Relativity theory does not imply that the future already exists: a counterexample★

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Abstract

It is often said that the relativistic fusion of time with space rules out genuine change or "becoming". I offer the classical sequential growth models of causal set theory as counterexamples.

1. Can one hold a "four-dimensional" point of view and still maintain consistently that things really happen? Is a spacetime perspective compatible with the idea of "becoming"? Many authors have denied such a possibility, leaving us to choose between a static conception of reality and a return to the pre-relativistic notion of linear time. In contrast, I want to offer a concrete example — a theoretical model of causal set dynamics — that illustrates the possibility of a positive answer to the above questions, according to which reality is more naturally seen as a "growing being" than as a "static thing".

Of course, one might doubt whether the static and dynamic conceptions of reality differ in more than words, given that the distinction between them does not seem to find a home in the mathematics of general relativity. Do the Einstein equations look any different when they are viewed "dynamically" rather than "under the aspect of eternity"?, a skeptic might ask. Or just because the psychological feeling of "the now" impresses itself

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on our minds, should that really matter to us as physicists? Such questions threaten to lead off into an impassable terrain of metaphysics, metamathematics, and the meaning of meaning. But this does not mean that the questions "being or happening?", "static or dynamic?" lack practical significance for the working scientist, because the answers one gives will inform the *direction* in which one searches for new theoretical structures. Thus, for example, the dynamical scheme that I will be using for illustration has sprung from the search for a theory of quantum gravity. We will see that it does provide a sort of mathematical home for the idea of becoming (as a process of growth or birth) and that, conversely, one would have been hard-pressed to arrive at such a dynamical scheme without starting from the idea of a process unfolding in time.

2. The model I'm referring to is that of *classical sequential growth* (CSG) regarded as a "law of motion" or "dynamical law" for causal sets. You can find in references [1] and [2] a full mathematical description of the model, and in [3] an account of how one resolves in that context the complex of conceptual difficulties known to workers in quantum gravity as "the problem of time". Here I will just try to summarize the basic ideas with an emphasis on those aspects most germane to the present discussion.

A CSG model describes a stochastic process in which elements e of the growing causal set C are born one by one, each with a definite subset of the already born elements as its ancestors. If one records the ancestral relationships among a set of elements produced in this manner, the resulting "family tree" will be an instance of a *causal set* [4]. Mathematically characterized, what one obtains is, more precisely, a past-finite partial order in which x precedes y iff x is an ancestor of y, x and y being arbitrary elements of C. In a CSG dynamics, the specific births that occur are (with trivial exceptions) not determined in advance; rather they happen stochastically, in such a manner as to define a Markov process. A specific member of the family of CSG models is determined by the set of transition probabilities of the Markov process; and these in turn can be expressed in terms of the basic parameters or "coupling constants" of the theory, as explained in [1].

For example, let e_0 be the first-born element, e_1 the next born, etc. The birth of e_0 can be construed as a transition from the empty causal set to the (unique) causal set of one element, and it occurs with probability 1. The next birth, however, can occur in two different ways: either e_0 will be an ancestor of e_1 (written $e_0 \prec e_1$), or it will not; and each of these two events will happen, in general, with non-zero probability. After the third birth the possible outcomes number five, and at subsequent stages the number of possible causal sets rises rapidly. After the fourth birth, one can have any of 16 non-isomorphic causal sets, while after the tenth there are already over two million distinct possibilities (2567284 to be precise). How likely any one of these possibilities is to be realized depends on how the parameters of the model are chosen. At one extreme, each new element acquires all the previous elements as ancestors, and the result is a *chain*, the causal set equivalent of one-dimensional Minkowski space. At the other extreme, none of the elements has ancestors (they are all "spacelike" to each other), and the result is an *antichain*, a causal set which does not correspond to any spacetime (although it can have an interpretation as analogous to a spacelike hypersurface when it occurs embedded in a larger causal set.) In between these extremes lie the more interesting regions in parameter space, where one encounters, for example, CSG analogs of cyclical cosmologies, with coupling constants that get renormalized in such a way that the cosmos grows larger with each successive cycle of collapse and re-expansion.

For present purposes, the most important point is that the causal set is analogous to a spacetime and the probabilities governing its growth play the role of the "law of motion" for the spacetime (i.e. the Einstein equations in the specific case of source-free gravity.) Of course, those of us working with causal sets hope that there's more to all of this than an analogy. We hypothesize that continuous spacetime is only an effective description of a deeper reality, a causal set whose dynamics is described by something very like a CSG model. To be physically realistic — and in particular to be able to generate a truly manifold-like causal set — this dynamics could not be classical; it would have to be quantal in an appropriate sense. A dynamical scheme of this sort is the ultimate objective of current work, but even though we don't possess it it yet, it is possible to imagine the kind of formalism to which it would correspond mathematically, namely the formalism of "generalized quantum mechanics" as codified in decoherence functionals and quantal measure theory. A dynamical scheme constructed along such lines would in the end be rather similar to a CSG model. The incorporation of interference (in the quantum sense) would mark a dramatic difference, of course, but the underlying kinematics or "ontology" would differ very little; and even the mathematical structure of the decoherence functional could find itself in close analogy to the probability measure that defines a CSG model.*

* Indeed, one can obtain a non-classical decoherence functional by letting the parameters of the CSG model become complex.

In particular the criterion of "discrete general covariance" could carry over essentially unchanged from the classical to the quantal case. And since considerations of Lorentz invariance and general covariance seem to lie at the heart of the arguments against a dynamical conception of reality, it seems fair enough to reflect on them in the context of CSG models. Indeed, the cosmology of the CSG models is sufficiently realistic that it's hard to imagine a question of principle relating to the "being-becoming" dichotomy that could not be posed in this simplified context.

3. To make my example more convincing however, I should probably try to explain a bit more in what sense a continuum spacetime can emerge from a causal set. Since this is essentially a kinematical question, it can be answered fairly satisfactorily in the present state of understanding. Indeed, I claim that the correspondence between certain causal sets and certain spacetimes is all I really need to make my case, because once you accept it, all that remains is to realize that a causal set can be generated by a process of "growth" or "birth" in a way that does not presuppose any notion of distant simultaneity or any concomitant notion of "space developing in time".

Perhaps a metaphor can bring out the key idea more clearly. Think of the causal set as an idealized growing tree (in the botanical sense, not the combinatorial one). Such a tree grows at the tips of its many branches, and these sites of growth are independent of one another. Perhaps a cluster of two leaves springs up at the tip of one branch (event A) and at the same moment a single leaf unfolds itself at the tip of a second branch (event B). To a good approximation, the words "at the same moment" make sense for real trees, but we know that they are not strictly accurate, because events A and B occur at different locations and distant simultaneity lacks objective meaning. If the tree were broad enough and the growth fast enough, we really could not say whether event A preceded or followed event B. The same should be true for the causal set. It is "growing at the tips" but not in a synchronized manner with respect to any external time. There is no single "now" that spreads itself over the entire process. †

† Milič Čapek [5] has proposed a musical metaphor for essentially the same idea: that of a fugue. In such a composition, each voice can seem for a while to unfold in its own region of space, its notes neither later nor earlier than the other's, until the musical lines come back together and intersect.

"But wait a minute", you might object. "Didn't you just describe the CSG growth process as a succession of births in a definite order, and doesn't the resulting ranking of the elements of C imply something akin to a distant simultaneity?" The answer to this objection is that a definite birth-order, or an "external time", did figure in the description I gave, but it is to be regarded as an artifact of the description analogous to one's choice of coordinates for writing down the Schwarzschild metric. Only insofar as it reflects the intrinsic causal order of the causal set is this auxiliary time objective. The residue is "pure gauge". Thus, any other order of birth which is compatible with the intrinsic precedence relation $\prec$ is to be regarded as physically equivalent to the first, in the same sense that two diffeomorphic metrics are physically equivalent. So even though a CSG model rests on no background structure in the usual sense (unlike continuum gravity, where the underlying differentiable manifold acts as a background), one still meets with an issue very like that of general covariance, stemming from the entry of an external time-parameter into the mathematical definition of the model. To complete my argument, then, I will have to explain how this issue has been addressed by the formalism, but first let me carry on with the task of explaining how a spacetime can emerge from a causal set in the first place.

Geometry = number + order

4. What might a stochastic process of the CSG type have to do with spacetime and geometry, given that the type of mathematical object involved (a past-finite poset), is not only discrete, but is at first sight far removed from anything like a four-dimensional manifold? Of course, the idea is that the continuity of spacetime is illusory, that spacetime itself is only an emergent reality, and that its inner basis is a causal set. In order for this to be the case, the apparently rather primitive structure of a discrete partial order must nonetheless conceal within itself the type of information from which a Lorentzian geometry can be recovered naturally, so that causal sets, or at least certain causal sets can be placed in correspondence with certain spacetimes. Fortunately the basis of this correspondence is easy to understand, at least in broad outline.

With respect to a fixed system of coordinates, the spacetime metric appears as a symmetric matrix $g_{\alpha\beta}(x)$ of Lorentzian signature. It is therefore described by 10 real functions of the coordinates, $g_{00}(x)$, $g_{01}(x)$, $\ldots g_{33}(x)$. Of these, the combination $g_{\alpha\beta}/|\det g|^{1/4}$ is determined if we know the light cones (i.e. the solutions of $g_{\alpha\beta}v^\alpha v^\beta = 0$), and the remaining factor of $\det(g)$ is determined if we know the *volumes* of arbitrary spacetime regions R since these are given by integrals of the form $\int_R \sqrt{-\det(g)}d^4x$. But we know the light cones once we know the causal ordering among the point-events of spacetime, or in other words which point-events can influence which others (the spacetime being assumed to carry a time-orientation). Now let us postulate (i) that this causal ordering directly reflects the ancestral relation $\prec$ in the causal set; and (ii) that spacetime volume directly reflects the *number* of causal set elements going to make up the region in question (the number of births "occurring in it"). We then have the ingredients for constructing a four-geometry M, and if the construction succeeds, we may say that resulting M is a good approximation to the underlying causal set C: $M \approx C$. When this is the case, C may be identified with a subset of M, and it turns out to be important (for questions like locality and Lorentz invariance) that this subset needs to be randomly distributed in order to honor the postulate that number = volume.

Implications of growth models

5. Having introduced the dynamics of sequential growth, and having pointed out that a causal set growing in accord with such a model is capable in principle of yielding a relativistic spacetime (not exactly, but to a sufficient approximation), I am tempted to stop at this point and let the example speak for itself. On one hand sequential growth seems to me to manifest "becoming" to the extent that any mathematical model can. It even provides an objective correlate of our subjective perception of "time passing" in the unceasing cascade of birth-events that build up the causal set, by "accretion" as it were. [♭] On the other hand, there is nothing in the model corresponding to a three-dimensional space "evolving in time". Rather, one meets with something which is "four dimensional" from the very beginning, but which at any stage of its growth is still *incomplete.* [⋆] It's true

♭ The notion of "accretive time" that arises here seems close to that of C.D. Broad, and also to that of the "Vibhajavadin" school within the Buddhist philosophical tradition.

⋆ In this paper, I am using "four-dimensional" as a shorthand for "of a spacetime character, as opposed to a purely spatial character". There is nothing in the definition of a causal set that limits it to a dimensionality of four, or indeed to any uniform dimensionality.

that if we stop the process at any stage, we can identify the maximal elements of C, and these form a kind of "future boundary" of the growing causal set. But this "boundary" A is an antichain, and as such can support intrinsically none of the metrical structures of physical space. It is only by reference to the many relations of causal precedence connecting the elements of A to their ancestors that geometrical attributes can be attached to A at all. † [6] Thus, the spacetime character is primary in CSG models, and any approximate notion of "spacelike hypersurface" is derived from it. Besides, stopping the process at a given stage has no objective meaning within the theory, because with a different choice of birth-order, the causet at the same stage of growth would look entirely different.

The example of the CSG models seems to me to refute the contention that relativistic spacetime is incompatible with genuine change, but I suppose that no example can ever bring to a close a debate that remains purely at the level of interpretation. If, on the other hand, we ask not whether becoming is "logically consistent" with four-dimensionality, but rather whether the combination of the two notions can be heuristically fruitful, then I think that the development of the CSG models is in fact persuasive evidence that it can.

The only other way to argue would be to refute, one by one, the supposed proofs that becoming and four-dimensionality exclude each other; but that would have to be attempted by someone much better versed in those arguments than I am. Perhaps, however, it is fair to say that most such arguments presuppose that the sole alternative to the "block universe" is a doctrine that identifies reality with a three-dimensional instant. If this is so then the conception that emerges from the CSG models of a four-dimensional, but still incomplete reality should be able, if not to settle the debate, then at least to widen its terms in a fruitful manner.

If we attend to our actual experience of time then no difficulty ever arises, as pointed out long ago by Poincaré. Our "now" is (approximately) localized and if we ask whether a distant event spacelike to us has or has not happened yet, this question lacks intuitive sense. But some "opponents of becoming" seem not to content themselves with the experience of

† Arguably, a reference to the enveloping spacetime is present in the continuum as well, but there it is disguised by the fact that one need refer only to an arbitrarily small neighborhood of a hypersurface in order to define, for example, its extrinsic curvature, whence reference to any *specific* earlier or later point can be deemed irrelevant.

a "situated observer". They want to imagine themselves as a "super-observer", who would take in all of existence at a glance. The supposition of such an observer *would* lead to a distinguished "slicing" of the causet, contradicting the principle that such a slicing lacks objective meaning ("covariance"). Super-observers do not exist however, and the attempt to put ourselves into their shoes brings the localized human experience of "the now" into conflict with the asynchronous multiplicity of "nows" of a CSG model (cf. the analogy of the growing tree).

6. Returning from metaphor to mathematics, I would like to deal briefly with two related features of relativity-theory that arguments against 'becoming' seem to rely upon at a technical level, namely Lorentz invariance and general covariance. To what extent might the concept of a growing causet clash with these features? With respect to the first, one can say something definite and quite rigorous: one can quote a theorem. With respect to the second, it is less easy to reach a sure conclusion since the meaning of general covariance in the context of a discrete and stochastic theory is still more elusive than it is in a continuous and deterministic setting.

Lorentz transformations

In speaking of Lorentz invariance we remain essentially at the level of kinematics, because, so far as one knows, the extant CSG models can give rise to significant portions of Minkowski spacetime $\mathbb{M}^4$ only with vanishingly small probability.[♭] Let us suppose, nevertheless, that some quantal growth process has produced a causet C resembling a large region of flat spacetime which we can idealize as being all of Minkowski space: $C \approx \mathbb{M}^4$. By definition, such a causal set is embeddable "randomly" in $\mathbb{M}^4$, just as if it had been created by running a Poisson process in $\mathbb{M}^4$. With respect to the Poisson probability-measure one can then prove that, with probability unity, it is impossible to deduce a distinguished timelike direction from the embedding [8]. In this sense, Lorentz invariance is preserved exactly by the causal set, and one sees again how artificial would be its decomposition into any sequence of antichains or other analogs of space-at-a-moment-of-time.

[♭] However, there seem to exist more general Markov processes that do produce, for example, the future of the origin in $\mathbb{M}^4$ [7]. These processes respect discrete general covariance in the sense of [1] but not Bell causality.

General covariance

7. Finally, let us return to the question of general covariance. In the familiar context of continuum relativity, this phrase has a double significance. In the first place it implies that only diffeomorphism-invariant quantities possess physical meaning (where the word "quantities" can be replaced, according to taste by "events, "questions", "predicates", or "properties"). ⋆ Given a spacetime metric, it is thus meaningful to ask for the maximum area of a black hole horizon but not for the value of the gravitational potential at coordinate radius 17. But aside from thus conditioning our definition of reality, general covariance also demands in the second place that a theory's equations of motion (or its action-functional) be diffeomorphism-invariant. Of course these two facets of general covariance are closely connected. Because general relativity is not a stochastic theory, it distinguishes rigidly between metrics that do and do not solve its field equations. Consequently, the second facet of covariance flows directly from the first as a consistency condition, because it would be senseless to identify two metrics one of which was allowed by the equations of motion and the other of which was forbidden; and conversely, the kinematical identification must be made if one wishes the dynamics to be deterministic. Thus, the first or "ontological" facet of general covariance tends to coalesce with its second or "dynamical" facet.

In relation to causal sets, the context changes because one is dealing with discrete structures and stochastic dynamics. If one tries to rethink the meaning of general covariance in this context, one can perhaps distinguish now three relatively independent facets. At the kinematic (or ontological) level, essentially the same words apply as in general relativity: the causal set elements "carry no inner identifiers", so that what has physical meaning is only the isomorphism equivalence class of the given poset C. General covariance for causets can thus be interpreted as invariance under relabeling, in analogy to the interpretation of general covariance as coordinate-invariance in the continuum.

But because the theory is stochastic this label-independence does not impose any obvious consistency condition on the assignment of probabilities (or eventually quantal amplitudes) to causets. It simply implies that the only probabilities with physical meaning

⋆ Underlying this limitation is the thought that spacetime points — or in this case elements of the causal set — possess no individuality beyond what they inherit from their relations to each other. According to John Stachel, they have "quiddity" without "haecceity".

are those attached to isomorphism equivalence classes of causets. In the CSG models, this is made precise by beginning with a probability measure $\widetilde{\mu}$ on a space $\widetilde{\Omega}$ of *labeled* causets, and passing from it to the induced measure μ on the quotient space Ω whose members are the equivalence classes [3]. In effect the probability of an element of Ω is the sum of the probabilities of all the members of that equivalence class. †

The passage from $\widetilde{\Omega}$ to Ω expresses (discrete) general covariance kinematically and the induced passage from $\widetilde{\mu}$ to μ expresses it dynamically. But what would correspond here to the invariance of the equations of motion — and do we require any such condition? In the analogous situation of gauge theories in $\mathbb{M}^4$, one often "fixes the gauge", but then takes care to integrate the resulting — non gauge-invariant — probability measure over entire gauge equivalence classes. (I am thinking of the Fadeev-Popov approach to the Wick-rotated quantum field theory.) This would be the analog of letting $\widetilde{\mu}$ depend on the labeling but only computing probabilities with respect to μ. However, before fixing the gauge one had a measure which *was* gauge invariant (though defined only formally), and this invariance is a crucial physical input to the theory. One might thus expect, in the causet case, that $\widetilde{\mu}$ should itself be relabeling invariant, for only in this way would the classical limit of the corresponding quantum theory have a chance to reproduce the Einstein equations. It turns out that a natural invariance condition of this sort can be found, and it is one of the two key inputs to the CSG models. The specific condition ♭

† In order to define μ consistently, one must take $\widetilde{\Omega}$ to be a space of infinite causets, ones for which the growth process has "run to completion". We meet here with an echo of the block-universe idea, that is in effect built into mathematicians' formalisation of the concept of stochastic process.

♭ Notice that this condition of "discrete general covariance" is not itself formulated covariantly. Notice also that it says something less than the following formal statement: "the probability of a completed causet C (a causet of countably many elements) is independent of its labeling." This distinction was brought to light by Graham Brightwell, who also pointed out that this stronger statement *does* hold in the CSG models, even though it's not implied by discrete general covariance alone. One should also mention here an important difference between diffeomorphism-invariance and relabeling-invariance: the former is expressed by an invariance *group* arising as the automorphism group of a background structure (the manifold); the latter is not a group (a given permutation need not preserve naturality of the labeling) and there's no background (unless you count the integers $\mathbb{N}$ from which our labels or parameter time n come, but even if you do count them, their states that for any finite causet C of cardinality n, the probability to arrive at C after n births is independent of the birth order of C's elements (provided of course that we limit ourselves to orderings that can actually happen, i.e. to so called natural labelings of C). Since, by construction, the CSG models fulfill this condition, one can conclude that in these models there is no clash: discrete general covariance coexists harmoniously with the concept of a dynamically growing causal set.

8. In the CSG models, a form of spatiotemporal discreteness plays a prominent role, and for that reason alone, one might question whether the example with which we've been working carries over to the spacetime continua of special and general relativity. On the other hand, the conception of a dynamically growing reality arguably retains its meaning in a continuous setting, even if it stretches one's intuition to a greater extent there. Accordingly, one might decide that "becoming" is not, after all, in conflict with the four-dimensional Lorentzian manifold of Relativity Theory. In that case, their compatibility would be something that we might have recognized much earlier, without ever taking causal sets into consideration. The simplifying hypothesis of a discrete spatiotemporal substructure would have served only as an inessential aid to our thinking.

On the other hand, one might in the end decide that a spacetime *continuum* necessarily is static, even though — as we have just seen — a *discrete* structure can consistently "happen". In that case, an adherent of 'becoming' could claim that our intuition of time as a flow, had we but listened to it attentively, was all along speaking to us of the discreteness of whatever process constitutes the inner basis of the phenomenon that we have been accustomed to conceptualizing as a spacetime continuum.

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automorphism group is trivial and does not generate relabelings).

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