP1) and (SP2) are not analytic, but may fail.

[31] See Brown and Pooley (2001; 2006) and Brown (2005).

If the metric field and the matter fields are to be regarded as ontologically independent entities, as the geometrical approach has it, it is unclear why the symmetry properties should coincide. Accordingly, this coincidence must be regarded as a 'miracle', as an unexplained empirical fact: 'As a matter of logic alone, if one postulates spacetime structure as a self-standing, autonomous element in one's theory, it need have no constraining role on the form of the laws governing the rest of the theory's models' (Brown and Pooley, 2006, p. 84). Without additional constraints, it is unclear why the dynamical symmetry properties of the matter fields should not be completely different than the symmetry properties of the metric field. Accordingly, problem cases can be constructed (Read et al., 2018). Regarding general relativity, for example, Einstein's field equations alone do not put any constraints on the matter field dynamics, that is they admit not only Lorentzian but also, for example, Galilean matter fields.

However, the case of general relativity presents a challenge for the dynamical approach as well. This is because the proponent of the dynamical approach to general relativity agrees that the metric field g is a fundamental entity, as the geometrical view has it. Hence, also the proponent of the dynamical approach has to explain why the symmetry properties of the matter fields should coincide with those of g, such that g obtains its chronogeometricity. The proponent of the dynamical approach does so by referring to the strong equivalence principle, which states that all laws of physics are locally Lorentz-invariant. So g obtains its chronogeometricity due to the empirical fact that the strong equivalence principle holds: the strong equivalence principle fixes the dynamical symmetry properties of the matter fields so that they coincide with the local symmetry properties of g.

Due to this recourse to an unexplained empirical fact—the equivalence principle—the dynamical approach to general relativity is explanatorily weaker than in the special-relativistic case. In this sense, the dynamical approach to general relativity is less successful. In particular, the dynamical approach is no longer preferable to the geometrical approach in terms of explanatory strength. In fact, Read (2020) argues that the dynamical approach to general relativity is indistinguishable from any tenable geometrical approach.

Now, I have recently argued that this shortcoming of the dynamical approach to general relativity can be fixed by the spin-2 theory of gravity, which yields an ontological reduction of g to matter field dynamics (see Salimkhani (2020b, 2023)). In brief, the argument is that spin-2 theory provides us with a non-geometrical derivation of the Einstein field equations and can be understood as a fixed-field formulation of general relativity that reduces general relativity to a special-relativistic theory of an interacting massless spin-2 field.[32] Put in terms of the famous God metaphor (Barnes, 2013, p. 876): If God had created a Lorentzian spin-2 field and the other Lorentzian matter fields, she would have created a world described by general relativity with g as the effective metric field.[33]

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[32] See Linnemann et al. (2023) for a critique and Salimkhani (2023, p. 132, fn. 18) for a short reply.

[33] See Salimkhani (2023, pp. 117–129) for the detailed argument.

7 A Dynamical Perspective on the Direction of Time

This ontological reduction of the metric field explains the coincidence of the symmetry properties of the matter fields and the metric field, and thus its chronogeometricity. In particular, the dynamical approach has to accept only one 'miracle' as unexplained and is thus preferable to the geometrical view.

But precisely because metric fields like the Minkowski metric or g are ontologically reducible to matter field dynamics, it is not merely the universal dynamical symmetry properties of the matter fields which are inherited by the metric field. Rather, the matter field dynamics pass on all dynamical properties. In particular, the matter field dynamics equip the metric field with an orientation, if and only if at least some of the matter field dynamics violate CP symmetry.[34]

Already Brown has occasionally pointed out the following: the spacetime fundamentalist, who thinks that the spacetime metric determines the dynamical symmetry properties of the matter fields, should be surprised why some matter fields violate parity, for example, although the respective metric field does not. Take special relativity: according to the symmetry properties of the Minkowski metric there should be no parity violating matter field dynamics. If the Minkowski metric is a fundamental entity that determines the dynamics of matter fields, then why should the Minkowski metric only transfer one of its symmetries, namely Lorentz symmetry, but not parity symmetry and so on? Turning around the ontological dependence relation between the metric and the matter fields solves this problem. Then the respective derivative metric field inherits all properties of the fundamental matter field dynamics. In other words, one only obtains the Minkowski metric, if all matter fields have Lorentzian dynamics and do not violate parity symmetry and so on. This reasoning can be used for the problem of the arrow of time: if matter field symmetries are more fundamental than spatiotemporal symmetries, the established (fundamental) directionality of the former may explain the (derivative) directionality of the latter.

So, if all matter fields have Lorentzian symmetry properties and in addition are not parity violating and so on—for example in a world in which there are only electrons, positrons, and electromagnetic interactions, that is, photons—the effective spacetime is flat Minkowski spacetime. If the world contains gravitons in addition, then spacetime is curved, as is described by GR. And if there are fields that violate CP (for example the fields associated to the weak force), this curved spacetime is equipped with an orientation.[35]

On this view, it is the contingent field content that decides whether a world has a spacetime that is time-symmetric or time-asymmetric—only spacetimes that do not exclusively ontolog-

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[34] See also Salimkhani (2023, pp. 188–189) based on Salimkhani (2020a, p. 181, fn. 113). This reasoning then justifies claims à la Maudlin (2007, pp. 117–118) against critique by, for example, Price (2011, p. 294). See also Roberts' (2022, pp. 188–189) response to Price.

[35] At first sight, this orientation may be conceptualized as a 'local' orientation if the processes themselves are understood to ground it. However, since the properties of these processes are universally fixed, the local orientations imply a global orientation. Alternatively, we may as well understand the orientation as a 'global' orientation from the start, if we take it to be grounded in the (plenist) fields.

ically depend on time-symmetric matter field dynamics exhibit an orientation. To be able to empirically access this orientation, we need to use the CP-violating dynamics.

Notably, obtaining a global orientation seems to work only for sufficiently well-behaved spacetimes or regions of spacetime, namely globally hyperbolic spacetimes. But this is in a sense automatically fulfilled, since spin-2 theory is only strictly equivalent to general relativity for globally hyperbolic spacetimes—all empirically relevant solutions to the Einstein field equations are globally hyperbolic (Wald, 1984, p. 202).

8 Conclusion

I have argued that CP violation is a fundamental aspect of our best physical theory that should not be dismissed when it comes to explanations of time's directedness. In particular, according to Earman, such dynamical symmetry properties need to be reflected in the symmetry properties of spacetime. For making this manifest, I have proposed to utilize recent results regarding the dynamical approach to relativity theory which suggest that the spacetime metric is ontologically reducible to the matter field dynamics. In turn, the symmetries match. Depending on the concrete matter field dynamics, the metric field is then equipped with an orientation, such that a direction of time can be conceptualized. If one accepts that matter field symmetries are more fundamental than spatiotemporal symmetries, as such a dynamical reading suggests, the established (fundamental) directionality in the matter field dynamics can explain the (derivative) directionality of spacetime.

I take it that the dynamical perspective thereby makes more precise and more pressing a conjecture that can already be formulated by spacetime substantivalists like Maudlin, who argues that since some laws of nature are time-reversal asymmetric (referring to CP violation), the laws require an intrinsic time asymmetry—and, hence, also spacetime itself requires some orientation in order to support such laws. The dynamical view is most apt for making this precise, because it dynamically explains this additional structure instead of just putting it in by hand—as Maudlin does it.[36] Furthermore, due to the ontological reduction we do not need to allude to an unexplained adaption between spacetime and laws and vague concepts of spacetime 'supporting' such laws. After all, this is at the heart of the debate on the dynamical approach. It is the ontological reduction that does away with certain otherwise unexplained miraculous facts.

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[36] Similarly, the dynamical perspective might shed light on the issue that a mere direction of time does not suffice to establish a 'passing' of time (but see Maudlin (2007)). Just because space may be equipped with a preferred direction, doesn't make space passing. If passage of time is understood in terms of some 'production' of 'new' states out of previous states, the dynamical picture might have something to contribute. After all, spacetime is conceived as derivative on matter field 'dynamics', which one could link to a process-based ontology.

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