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Re-evaluating space-time

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Abstract

Special relativity inspired a fundamental shift in our picture of reality, from a spatial state evolving in time to a static block universe. We will highlight some conceptual issues raised by the block universe viewpoint, particularly concerning its complexity, causality, and connection to quantum theory. In light of these issues, and inspired by recent results showing that relativity can emerge naturally in discrete space-time dynamics, we will explore whether the evolving state picture might be more natural after all.

1 Introduction

Special relativity [1] lies at the heart of modern physics, and has played a central role in advancing the subject over the last century. It also inspired a fundamental shift in our picture of reality, from a spatial state evolving in time to a static block universe. This conceptual shift raises some deep issues, particularly concerning causality and complexity, which this paper seeks to highlight and address. In light of these issues, we will consider whether relativity could emerge naturally without requiring such a large conceptual shift. For simplicity, we will focus mainly on special relativity, but similar arguments could be applied to the Hamiltonian formulation of general relativity [2], in which space-time can be described in terms of a space-like surface evolving in time.

If reality consists of a state evolving in time via physical laws, causality follows naturally - from an exact description of the state at a particular time, we can determine the state at any future time by applying the physical laws (even if the laws are probabilistic, we can characterise the final probability distribution). If, on the other hand, reality is described by a block universe, a four-dimensional 'box' containing a static structure, it seems highly surprising that we would be able to predict the entire contents of the box from one slice through it. Indeed, causality makes the block universe a highly redundant object. Considering all possible laws for constructing block universes, it seems that causality itself then requires a deeper explanation.

The block universe also seems an intrinsically very complex object to exist without some mechanism for its construction, whereas in the evolving state picture, one could easily imagine that both the initial state and physical laws are simple, and complexity is only generated dynamically (indeed, this could also explain the apparent asymmetry in the universe's boundary conditions). Note that complexity here refers to the amount of computational time required to generate an object, as well as to the compressibility of its description[1]. The intuition is that any substantial computation must be done within the universe, rather than prior to the universe existing.

There are further issues with the block universe in quantum theory, where most interpretations favour the evolving state picture. Finally, the block universe conflicts strongly with our intuition that the 'present' is special.

None of these issues are definitive, and it is certainly possible that these concerns about the block universe can be addressed. However, it is also interesting to consider whether the evolving state picture yields a more natural view of reality even in light of relativity. Formally, it is entirely consistent with special relativity for there to exist a preferred reference frame in which the true state evolves. The issue is that this reference frame would be undetectable, and that relativity then seems unnatural - why should the laws of physics be the same in any inertial frame when only one is 'real'?

A possible solution would be to derive special relativity from a different set of assumptions, such that it emerges naturally even in the evolving state picture. Recent work on particles in discrete space-time suggests that this is highly plausible - relativistic evolution laws emerge naturally there at large scales despite the existence of a preferred frame [4–12]. The key is the existence of a bounded speed of information propagation, which is an appealing assumption in any picture. Can this form part of a natural alternative set of assumptions from which to derive special relativity?

[1] Note that this differs from Kolmogorov complexity [3], which only captures compressibility. The Kolmogorov complexity would generally be small for a block-universe as one could write a compact program to generate it by iterating the physical laws on the initial state

2 Conceptual issues with a block-universe approach

Amongst the general public, the most widely held view about space-time is that only the present is real, and that it changes with time. However, this view encountered a serious problem with the advent of special relativity, which showed that different observers (in particular, those in relative motion with each other) disagree about what constitutes the present. There are two natural options at this point. The first is to claim that the present in some particular reference frame is real, and to explain why observers moving with respect to this frame reach 'mistaken' beliefs about reality [13, 14]. We will return to this approach in section 3. However, this goes against the central principle of relativity that all inertial frames are equivalent with respect to all of the laws of physics.

The second approach, which is the almost universal strategy adopted by theoretical physicists, is to move to a reference-frame independent picture of a block universe. In the block universe approach, reality is a four dimensional space-time manifold [15] in which all events from the beginning to the end of the universe are contained. Describing the universe from the perspective of one particular inertial frame then involves foliating the universe into space-like slices in a particular way. This viewpoint has been hugely successful, and played a key role in the development of general relativity. However, in this section we will highlight some important conceptual issues raised by this shift.

2.1 Causality

All of our physical investigations into the universe so far have confirmed its causal nature – that the future state of the universe can be predicted from its present state via the application of physical laws. In quantum theory, these predictions are generally probabilistic rather than deterministic, but even in this case the probability distribution of any measurement's outcome can be accurately predicted using the Born rule[2] This causal structure is present at the most basic level in the evolving state picture of reality, as the future state of the universe is indeed generated from the present one via physical laws. However, in the block universe approach, causality does not seem inevitable. Indeed, special relativity appears to formally allow tachyons [18]

[2]The idea of retrocausality can be helpful in explaining quantum effects, particularly in cases involving post-selection, such as in the two-state vector formalism [16]. However, a standard causal explanation is also possible. There are also interesting recent results on quantum causal models [17].

which travel faster than light (and thus backwards in time according to some observers), and general relativity permits the existence of closed time-like curves [19]. Moving further away from the specific theories describing our universe, if we consider general rules for describing the contents of a four-dimensional ‘box’, it seems plausible that most such theories would not be causal. For example, one might imagine rules for constructing and linking four dimensional loops inside the box. Perhaps anthropic arguments can be made that universes without at least approximate causality cannot support intelligent life, or it can be show that causality follows from a natural local differential structure of the physical laws, or that given a more general structure one can always find coordinates and time direction for which it is causal. However, a significant advantage of the evolving state picture over the block universe approach is that it offers a simple explanation of observed causality.

2.2 Simplicity

Although it is difficult to speculate about the origins of the universe, one potential issue with the block universe approach is that it requires the entire complex structure of the universe, for all time, to ‘come into existence’ without any mechanism by which it is created. In this view, physical laws themselves are also somewhat redundant, as they arguably just describe some particular properties of the block universe.

By contrast, in the evolving state picture, all that has to ‘come into existence’ is a simple initial state for the universe and a simple set of physical laws. All the later complexity of the universe is then generated dynamically from this starting point, and one can argue that this evolution explains the thermodynamic arrow of time [20].

Note that by ‘simple’ here, we mean something which could be generated on a computer with parallel processing capabilities by a short program in a short time. For example an array of zeroes would be simple (as they could all be generated in parallel), but the Block-universe would be complicated (as one would have to either store the entire structure in memory or compute it from the initial state). It would be interesting to develop this idea further in future work.

Some alternative pictures, such as a growing block universe [21], include an explicit process by which the block universe is formed, and would also count as simple models in the sense described here. However, these do not seem to offer any particular advantages over the evolving state picture.

2.3 The apparent significance of the present

Another apparent advantage of the evolving state picture is that the 'present' is real and changing, and this fits intuitively with our conscious perception of reality. By contrast, in the block universe picture there is no objective present, and young and old versions of each individual co-exist and are presumably all conscious, and all experiencing their own subjective 'now'. It is interesting that many people seem happy to accept a block universe view of spacetime, but reject the 'parallel worlds' of Everettian quantum theory [22]. Although it is certainly possible that the reality of the present, and the dynamic nature of reality, are subjective illusions, a picture of reality closer to our conscious perceptions is appealing.

2.4 Quantum interpretations and time

The arguments above could be applied to both classical and quantum theory. However, the block universe picture arguably fits less well in the quantum case. Most discussions of quantum theory are carried out in the evolving state picture, and this viewpoint is adopted in many of the standard interpretations of quantum theory, including the Copenhagen, Everettian [22], Collapse [23], and Bohmian [24] approaches. In contrast, approaches highlighting a block universe view of quantum reality include the consistent histories approach [25], the two state-vector picture [26–28], and Kent's work on Lorentzian models of quantum reality [29, 30].

In quantum field theory, it is standard to consider the algebra of observables associated with each space-time point, which naturally fits into a relativistic block universe picture. However, if we consider reality to be composed of this set of observables, then one suffers even more from the simplicity argument above, as one must consider a set of operators on infinite dimensional Hilbert space for every space time point, each of which has a complicated structure. The interplay between the information contained in the observables and the (static) initial state is also subtle here, and difficult to interpret directly.

Following an Everettian approach, one could also foliate space-time into a set of space-like quantum states at different times, and note that different foliations yield the same physical predictions. However, it is not clear how to describe the underlying un-foliated reality.

Finally, the Wheeler-de-Witt [31] equation of quantum gravity leads one to consider time as represented by correlations in an essentially spatial state. Recent work has further developed this viewpoint [32], and it offers an interesting alternative picture of reality to explore further, but is similar in spirit to the block universe picture, and many of the issues raised above would also apply to this model.

3 Emergent relativity in a preferred frame

Given the issues raised in the previous section, it is interesting to explore alternatives to the block universe picture. One possibility which is entirely consistent with the predictions of special relativity (if not its spirit) is to assume that a preferred reference frame exists, and that only the spatial state corresponding to a particular moment of time in this frame is real. Time evolution then becomes a fundamental property of reality describing how the spatial state of the universe changes. This viewpoint is known as presentism, in contrast with the eternalism of the block universe picture[3].

If all of the physical laws in the preferred frame are consistent with relativity (i.e. Lorentz covariant), then it would be impossible to detect from within the universe what the preferred reference frame was. The existence of an undetectable property of the universe is philosophically unappealing, but does not seem to be a compelling argument against this view. More concerning is that the relativistic symmetry of the physics laws then seems unnatural – *why should the laws of physics be the same in any inertial frame when only one is real?*

3.1 Deriving relativistic symmetries from alternative assumptions?

One way of addressing this concern would be to derive special relativity from an alternative set of assumptions which do not include the principle that all reference frames are equivalent. In particular, this seems more plausible given recent work on quantum particle dynamics in discrete spacetime [4–12], in which relativistic symmetries emerge naturally in the continuum limit despite the underlying discrete model having a preferred frame (for example a lattice of spatial points and discrete time steps). In particular, it has been shown that the simplest quantum walks on a lattice behave like massless relativistic particles at scales much larger than the lattice scale,

[3] A similar alternative is the 'moving spotlight' view of time. In this picture the entire block universe exists, but in addition a particular spatial slice representing an objective present is 'highlighted', and this highlight evolves up the block universe. However, this view seems to suffer from almost all of the disadvantages of the block universe , as well as those of a preferred frame.

given some natural non-relativistic assumptions [4, 9, 11]. Similar results have also been obtained for discrete quantum cellular automata models of quantum fields (and thus multiple particles) [6–8, 12], and discrete versions of Lorentz transforms have also been constructed [5, 10]. Note that in all of these cases, relativity is not assumed initially, but emerges from the other assumptions used to construct the models.

A key ingredient in these results is the finite speed of causal influence, in which particles only move by a finite distance (e.g. by one lattice site) in each time-step[4]. Even starting from a presentist viewpoint, the principle that causal influences travel at a bounded speed seems a very natural property, which would have warranted investigation even without any consideration of relativity. In particular, this property means that in order to determine the state in a finite region after a finite time, one only needs to know the initial state of a larger finite region, and not the state of the entire universe. Furthermore, it means that the state of the universe in different regions can be evolved 'efficiently' in parallel. Note that these approaches do not address the non-locality of quantum measurements highlighted by Bell's theorem, however this need not require any non-local influences if an Everettian approach is adopted, and in any case such phenomena cannot be used to transmit information.

4 Conclusions

The block universe picture of reality leads to a radically different notion of time to our everyday intuitions. In this paper, we have highlighted some issues raised by this conceptual shift – in particular how such a complex structure could come to exist without evolving, why such a model should lead to the observed causality of our universe, how it fits with our subjective perception of time, and the role played by time in interpretations of quantum theory.

In light of these issues, we reconsider the presentist view of reality as a spatial state evolving in time. Can an alternative explanation be found for the emergence of relativisitic behaviour even when reality has a preferred frame? Results showing the emergence of approximate Lorentz symmetry for models of particles in discrete space and time suggest this may be possible, and it would be very interesting to generalise these results.

Understanding relativity as an emergent symmetry would not only allow

[4]or more generally that operators localised in a spatial region only evolve into operators on a slightly larger region.

us to recover a more natural view of reality as a time-evolving spatial state, but would provide a basis for further research into models in which relativity is only approximate, including discrete models of space and time. This may prove crucial in opening new research directions in quantum gravity and particle physics.

Acknowledgements

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