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摘要

This chapter presents the most interesting philosophical issues as they arise in causal set theory. The first concerns the apparent disappearance of spacetime at the fundamental level. It shows how the looming empirical incoherence is averted if we adopt spacetime functionalism. Second, classical sequential growth dynamics rekindles hope for a fundamental passage of physical time compatible with relativistic physics. The chapter argues that this hope is faint at best, as a block view offers the most natural interpretation of dynamical causal set theory. Third, causal set theory admits a very natural structuralist interpretation, enabling a fruitful interaction between debates in philosophy of science concerning structural realism and the metaphysics of causal sets.

本章介绍因果集理论中涌现出的最值得关注的哲学问题。第一个问题涉及基本层面上时空的明显消失。本章表明，如果我们采纳时空功能主义，就可以避免迫近的经验不融贯问题。第二个问题中，经典顺序增长动力学为与相对论物理学相容的物理时间的基础流逝重燃希望。本章提出，这一希望充其量十分渺茫，因为块宇宙观才是对动力学因果集理论最自然的诠释。第三个问题，因果集理论可以得到非常自然的结构主义诠释，这为科学哲学中结构实在论的争论与因果集形而上学之间带来了富有成效的互动。

I thank Fay Dowker and Sumati Surya for discussions and feedback on earlier versions of this chapter. This work was supported financially by the John Templeton Foundation (the views expressed are those of the author, not necessarily those of the sponsors).

我感谢费伊·道克 (Fay Dowker) 和苏马蒂·苏里亚 (Sumati Surya) 就本章的早期版本展开讨论并给出反馈。本工作得到约翰·邓普顿基金会的资金支持 (文中表达的观点仅代表作者，不一定代表赞助方的观点)。

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Keywords

关键词

Causal set theory - Emergence of spacetime - Empirical incoherence . Spacetime functionalism · Philosophy of time · Presentism · Eternalism · Asynchronous becoming - Structuralism - Structural realism

因果集理论-时空涌现-经验不融贯性。时空功能主义 · 时间哲学 · 现在论 · 永恒论 · 异步生成-结构主义-结构实在论

Introduction

引言

A central task - perhaps the central task - of natural philosophy, as understood more broadly than physics, is to explain the manifest image of the world on the basis of the scientific image, in Wilfrid Sellars's memorable terms. In other words, natural philosophy is to deliver an account of how the world can manifest itself to us as it does if it is structured as our best science tells us. This may sound like a trivial commonplace not worth pausing over, but as fundamental physics gets ever more removed from our direct experience of the world, the task, while remaining eminently important, turns increasingly delicate.

用威尔弗里德·塞拉斯的名言来说，范畴比物理学更广的自然哲学，其核心任务——或许就是核心任务——就是以科学图景为基础，解释我们眼前这个世界的显象图景。换句话说，自然哲学要解释的是: 倘若世界的结构真如我们最顶尖的科学所言，那它何以会向我们呈现出如今我们所见的这般模样。这听上去像是不值一提的平庸常识，但随着基础物理学和我们对世界的直接体验愈发脱节，这项始终至关重要的任务也变得越来越棘手。

As we move in our quest for a quantum theory of gravity beyond the well-trodden standard model of particle physics and general relativity (GR), the task becomes both more critical and more fragile than ever before. It becomes more critical because the apparent non-spatiotemporality of the fundamental structures postulated in approaches to quantum gravity threatens the empirical coherence of these approaches. In order to avert this threat, it needs to be shown how these structures yield, at the appropriate scales, a framework for the familiar spatiotemporal world. It becomes more fragile because the currently leading approaches to quantum gravity tend to postulate fundamental structures rather different from the relativistic spacetimes to which they are supposed to give rise. This increased gap requires hard technical and conceptual work to be bridged, and, alas, success is not guaranteed.

> 在我们探寻超越粒子物理学标准模型与广义相对论 (GR) 的量子引力理论的征程中，这项任务如今比以往任何时候都更为关键，也更具不确定性。它之所以更为关键，是因为量子引力研究各流派所假设的基础结构显然不具备时空属性，这会威胁这些流派的经验一致性。为化解这一威胁，我们需要证明这些结构如何能在合适的尺度上衍生出我们所熟悉的时空世界框架。它之所以更具不确定性，是因为目前量子引力的主流流派大多假设基础结构与它们本应衍生出的相对论时空差异显著。两者间更大的鸿沟需要我们投入大量艰深的技术与概念工作来弥合，可惜的是，success is not guaranteed.

The degree to which the structures of quantum gravity will be non-spatiotemporal is an interesting and involved question, as is the potential philosophical fallout. As argued at length in the forthcoming monograph by Huggett and Wüthrich [22], major approaches to quantum gravity such as string theory, loop quantum gravity, and causal set theory all postulate fundamental structures which turn out to be nonspatial or nontemporal in significant ways. We will return to the issue of how spatial and how temporal causal sets really are in section ”Emergence”, but let us suppose, for the sake of argument, that the fundamental structures are indeed non-spatiotemporal in significant ways. The problem of empirical incoherence, then, is that the following three propositions cannot all be maintained (The presentation of the problem of empirical incoherence here is close to that of Yates [57, §6.1.1]. An earlier formulation of the problem can be found in Huggett and Wüthrich [21].):

> 量子引力结构的非时空性程度，以及由此可能引发的哲学影响，都是复杂且值得探讨的问题。正如赫格特与于特里希即将出版的专著 [22] 中所详细论述的，弦论、圈量子引力、因果集理论等主流量子引力研究进路，都假设了在很大程度上最终属于非空间或非时间的基础结构。我们会在“涌现”一节回到“因果集究竟在多大程度上是空间的、多大程度上是时间的”这一问题，但为了方便论证，我们暂且假设这些基础结构确实在很大程度上是非时空的。那么经验不连贯性问题就在于，以下三个命题无法同时成立 (本文对经验不连贯性问题的表述接近耶茨 [57, §6.1.1] 的表述，该问题更早的表述可见赫格特与于特里希 [21]):

1. A fundamental theory in physics is empirically coherent only if it delivers empirical predictions.

> 1. 物理学中的基础理论只有给出可观测的预言，才具备经验自洽性。

2. Empirical predictions in physics are formulated in terms of local beables and so presuppose their existence.

> 2. 物理学中的经验预测是局域可观测量的形式表述的，因此预先假定了局域可观测量的存在。

3. The fundamental ontology of physics is non-spatiotemporal.

> 3. 物理学的基础本体论是非时空性的。

Crucially, it is assumed that physics presupposes what Bell [5, 234] dubbed as ”local beables,” i.e., things which are real (exist) or are at least candidates for being - hence ”be-ables” - and which are associated with some determinate region of spacetime, hence ”local.” In other words, empirical predictions in physics assert something about physical entities (fields, particles, pulsars, more directly photographic plates, Geiger counters, pointers, computer readouts, etc.), which they take to be localizable in space and time, and their states. Crucially, local beables can only exist if space and time (or better spacetime) exist. Given the first two propositions above, it is a necessary condition for the empirical coherence of a fundamental theory in physics that there be spacetime. However, if the third proposition is true, then that necessary condition can apparently not be satisfied, leaving the theory empirically incoherent.

关键在于，现有物理学预设了贝尔 [5, 234] 所称的“定域存在物”，即真实存在 (或至少具备存在资格——故得名“存在物”)、且归属某一确定时空区域的事物，因此称为“定域”。换言之，物理学中的经验预测对物理实体 (场、粒子、脉冲星，更直接的例子如照相底片、盖革计数器、指针、计算机读数等等) 及其状态作出论断，这些物理实体都被认为可在时空中定位。核心点在于，定域存在物只有在空间和时间 (更准确说是时空) 存在的前提下才能存在。结合前述前两个命题，时空存在是物理学基础理论具备经验一致性的必要条件。然而，如果第三个命题成立，这个必要条件显然无法满足，该理论也就不具备经验一致性。

In essence, the problem of empirical incoherence represents one important aspect of the central task of natural philosophy, as it links the fundamental structures of quantum gravity ultimately to how the world manifests itself to us, which is, among other things, evidently spatiotemporal. We will consider the disappearance and emergence of spacetime in causal set theory in section ”Emergence”.

本质上，经验不连贯性问题是自然哲学核心任务的一个重要方面，因为它将量子引力的基础结构最终关联到世界向我们展现的方式，而世界显然是时空性的。我们将在“涌现”一节讨论因果集合论中时空的消失与涌现。

The following section, section ”Philosophy of Time”, will discuss another philosophical issue in causal set theory, which has recently risen to prominence: the interpretation of the dynamics in causal set theory and its implications for the philosophy of time. The problem of empirical incoherence and the emergence of spacetime can be considered a foundational problem in the context of causal set theory (and other approaches to quantum gravity), i.e., a possibly philosophical problem which arises in the context of developing and interpreting our best physical theories. In other words, in foundational problems, we start from physics and become in some sense ”philosophical,” while our ultimate interests remain in physics. In contrast, in philosophical problems, we start out from originally philosophical questions and turn to physics, hoping to find at least partial answers to our ultimately philosophical questions. Let it be noted that this distinction is at best a first approximation, as it depends on there being a principled distinction between physics and philosophy, a distinction which I believe is at best gradual and approximate when it comes to topics such as those treated in this chapter.

下一章节“时间哲学”将探讨因果集理论中近年来备受关注的另一哲学问题: 因果集理论动力学的解释及其对时间哲学的启示。经验不连贯性问题与时空涌现可视为因果集理论 (以及其他量子引力研究路径) 语境下的基础性问题，也就是在发展和解读我们最优物理理论的过程中产生的、可能属于哲学范畴的问题。换句话说，处理基础性问题时，我们从物理学出发，在某种意义上走向“哲学化”，但核心关切仍停留在物理学领域。与之相对，处理哲学问题时，我们从原本的哲学问题出发，转向物理学，希望能为我们最终的哲学问题找到至少部分答案。需要注意的是，这一区分充其量只是初步近似，因为它依赖于物理学和哲学之间存在原则性区分，但我认为，在本章所讨论的这类主题中，二者最多只是程度和近似层面的区分。

As section ”Philosophy of Time” is concerned with the nature of time and whether time is essentially dynamical or not and turns to causal set theory to see which side in this debate garners support from quantum gravity, we are here faced with a philosophical question in this sense. In this section, we will mainly consider how the classical sequential growth dynamics proposed by Rideout and Sorkin [40] ought to be interpreted and whether or not it thus supports a metaphysics of ”becoming,” of temporal dynamism. The main conclusion of this section will be that the ”block universe” view still seems preferable in light of fundamental physics. However, although causal set theory takes up some prior arguments in favor of dynamism from the context of GR, it also adds some genuinely novel and interesting twists to the debate.

由于“时间哲学”一章关注时间的本质，探究时间本质上是否是动态的，并借助因果集理论考察这场辩论中哪一方能获得量子引力的支持，我们在此面对的正是上述意义上的哲学问题。本节我们主要探讨应如何解读赖德奥特和索金提出的经典顺序增长动力学 [40]，以及它是否由此支持“生成”的形而上学，即时间动态论。本节的核心结论是，从基础物理学来看，“块宇宙”观仍然更可取。不过，尽管因果集理论吸纳了广义相对论语境下支持动态论的一些已有论证，它也为这场辩论带来了真正新颖且有趣的新走向。

Before reaching the conclusions in section ”Conclusions”, section ”Structuralism” considers the metaphysics of causal sets more generally and in particular the nature of the basal events. As it turns out, structuralism offers a very natural interpretation of causal sets. As a structuralist interpretation rejects the idea that fundamental entities have intrinsic natures beyond their structural roles, this raises the issue of how to deal with elements of so-called non-Hegelian sets, i.e., basal events with exactly the same relational profile: if the identity of an event is exhausted by its relational profile, it seems as if there cannot be distinct events with the same relational profile.

在“结论”部分得出最终结论之前，“结构主义”一章将更宽泛地探讨因果集的形而上学，尤其是基础事件的本质。可以发现，结构主义为因果集提供了一种非常自然的解释。由于结构主义解释拒绝“基础实体除结构角色外还拥有内在本质”这一观点，这就引出了如何处理所谓非黑格尔集合元素的问题，也就是拥有完全相同关系属性的基础事件: 如果一个事件的同一性完全由其关系属性决定，那么似乎不可能存在拥有相同关系属性的不同事件。

Apart from probing deep questions about the metaphysics of causal sets, these interpretive considerations straightforwardly enrich the important debate in philosophy of science surrounding the formulation and tenability of structural realism. While I will argue that the structuralist interpretation provides the natural template for causal set theory (as it possibly does for other physical theories), I will caution against taking this result to deliver strong support for a thoroughgoing form of structural realism.

除了探究因果集形而上学的深层问题，这些解释性思考直接丰富了科学哲学中围绕结构实在论的表述与可信度展开的重要辩论。尽管我会论证结构主义解释为因果集理论提供了自然的解释框架 (就像它对其他物理理论可能也成立一样)，但我也要提醒，不能认为这一结论就能为彻底的结构实在论提供有力支持。

Emergence

涌现

As I have stated in section ”Introduction”, part of the wider task of fundamental physics is to tie its theories back to the world as we experience it. For theories in quantum gravity, this task involves showing how something closely approximated by relativistic spacetimes emerges from the fundamental structures postulated. This is not a novel situation in physics: whenever a successor theory is proposed, one of its central duties is to deliver the old theory, or something sufficiently close to it, in an appropriate limit or approximation. The task, and particularly what would count as its successful completion, is not given in terribly precise terms and remains open to renegotiation in the scientific proceedings. Ultimately, it is the peers in the scientific community who will, collectively, decide over success or failure. It is clear that delivering on this task is a conditio sine qua non for the acceptance of novel theories in fundamental physics.

正如我在“引言”章节中所述，基础物理学的 broader 目标之一，就是将其理论关联回我们所体验的世界。对于量子引力理论而言，这项工作要求证明，类相对论时空是如何从假设的基础结构中演生出来的。这在物理学中并非新情况: 每当提出一个继任理论，它的核心职责之一就是在适当的极限或近似下推导出旧理论，或是与旧理论足够接近的理论。这项任务，尤其是对“任务成功完成”的判定，目前并没有非常精确的定义，在科学研究进程中仍可不断调整。最终，是科学界的同行们集体决定成败。很显然，完成这项任务是基础物理学新理论获得认可的必要前提。

The Basics of Causal Set Theory

因果集理论基础

Consequently, it is one of the central problems in causal set theory to show how the causal sets it postulates are approximated by relativistic spacetimes. Perhaps this task would be straightforward if causal sets were clearly spatiotemporal. After all, there is a reasonable hope that they are, as they are so closely modeled on what is taken to be the essential features of relativistic spacetimes. Causal set theory, as a research program, starts out from a series of results in classical GR which culminated in what is known as ”Malament’s theorem” [34]. Roughly put, Malament’s theorem states that for causally sufficiently well-behaved spacetimes, their full geometry can be reconstructed from the causal relations among events plus a conformal factor. One of the elegant aspects of causal set theory is that if we replace the continuum of relativistic spacetime by a discrete structure, then this conformal factor is fixed in a rather natural way: the cardinality of a subset of a causal set offers a natural measure of its ”size.” In this way, causal set theory departs from a beautifully simple starting point: the discrete fundamental structure is ordered by a relation of causal precedence.

因此，因果集合理论的核心问题之一就是证明，该理论所假设的因果集如何能被相对论时空近似。如果因果集显然是时空性的，这项任务或许会十分直接。毕竟我们有合理的理由对此寄予希望，因为因果集本身就是紧密仿照相对论时空的被认定的核心特征构建出来的。因果集理论作为一个研究项目，发端于经典广义相对论的一系列成果，这些成果最终得到了我们所知的“马拉门特定理”[34]。粗略来说，马拉门特定理表明: 对于因果性质足够良好的时空，其完整几何可以由事件之间的因果关系外加一个共形因子重构出来。因果集合理论一个优雅之处在于，如果我们把相对论时空的连续统替换为离散结构，那么这个共形因子会以一种相当自然的方式确定下来: 因果集子集的基数就为其“尺寸”提供了自然度量。这样一来，因果集理论就从一个极为简洁的起点出发: 离散基本结构由因果先后关系来定序。

Fundamentally, a causal set is thus a discrete partial order (Causal set theory was first proposed in

Bombelli et al. [6]; for reviews, see Dowker [13], Sorkin [48], Surya [50]; for a philosophical review, see Huggett and Wüthrich [22, chapter 3].). First, the discreteness is imposed a priori. This has some technical advantages as some notorious divergences which show up in a continuum theory are thus avoided. However, the main motivation, I take it, is that the fundamental structure which will give rise to relativistic spacetimes is assumed to be a discrete structure because this is what one could expect, perhaps on the basis that in quantum theories, many physical observables have discrete spectra. The proof of the pudding is in the eating, which for a theory in fundamental physics means that its basic posits, whatever their original motivation, must receive confirmation in the usual ways of science: the theory is empirically correct and usefully predictive, and it enjoys theoretical advantages such as explanatory power or simplicity over its empirically equivalent rivals. Theories of quantum gravity to date remain, of course, far from being confirmed.

从根本上说，因果集就是一种离散偏序 (因果集理论最早由 Bombelli 等人提出 [6]；综述见 Dowker [13]、Sorkin [48]、Surya [50]；哲学综述见 Huggett 和 Wüthrich [22，第 3 章])。首先，离散性是先验设定的。这带来了一些技术优势，连续统理论中一些臭名昭著的发散因此得以避免。不过我认为，其主要动机在于，衍生出相对论时空的基本结构被假定为离散结构，这种期待的来源或许是量子理论中诸多物理可观测量都具有离散谱。实践是检验真理的唯一标准，对于基础物理学中的理论来说，这意味着无论基本假设最初的动机是什么，它们都必须通过科学的常规方式得到确证: 理论要在经验上正确、能做出有效预测，并且具备理论优势，比如相较经验上等价的竞争对手拥有更强的解释力或更简洁。当然，迄今为止的量子引力理论都远未得到确证。

Second, events are partially ordered by causal precedence in Minkowski spacetime, but this is not generally true in GR. Given that there are pairs of spacelike-related events in relativistic spacetimes which do not stand in a relation of causal precedence, demanding that the order be total would clearly be too strong and would violate a central insight of relativistic physics. However, the demand of events being ordered partially is still too strong, as GR permits models of spacetimes which contain closed timelike curves. In those spacetimes, the relation of causal precedence is no longer antisymmetric and so not a partial order (A binary relation R is antisymmetric over a set C just in case $\forall x, y \in C$, if xRy and yRx , then $x = y$. Clearly, if there are closed timelike curves, then a spacetime event a could both precede and be preceded by an event b in that spacetime. Since a and b are distinct, antisymmetry is violated.). Again, that the fundamental order is partial is a stipulation of the theory which may be vindicated a posteriori by the theory's success; but it does seem to rule out as unphysical relativistic spacetimes which are not causally sufficiently well behaved that the causal ordering is partial (However, this appearance may be false, as is argued in Wüthrich [55].).

第二，在闵可夫斯基时空中，事件由因果先后关系偏序排列，但这在广义相对论中并不普遍成立。由于相对论时空中存在成对类空关联事件，它们之间不存在因果先后关系，因此要求序是全序显然要求过高，也违背了相对论物理学的核心洞见。不过，即便只要求事件满足偏序，要求仍然过高，因为广义相对论允许包含闭合类时曲线的时空模型。在这类时空中，因果先后关系不再满足反对称性，因此不再是偏序 (二元关系 R 在集合 C 上是反对称的，当且仅当 $\forall x, y \in C$ ，若 xRy 且 yRx ，则 $x = y$ 。显然，如果存在闭合类时曲线，那么某个时空事件 a 既可以先于该时空中的事件 b 发生，也可以后于它发生。由于 a 和 b 是不同的事件，反对称性就被违反了。)。再次说明，基本序为偏序是该理论的约定，它可以通过理论的成功在后验得到辩护；但这似乎确实将因果性质不够良好、不满足因果序为偏序的相对论时空排除在了非物理范畴之外 (不过正如 Wüthrich [55] 所论证的，这种表象可能是错误的。)。

Third, it should be noted that the theory as stated thus far is not a quantum theory, as of course is the goal. How a quantum theory of gravity based on classical causal set theory will look like is not clear (For a review, see Surya [50], particularly §6.3.). Perhaps the quantum aspects of the theory will be confined to its dynamics (see the next point); or we might theorize that the state of the world is generically a superposition of causal sets; or its quantum nature is expressed in yet other ways. For the purposes of the present chapter, we will restrict ourselves to the classical theory as it stands now.

第三，需要注意的是，到目前为止我们所阐述的理论还不是量子理论，而量子引力当然才是我们的目标。基于经典因果集理论的量子引力会是什么样子，目前还不明确 (综述见 Surya [50]，尤其是第 6.3 节。)。该理论的量子方面或许只会体现在动力学中 (见下一点)；也或许我们可以认为，世界的态一般来说是不同因果集的叠加；又或者它的量子性会以其他方式体现。就本章的目标而言，我们将只讨论目前成型的经典理论。

Finally, the mere stipulation that the fundamental structure be a discrete partial order turns out to be far too weak. In fact, there is a rigorous sense in which almost all causal sets will be ”pathological” insofar as they will not deliver anything near a useful model of the cosmos. As it turns out, almost all sufficiently large discrete partial orders consist of only three highly connected ”layers” or ”generations” of basal elements [23]. If considered cosmological models, almost all sufficiently large causal sets would represent worlds with highly non-local causal connections and which ”last” for a mere three Planck times, during which they double in size from the first ”moment” to the second and then halve in size as they transition to the final ”moment.” It is thus clear that additional conditions must be imposed in order to arrive at a theory whose postulated structures more generically qualify as promising candidates to model fundamental physical reality. There are potentially many ways in which a useful restriction to viable models could be accomplished. Although it may be attractive to focus on additional conditions with a prima facie physical plausibility, the conditions imposed will ultimately (and a posteriori) be judged by the success of the resulting theory. Causal set theorists typically assume that these conditions should specify a reasonable dynamics which in some sense governs the ”growth” of a causal set - a sense which will be studied in section ”Philosophy of Time”; only causal sets which could have come into being by a process compatible with the stipulated dynamics will be deemed physically possible.

最后，仅规定基础结构是离散偏序关系，结果表明该条件太过薄弱。事实上，在严谨意义上几乎所有因果集都是“病态的”，它们无法给出任何接近可用宇宙模型的结果。研究发现，几乎所有足够大的离散偏序都仅由三层高度连通的基础元素“层”或“代”构成 [23]。如果将其作为宇宙学模型来看，几乎所有足够大的因果集所代表的世界都拥有极强的非定域因果关联，且整个世界“持续”仅三个普朗克时间: 从第一个“时刻”到第二个“时刻”，尺寸翻倍，随后过渡到最终“时刻”时尺寸减半。因此很明显，要得到一个其公设结构普遍更有希望成为基础物理现实模型候选的理论，就必须附加额外条件。要对可行模型做出有效限定，存在多种潜在方法。尽管聚焦于乍看具有物理合理性的额外条件颇具吸引力，但所加的条件最终 (且须后验地) 都会由所得理论的成败来评判。因果集理论研究者通常假定，这些条件应当明确一套合理动力学，该动力学在某种意义上支配因果集的“生长”——我们会在“时间哲学”一节讨论这一内容；只有符合所规定动力学、通过该过程生成的因果集才会被判定为物理上可能。

The Non-spatiotemporality of Causal Sets

因果集的非时空性

In spite of the fact that the resulting causal sets have been closely modeled on relativistic spacetimes, there are some significant differences. The most salient departure from relativistic models is that causal sets are not obviously spatiotemporal. Consequently, the problem of empirical incoherence lurks.

> 尽管最终生成的因果集是以相对论时空为核心模型构建的，但二者仍存在一些显著差异。因果集最突出的偏离相对论模型之处在于，因果集并不具备明确的时空属性。因此，经验不融贯性问题隐然存在。

How are causal sets less than fully spatiotemporal? They are obviously discrete structures, but their non-spatiotemporality runs deeper than that. Although the fundamental ordering relation is a relation of causal precedence, it shares features one would expect to hold of a temporal precedence relation. If we rule out temporal loops and assume the transitivity of temporal precedence, as seems intuitive, then temporal precedence is also antisymmetric, just as causal precedence was assumed to be. In relativistic theories, temporal precedence, however one concretely defines it then at most orders events partially, again just as does causal precedence. It seems as if causal precedence is structurally similar to a minimal form of relativistic temporal precedence with neither metric relations such as durations nor any ”flow” or passage of time.

> 因果集为何不是完全时空性的？因果集显然是离散结构，但它的非时空性远不止于此。尽管因果集的基本序关系是因果先后关系，但它具备人们通常认为时间先后关系应当拥有的性质。如果我们按直觉排除时间循环，并假设时间先后关系具有传递性，那么时间先后关系也是反对称的，这和因果集对因果先后关系的假设一致。在相对论中，无论如何具体定义时间先后关系，它最多也只是对事件的偏序，这点同样和因果先后关系一致。看起来因果先后关系在结构上就类似于最简形式的相对论时间先后关系，既不包含时长这类度量关系，也不包含时间的“流动”或流逝。

The extent to which one takes this distinction between causation and time seriously depends on one’s metaphysical position regarding the relation between causation and time. In fact, Dowker [15, 136n] takes the fundamental relation in causal set theory to be one of temporal, not causal, precedence and asserts that it would thus be more appropriate that the approach be called ”temporal set theory.” Against this stance, one could argue that the causal structure of relativistic spacetimes, on which the relation is directly modeled, is primarily causal and at best derivatively temporal. After all, this structure tracks the causal connectability of events by light signals. It can be shown [22, §3.1.1] that important results such as Malament’s theorem are closely intertwined with the history of causal theories of time. These theories invert the usual metaphysical hierarchy between time and causation and assume that causation is the more fundamental of the two and that, consequently, time derives from causation, not vice versa (See Baron and Le Bihan [4] for a recent version of such a causal theory of spacetime.). If this is right, then the fundamental relation in causal set theory is one of causal precedence, and time will only emerge from the causal structure.

人们对因果与时间之间这一区分的重视程度，取决于其在因果和时间的关系问题上持有的形而上学立场。事实上，道克尔 [15, 136n] 认为因果集理论的基本关系是时间先后关系，而非因果先后关系，并且主张该理论更合适的名称应该是“时间集理论”。针对这一观点，我们可以反驳: 该关系直接模仿的是相对论时空的因果结构，而这一结构本质上是因果性的，时间性最多只是派生性的。毕竟，该结构描述的是事件之间能否通过光信号建立因果连接。已有研究证明 [22, §3.1.1]，马拉门特定理这类重要结论与时间因果论的发展历史密切相关。时间因果论颠倒了时间与因果之间惯常的形而上学层级，认为因果比时间更根本，因此时间派生于因果，而非反过来 (参见巴伦和勒比昂 [4]，了解该时空因果论最近的一个版本)。如果该观点正确，那么因果集理论的基本关系就是因果先后关系，时间只会从因果结构中涌现出来。

Space is much more clearly absent from causal set. Without going into an analysis of the essence of space, space is usually so-called because it has a certain topological and geometrical structure which allows us to speak of (typically unary, binary, ternary, or quaternary) spatial relations of being nearby, far away, between, collinear, orthogonal, parallel, three-dimensional, etc. One might argue that many of these relations track a folk (or perhaps Euclidean) notion of space and are absent in GR also and that our task is merely that of recovering relativistic spacetime, implicitly assuming that Euclidean space (or Newtonian spacetime) approximates relativistic spacetime in certain states.

空间性质在因果集中的缺失要明显得多。无需分析空间的本质，空间之所以通常被称为空间，是因为它具有特定的拓扑与几何结构，这些结构让我们能够谈论 (通常是一元、二元、三元或四元的) 空间关系，比如相邻、相距遥远、在……之间、共线、正交、平行、三维等等。有人可能会提出，这些关系大多符合日常 (或许是欧几里得式的) 空间概念，广义相对论中本来也不存在这些概念，我们的任务仅仅是重建相对论时空，这已经隐含了欧几里得空间 (或牛顿时空) 在某些状态下逼近相对论时空的假设。

This point is perfectly valid, but as it turns out, there is a sense in which what ought to be taken as ”space” in a causal set has none of these structures. In fact, it has no structure at all. Spatial structure only emerges as we consider ever larger and sufficiently well-behaved causal sets. In order to see this, let us first identify what should reasonably be taken as ”space” in a causal set. In a relativistic spacetime, one way to construct space (at a time) is to introduce a foliation of spacetime, i.e., a partition of the four-dimensional Lorentzian manifold into three-dimensional spacelike hypersurfaces which are ordered by the values of a real-valued smooth function with nowhere vanishing, timelike gradient. The partition is then interpreted as a slicing of spacetime into space at subsequent moments in time.

这一观点完全合理，但事实证明，因果集中可被视为“空间”的部分，确实不具备任何这类结构——实际上完全没有任何结构。空间结构只有在我们考察规模更大、性质足够良好的因果集时才会涌现出来。想要理解这一点，我们首先要明确因果集中什么能被合理地视为“空间”。在相对论时空中，构建 (某一时刻的) 空间的一种方式是对时空做叶状结构分解，即将四维洛伦兹流形拆分为一系列三维类空超曲面，这些超曲面可通过一个梯度处处非零的类时光滑实值函数来排序。该拆分就被解释为将时空切分为不同时间时刻的空间切片。

In a causal set, lacking much of this structure, a foliation of the kind we seek would still partition the causal set into subsets which are ordered and labeled by a sequence of integers. These subsets would then represent space at a moment in time, at least if an additional condition is satisfied: their elements have to be pairwise ”incomparable,” i.e., none of their elements can causally precede, or be causally preceded by, another element of the same subset. In technical terms, this means that subsets must be ”antichains.” If this condition of being spatial were violated, then causal precedence could be ”instantaneous” - and the fundamental relation should certainly not be considered ”temporal” in any way. Furthermore, the antichains should be inextendible in the sense that any element of the causal set not in the antichain causally precedes or is causally preceded by an element of the antichain. For finite partially ordered sets, it can be shown that such a partition into antichains always exists [8,55]. Just as for relativistic spacetimes, however, these foliations will in general be highly non-unique.

在缺乏这类大量结构的因果集中，我们所寻求的那种叶状结构仍会将因果集划分为若干子集，这些子集由整数序列排序和标记。这些子集就能代表某一时刻的空间，至少在满足一个附加条件时是如此: 子集内的元素必须两两“不可比”，即同一子集内没有任何一个元素能在因果上先于另一个元素，或被另一个元素在因果上先于。从技术上讲，这意味着这些子集必须是“反链”。如果这个空间性条件被违反，那么因果优先就可以是“瞬时的”——而这种基本关系无论如何都绝不能被视为“时间性的”。此外，反链应当是不可扩张的，即因果集中所有不在该反链内的元素，都存在反链中的某个元素在因果上先于它或被它在因果上先于。对于有限偏序集，可以证明这种划分为反链的操作始终存在 [8,55]。然而，就像相对论时空一样，这些叶状结构通常来说远非唯一。

One can think of these antichains as representing ”space” (at a ”time”) and of the partition as a sequence of ”nows.” The trouble, it turns out, is that antichains are by definition entirely structureless sets. ”Space” as we have identified it has no topological or geometric structure at all. Space, in causal set theory, is altogether absent: causal sets seem to have no spatial structure.

我们可以将这些反链视作代表 (某一“时刻”的)“空间”，将整个划分视作一系列“现在”。事实证明，问题在于反链从定义上就是完全无结构的集合。我们划分出的“空间”根本不具备拓扑结构或几何结构。在因果集理论中，空间是完全缺失的: 因果集似乎不包含空间结构。

However, if causal sets give rise to something well approximated by relativistic spacetimes at some scale, then we will have to be able to reconstruct something from causal sets which resembles the spatial structure of relativistic spacetimes. In more general terms, we will have to find a way to extract geometric and topological information from fundamental causal sets in order to relate them to spacetimes.

然而，如果因果集在某一尺度上能产生可以被相对论时空很好近似的事物，那么我们就必须能够从因果集中重构出类似相对论时空空间结构的事物。更一般地说，我们必须找到一种方法，从基础因果集中提取几何和拓扑信息，从而将它们与时空联系起来。

Spacetime Functionalism and the Emergence of Spacetime

时空功能论与时空的涌现

As the previous section has shown, it seems clear that causal sets are less than fully spatiotemporal. In order to avoid the problem of empirical incoherence, and more generally to retrieve the manifest image of the world from the scientific one, it is necessary to show how relativistic spacetimes ”emerge” from causal sets. More specifically, this means that it needs to be established how relativistic spacetimes are excellent approximations to causal sets at certain scales or in certain regimes.

正如上一节所示，因果集显然并非完全时空性的。为了避免经验不融贯问题，更笼统地说，为了从科学图景中得到世界的显象图景，我们必须说明相对论时空是如何从因果集中“涌现”出来的。更具体地说，这意味着我们需要确定相对论时空在何种尺度或区域中是对因果集的良好近似。

As I have argued with co-authors on several occasions [21,22,25,26], functionalism offers the right template to understand the relationship between fundamental structures as postulated and described in theories of quantum gravity and relativistic spacetimes and in that represents a key tool to discharge the central task outlined at the outset. Generally speaking, functionalism identifies an entity not by its internal constitution, but instead by its ”functions” or the roles it plays. Functionalism about spacetime, then, claims that what makes something spacetime is that it ”plays the spacetime role.” In particular, spacetime functionalism charges us with two subtasks.

正如我曾与合著者在多处 argued [21,22,25,26]，功能论为理解量子引力理论假设描述的基础结构与相对论时空之间的关系提供了正确框架，因此它是完成开篇所述核心任务的关键工具。一般而言，功能论不通过内部构造定义一个实体，而是通过它的“功能”或它承担的角色来定义。因此时空功能论主张，某个事物成为时空的条件是它“承担了时空的角色”。具体而言，时空功能论给我们布置了两个子任务。

First, spacetime or spacetime properties are ”functionalized.” This means that we characterize spacetime in terms of its functions or of the roles it plays, e.g., in our theories in physics or, ultimately, in giving a scientific explanation of our phenomenology of the world. Without offering a comprehensive answer here, it is clear that spacetime fulfils roles such as determining the relative localization of physical entities, ordering events in time, metrical relations such as spatial distances or temporal durations, and the like. An important point to be noted regarding the first step is that functionalism does not insist that any particular entity, such as ”spacetime” itself, exists: it remains silent on whether (relativistic) spacetime exists. Instead, any kind of fundamental substances or properties are permitted, as long as they play the appropriate functional roles. In fact, these roles can be multiply realized. The general slogan of spacetime functionalism, as captured in the title of Lam and Wüthrich [25], is ”spacetime is as spacetime does.”

第一，时空或时空性质被“功能化”。这意味着我们根据时空的功能或它承担的角色来刻画它，例如它在我们物理学理论中的作用，或是最终它对我们关于世界的现象学给出的科学解释中所起的作用。本文在此不给出全面的回答，但很明显，时空承担了如下角色: 确定物理实体的相对位置，对事件按时间排序，给出空间距离、时间持续度这类度规关系等等。关于第一步需要注意的重点是，功能论并不坚持任何特定实体 (比如“时空”本身) 必须存在: 它对 (相对论) 时空是否存在不做断言。相反，它允许任何种类的基础实体或性质，只要它们能承担恰当的功能角色。事实上，这些角色可以被多重实现。正如 Lam 和 Wüthrich[25] 的标题所总结的，时空功能论的通用口号是““时空之所是，即时空之所为”。

Second, once the functions of spacetime are specified, we provide an explanation of how the fundamental entities or properties can execute these functional roles. Given the multiple realizability permitted in the first step, the fundamental entities which fill the roles of spacetime may themselves be quite different from relativistic spacetime. However different they turn out to be, however, an explanation of how they nevertheless fulfil the relevant functional roles of spacetime must be given. For instance, this means that it must be shown how the fundamental structures deliver (relative) localization of entities, the ordering of events in space and time, and have spatial distances and temporal durations, and so on, at the emergent level.

第二，一旦确定了时空的功能，我们就需要解释基础实体或性质如何能够执行这些功能角色。由于第一步允许多重实现，承担时空角色的基础实体本身可以与相对论时空非常不同。但无论它们最终多么不同，我们都必须解释它们为何能够承担时空相关的功能角色。例如，这意味着我们必须说明，基础结构如何在涌现层次上实现实体的 (相对) 定位、事件的时空排序、空间距离和时间持续度等等。

If this functionalist agenda is successfully completed for a research program in quantum gravity, then the threat of empirical incoherence is thwarted: as the spacetime features necessary for empirical confirmation are shown to be available at the relevant scale in the approach at stake, empirical confirmation can then proceed in the usual way even if the fundamental ontology of the theory diverges significantly from that of relativistic spacetimes.

如果这种功能论纲领能在某个量子引力研究项目中成功完成，经验不融贯的威胁就会被消除: 只要该进路能表明经验确证所需的时空特征在相关尺度上存在，即便该理论的基础本体论与相对论时空本体论差异很大，经验确证也可以照常开展。

In light of the fact that approaches to quantum gravity remain active research programs with the as of yet unfulfilled ambition of delivering a complete and concretely worked out (and empirically confirmed) theory of quantum gravity, the second step of the functionalist agenda can only be sketched. Although causal set theory is no exception and remains a work in progress, its advocates have started to outline in some detail how a functionalist program might be implemented in causal set theory, although of course not under this name. Let us consider some work in this direction (For more details, see Lam and Wüthrich [25, §4] and Huggett and Wüthrich [22, chapter 4].).

鉴于量子引力研究进路目前仍是活跃的研究项目，尚未实现得到一个完整、具体成型且得到经验确证的量子引力理论的目标，功能论纲领的第二步目前只能勾勒出轮廓。因果集理论也不例外，仍在发展过程中，但它的支持者已经开始较为详细地勾勒功能论纲领如何在因果集理论中落地，当然他们并未使用“功能论”这个名称。我们接下来考察这一方向上的一些研究 (更多细节参见 Lam 和 Wüthrich [25, §4] 以及 Huggett 和 Wüthrich [22, 第 4 章]。)

First and this is vital to the functionalist strategy, causal set theory needs not to recover the whole continuum or manifold structure of GR. However, some causal sets ought to be ”manifoldlike” in order to show that they are well approximated by relativistic spacetime described by manifolds of reasonably low dimensionality and with Lorentz signature and non-pathological causal structure. By showing that causal sets satisfying the dynamical laws are ”manifoldlike,” one can thus establish that they satisfy a necessary condition to perform the relevant spacetime functions. This involves showing that there exists an embedding of a causal set into a spacetime such that the causal relations are preserved, the mapping distributes the elements of the causal set sufficiently uniformly into the manifold, and the spacetime has no non-trivial structure at scales below the mean point spacing.

首先，这对功能论策略至关重要: 因果集理论不需要还原广义相对论的整个连续统或流形结构。但部分因果集必须是“类流形的”，这样才能证明它们可以被具有合理低维、洛伦兹号差和非病态因果结构的流形所描述的相对论时空良好近似。证明满足动力学定律的因果集是“类流形的”，就能确立它们满足承担相关时空功能的必要条件。这需要证明: 存在一个因果集到时空的嵌入，使得因果关系被保留，该映射将因果集的元素足够均匀地分布到流形中，且时空在平均点间距以下的尺度不存在非平凡结构。

Suppose that a sufficiently large causal set is manifoldlike in this sense and is well approximated by a physically reasonable spacetime. The next task is then to show that the approximating spacetime is ”approximately unique.” (That this is indeed the case is the famous ”Hauptvermutung.”) This condition is imposed in order to ensure the uniqueness of the emerging spacetime and so that one and the same causal set cannot play inconsistent spacetime roles. It turns out that both a rigorous formulation of this condition and proof of its satisfaction are scientifically hard problems that have so far defied complete control.

假设一个足够大的因果集在此意义上具有流形性质，且可以被一个物理合理的时空很好地近似。那么接下来的任务就是证明这个近似时空是“近似唯一的”(著名的“主要猜想”就认为事实的确如此)。引入这一条件是为了保证涌现出的时空具有唯一性，避免同一个因果集扮演相互矛盾的时空角色。事实证明，对该条件做出严格表述并证明其成立都是非常困难的科学问题，目前尚未得到完整解决。

The next, and final, task of the functionalist research program is to show how causal sets can fill the roles of spatiotemporal localization, spatial distance, temporal duration, topology, etc. This job requires the construction of concrete means of extracting this kind of information from causal sets. Although much remains to be done, physicists have published substantive work in this direction. Recall from subsection ”The Non-spatiotemporality of Causal Sets” that causal sets have no spatial structure at all. Establishing how causal sets can give rise to spatial geometry and spatial topology thus becomes a central problem to be addressed in the functionalist program. Indeed, physicists have worked to define spatial topology [32, 33] in terms native to the fundamental causal set and similarly with spatial structure and distance [38, 39]. These efforts aim to deliver on the second functionalist task of showing how the fundamental structures can play spacetime roles and thus constitute paradigm examples of functionalist work.

功能主义研究纲领的下一个、也是最后一个任务，是证明因果集如何能够承担时空定位、空间距离、时间时长、拓扑等的角色。这项工作需要从因果集中提取这类信息的具体方法。尽管仍有许多工作有待完成，物理学家已经在此方向取得了实质性进展。回顾“因果集的非时空性”小节可知，因果集根本不存在空间结构。因此，明确因果集如何产生空间几何与空间拓扑就成了功能主义纲领需要解决的核心问题。实际上，物理学家已经在基础因果集的原生框架下定义了空间拓扑 [32, 33]，并对空间结构和距离做了同样的工作 [38, 39]。这些努力旨在完成第二项功能主义任务，即证明基础结构如何能够扮演时空角色，因此它们本身就是功能主义研究的典型范例。

If this second step is completed, then it is fully established that causal sets are suitable to perform the relevant roles of spacetime. On the functionalist paradigm, completing the two steps of the program is all there needs to be done to show how spacetime emerges in causal set theory and thus to avert the threat of empirical incoherence.

如果第二步得以完成，就可以完全确定因果集适合承担时空的相关角色。在功能主义范式下，完成该纲领的两个步骤就足以说明时空如何在因果集理论中涌现，从而消除经验不融贯的威胁。

There are at least two ways in which this conclusion can be resisted: the first challenges the original verdict according to which the fundamental structures are non-spatiotemporal, and the second accepts the verdict, but puts doubt on the success of the functionalist program. Roughly put, this tracks a dilemma posed by Yates [57] with which he struck spacetime functionalism: either our theory of the fundamental structures is relevantly isomorphic to the theory of spacetime it replaces, or it is not (To be more precise, Yates strikes a particular form of spacetime functionalism with this dilemma, so-called realizer spacetime functionalism.). If it is, then we should certainly expect that the functional reduction succeeds in deriving spatiotemporal structures from the fundamental ones; but then the fundamental structures were spatiotemporal after all, rendering spacetime functionalism otiose. If it is not, then it is hard to see how spacetime functionalism could connect the non-spatiotemporal fundamental theory to higher-level spacetime theories, delivering its impotence. Either way, spacetime functionalism fails to do the work which it was advertised to do.

至少可以从两种角度反驳这一结论: 第一种质疑基础结构是非时空性这一原始判断，第二种接受该判断，但质疑功能主义纲领的成功。大致来说，这对应耶茨 [57] 针对时空功能主义提出的一个二难推理: 我们的基础结构理论要么和它所取代的时空理论具有相关同构性，要么不具有 (更准确地说，耶茨的二难推理针对的是特定形式的时空功能主义，即所谓的实现者时空功能主义)。如果同构，那么我们当然可以预期功能还原能够成功从基础结构推导出时空结构；但如此一来，基础结构本身本来就是时空性的，时空功能主义就成了多余的。如果不同构，那么很难看出时空功能主义如何能将非时空的基础理论和高层时空理论联系起来，这也就意味着它无能为力。无论哪种情况，时空功能主义都无法完成它宣称要完成的工作。

Let me address this dilemma before returning to other objections. It is clear that spacetime functionalism had a problem if it failed to connect the two levels, as it was indeed built to do precisely that. So it better avoid the second horn of the dilemma. However, success, as on the first horn, does not imply that the fundamental ontology was spatiotemporal and that, therefore, there was no point in introducing functionalism. In fact, we have seen above how causal sets are at least not directly spatial, indeed spatially structureless, and recovering spatial structure is rather elaborate and highly indirect, as the literature on this cited above testifies. Substantive work is necessary to establish the connection. Moreover, not all causal sets will be sufficiently ”well behaved” to give rise to non-degenerate spatiotemporal structure, further supporting the fact that causal sets are not directly and automatically spatiotemporal. In general, the situation in quantum gravity is far murkier than is suggested by Yates's dilemma, and the fundamental structures are not so easily comparable to relativistic spacetimes. In fact, this connection is even more tenuous in some other approaches to quantum gravity than it already is in causal set theory.

在讨论其他反驳之前，我先来处理这个二难推理。很明显，如果时空功能主义无法连接两个层级，那它就确实存在问题，因为它本来就是为了完成这个目标才被提出的。所以它最好能避开二难推理的第二支。不过，即便像第一支那样取得成功，也不意味着基础本体论本来就是时空性的，因此不代表引入功能主义毫无意义。事实上，我们之前已经说明，因果集至少不直接具有空间性，它本身完全没有空间结构，而重建空间结构的过程相当复杂、高度间接，上文引用的相关文献也印证了这一点。我们需要开展大量实质性工作才能建立起二者的连接。此外，并非所有因果集都足够“良态”，能够产生非退化的时空结构，这进一步证明因果集并非直接、自动就是时空性的。总的来说，量子引力中的实际情况比耶茨的二难推理所暗示的要模糊得多，基础结构也没那么容易和相对论时空做比较。事实上，在其他一些量子引力研究进路中，这种连接比因果集理论中的还要更微弱。

Returning to the two ways of resisting the general conclusion of this section, by denying non-spatiotemporality or by rejecting functionalism, one finds traces of both in the literature. As for the first camp, Le Bihan and Linnemann [28] argue that many approaches to quantum gravity, including causal set theory, postulate fundamental structures, which are spatiotemporal, or at least include a fundamental asymmetry between space and time. The latter, rather weak, claim according to which there are clear signs in causal set theory of a distinction between space and time certainly seems true, but too weak to change anything that was said above. In order to challenge our conclusions, the much stronger claim that causal sets are rather directly spatiotemporal would have to be supported. Even if we were to interpret the causal relations as relations of temporal precedence, as we have seen above in Dowker [15, 136n], this would not change anything about the fact that direct spatial structure is absent in causal sets. Given the significant differences between causal sets and relativistic spacetimes, this first family of objections does not seem to cut very deeply into our conclusions.

回到反驳本节普遍结论的两种进路——否认非时空性，或是拒绝功能主义——文献中都能找到二者的踪迹。就第一派而言，勒·比汉和林内曼 [28] 提出，包括因果集理论在内的许多量子引力进路都假设了基本结构是时空性的，或至少包含空间与时间之间的根本不对称性。后者是一个相当弱的主张，即因果集理论中存在明确迹象表明空间与时间有区分，这一点看似确实成立，但弱到不足以改变上文的任何结论。要挑战我们的结论，就必须为更强的主张辩护: 即因果集本身是直接时空性的。正如我们上文在道克 [15, 136n] 中所见，即便我们将因果关系解读为时间先后关系，也无法改变因果集中不存在直接空间结构这一事实。考虑到因果集与相对论时空存在显著差异，这类第一类反对意见似乎并未对我们的结论造成深刻冲击。

As for the second type of objections, there are of course standard objections against functionalism in the context of the philosophy of mind, from where the position has been borrowed (Levin [30, § 5] is a standard reference for these objections to functionalism as a program in the philosophy of mind. See Lam and Wüthrich [25] for responses to analogous objections to spacetime functionalism.). Without rehashing these general objections here, let us focus on two related criticisms. In the slightly different context of wave function realism, Ney [36]'s "macro-object objection" raises concerns about spacetime functionalism being unable to account for the constitution of macroscopic objects, such as four-dimensional objects of our experience and perhaps spacetime itself. Just like a hologram may capture some of the features of the object it depicts but nevertheless falls short of fully constituting that object, spacetime functionalism cannot deliver a satisfactory account of the constitution of such objects. However, as explicated in Lam and Wüthrich [25, §3], the macro-object objection relies on a very robust and ultimately spatiotemporal notion of constitution, which can be avoided altogether by endorsing a non-spatiotemporal mereology [3]. Furthermore, taking spacetime functionalism seriously implies that, faithful to its slogan "spacetime is as spacetime does," if there is a nature or an essence to spacetime, then it is exhausted by the functions it plays in our theories in physics or perhaps for understanding human experience more generally. Requiring that the constituents of spacetime have a true, intrinsically spatiotemporal (but completely ineffable) nature is just to beg the question against spacetime functionalism. If we can show that each and every empirically relevant role of spacetime can be played by our fundamental structures, there remains nothing else to show.

至于第二类反对意见，时空功能主义这一立场借自心灵哲学，而心灵哲学语境下当然存在针对功能主义的标准反驳 (列文 [30, § 5] 是这些针对心灵哲学领域功能主义纲领的反驳的标准参考文献。关于对时空功能主义的类似反驳的回应，参见 Lam 和 Wüthrich [25]。) 在此不重复这些一般性反驳，我们集中讨论两个相关批评。内伊 [36] 在略有不同的波函数实在论语境下提出了“宏观客体反驳”，他担忧时空功能主义无法解释宏观客体的构成，比如我们经验中的四维客体，甚至可能包括时空本身。就像全息图可以捕捉它所描绘客体的部分特征，却不足以完全构成该客体，时空功能主义也无法给出关于这类客体构成的令人满意的说明。然而，正如 Lam 和 Wüthrich [25, §3] 所阐释的，宏观客体反驳依赖一种非常稳固、且最终是时空性的构成概念，而我们完全可以通过认可一种非时空分体论来避开它 [3]。此外，认真对待时空功能主义就意味着，忠于其口号“时空之所是即时空之所为”: 如果说时空有某种本性或本质，那么它完全被时空在我们物理学理论中，或是更宽泛地在理解人类经验中所发挥的功能穷尽了。要求时空的组成部分拥有一种真实的、内在时空性 (却又完全不可言说) 的本性，这恰恰是对时空功能主义的乞题。如果我们能证明，时空所有与经验相关的作用都可以由我们的基本结构承担，那就不存在其他需要证明的东西了。

Relatedly, Le Bihan [27] distinguishes between ”hard” and ”easy problems” of spacetime emergence, in a loose analogy to the problem of consciousness in the philosophy of mind. He invokes the cognitive dissonance aroused by the inconceivability of a non-spatiotemporal world as evidence for an explanatory gap, which spacetime functionalism cannot close. Le Bihan (S374) insists that a physical ”what it is like,” such as the spatiotemporal ordering of events through experience or the metricity of their spatiotemporal relation, stands in need of explanation. Without further going into the details here (Those can be found in Huggett and Wüthrich [22, §2.4].), and while acknowledging the existence of a cognitive dissonance about the emergence of spacetime, the program of spacetime functionalism, if successfully executed, closes any explanatory gap that needs closing.

与之相关，勒·比汉 [27] 松散类比心灵哲学中的意识问题，区分了时空涌现的“硬问题”和“易问题”。他援引非时空世界不可设想所引发的认知失调，作为时空功能主义无法填补的解释鸿沟的证据。勒·比汉 (S374) 主张，物理层面“它到底是什么样的”，比如经验中事件的时空排序，或是它们时空关系的度规性，都需要解释。在此我不展开细节 (细节可参见 Huggett 和 Wüthrich [22, §2.4]。)，尽管我承认关于时空涌现存在认知失调，但如果时空功能主义纲领能成功执行，它就能填补所有需要填补的解释鸿沟。

In sum, the (partial) non-spatiotemporality of the fundamental ontology of theories of quantum gravity, including causal set theory, turns out to open deep and fruitful philosophical questions concerning the nature of spacetime. I have argued that these questions are best addressed by adopting spacetime functionalism.

总而言之，包括因果集理论在内的量子引力理论的基本本体论是 (部分) 非时空的，这一事实带来了关于时空本性的深刻且富有成果的哲学问题。我已经论证，这些问题最好通过采纳时空功能主义来解决。

Philosophy of Time

时间哲学

Leaving these foundational issues behind, we turn to philosophical issues as they arise in the context of causal set theory. Perhaps the most obvious philosophical implications of causal set theory are to be found in the philosophy of time, at least judging by the number of authors and papers devoted to this topic: Arageorgis [1], Butterfield [9], Dowker [12, 14, 15], Earman [16], Huggett [20], Sorkin [46, 47], and Wüthrich and Callender [56]. At the center of the debate resides the question whether causal set theory, unlike much of the rest of contemporary fundamental physics, supports a notion of ”becoming” against the standard eternalist orthodoxy. This section follows the main arguments on both sides of the debate.

放下这些基础问题，我们转向因果集理论背景下产生的哲学问题。至少从研究该主题的作者和论文数量来看，因果集理论最显著的哲学意义或许就体现在时间哲学领域: 相关研究者包括阿拉乔尔基斯 [1]、巴特菲尔德 [9]、道克 [12, 14, 15]、厄尔曼 [16]、赫格特 [20]、索金 [46, 47]、于特里希与卡伦德 [56]。争论的核心问题是: 与当代基础物理学的大部分其他理论不同，因果集理论是否支持“生成”概念，反驳标准的永恒论正统观点。本节将介绍争论双方的主要论据。

The Debate in Philosophy of Time

时间哲学中的争论

In philosophy of time, two main camps face one another. On the one hand, we have those who favor a metaphysics of time which places the apparent dynamical aspects of time on center stage, the sense that things ”become,” that there is a ”passage of time,” that time ”flows.” Views in this family are chiefly motivated by intuition based on the apparent phenomenology of temporality. They inevitably give a fundamental role in their metaphysics to an ever-changing, updating, and dynamically advancing ”present.” Presentists consider present events and objects the only ones to really exist, with past ones having passed away and future ones yet to become. For presentism, the sum total of existence thus only contains present entities. Growing block theorists also admit past entities as genuinely existing, with the sum total of what exists being presented by an ever-growing block to which new slivers of existence are continually being added as they become. The present is awarded a special status in that it represents the cusp of the growing block, the advancing front of becoming.

在时间哲学中，存在两个相互对立的主要阵营。一方面，有学者支持将时间明显的动态特征置于核心位置的时间形而上学，即认为事物会“生成”，存在“时间流逝”，时间会“流动”。这类观点主要源于时间性直观现象学带来的直觉。在这类形而上学中，不断变化、更新、动态推进的“现在”必然占据基础性地位。现在论认为只有当下的事件和物体真正存在，过去的事物已经消逝，未来的事物尚未生成。因此，对现在论来说，存在的总和仅包含当下的实体。成长块理论也承认过去实体真实存在，存在的总和是一块不断增长的块，随着新事物不断生成，新的存在碎片会持续被添加到这块上。现在被赋予特殊地位，它就是成长块的顶端，也就是生成不断推进的前沿。

In contrast to these dynamical metaphysical views, we find, on the other hand, those who eliminate this dynamical aspect from their fundamental metaphysics.

与这些动态形而上学观点相对，另一方面，有学者从基础形而上学中完全剔除了这种动态特征。

Fundamentally, there is ”being,” but no ”becoming.” Becoming, to the extent to which it is an objective feature of reality, emerges at some scale, perhaps from interactions between fundamental physics and the cognitive apparatus of perceiving agents such as human beings. Views in this camp are often, though not invariably, motivated by contemporary fundamental physics. Eternalism is the view that the present does not play a special role and that, consequently, present entities do not enjoy a special ontological status. Eternalism is sometimes described as the view according to which past, present, and future entities all exist on a par. This characterization is problematic in that it still seems to presuppose a distinction between past, present, and future when eternalism denies that there is, objectively and fundamentally, any such distinction to be had. With this distinction gone, eternalism then accepts that the dynamical features of time which depended on it cannot be fundamental. The sum total of existence according to eternalists contains what presentists would call past, present, and future entities.

从根本上来说，只有“存在”，没有“生成”。即便生成是实在的一个客观特征，它也只是在某个尺度上涌现出来的，或许是基础物理和人类这类感知认知主体的认知机制相互作用的产物。这个阵营的观点虽然不绝对，但往往受到当代基础物理学的启发。永恒论认为现在并不扮演特殊角色，因此当下实体也不享有特殊存在论地位。永恒论有时被描述为过去、现在、未来的实体同等存在的观点。这种描述存在问题，因为它似乎仍然预设了过去、现在、未来的区分，但永恒论从客观、根本层面否认存在这样的区分。取消这个区分后，永恒论就承认依赖该区分的时间动态特征不可能是基础性的。根据永恒论，存在的总和包含现在论所称的过去、现在和未来实体。

There is a danger that the debate is trivialized with both sides agreeing on obvious facts. It turns out that it is surprisingly difficult to articulate presentism as a substantive metaphysical position such that it is neither trivially true (because it just asserts that nothing exists, now, that is not present) nor obviously false (because it commits to nothing existing, at some time or other, that is not present) (This concern has been articulated many times over, although in somewhat different forms, for example, in [10, 31, 35, 44].). All hands agree that dinosaurs existed in the past, but that they no longer exist now. But presentism, and the entire debate between the distinct metaphysical theses in play here, cannot be captured adequately if we think of ”existing” as implicitly demanding a temporal locution: either existence is existence now or it is existence at some time or other. We need a concept of existence simpliciter free of any such temporal implication.

这场争论存在被平庸化的风险，双方会认同所有显见事实，结果令人惊讶的是，很难把现在论阐释成一个实实在在的形而上学立场，要么它变得老生常谈 (因为它只是断言，现在不存在非当下的事物)，要么它就显然错误 (因为它主张，在任何时间，都不存在非当下的事物)(这种担忧已经以不同形式被多次提出，例如见 [10, 31, 35, 44])。所有人都认同恐龙曾在过去存在，但现在不复存在。但如果我们认为“存在”默认需要时间限定——要么是现在存在，要么是在某个时间存在——就无法恰当把握现在论，也无法把握这场围绕不同形而上学命题展开的整个争论。我们需要一个不带任何时间含义的纯存在概念。

In spite of what one sometimes reads in the literature, eternalists also think that dinosaurs do not exist now. They think that dinosaurs exist simpliciter, i.e., that they are part of the sum total of existence; but it is simply not the case that eternalists think that everything, including past and future entities, exists now (For just one prominent example of a problematic characterization of eternalism, see Emery et al. [17, §6].). The locution ”now” is simply inadmissible in fundamental discourse and can at best be an indexical which functions like ”here” and ”I.” Indexicals like ”here” and ”I” and, the eternalist would add, ”now” do not figure in fundamental descriptions of our world. Consequently, any aspect of our metaphysics which depends on a fundamental present cannot be part of the fundamental description. In general, we are again led to the conclusion that ”existence” cannot imply existence at a particular time for the position (and hence the debate) to be meaningful.

和文献中常见的说法不同，永恒论者也认为恐龙现在不存在。他们认为恐龙纯存在，也就是说恐龙是存在总和的一部分；但永恒论者根本不主张所有事物，包括过去和未来实体，都现在存在 (关于这种对永恒论的不当描述，仅举一个知名例子，见 Emery 等人 [17, §6])。“现在”这个说法根本就不允许出现在基础话语中，它最多就是一个索引词，功能和“这里”“我”类似。永恒论者会补充说，“这里”“我”这类索引词，还有“现在”，都不会出现在我们世界的基础描述中。因此，任何依赖基础现在概念的形而上学内容都不可能是基础描述的一部分。总的来说，我们再次得到结论: 要让这个立场 (以及这场争论) 有意义，“存在”就不能蕴含“在某个特定时间存在”。

Perhaps a useful way of thinking about the debate is to recognize that there are obvious sub- and superset relations among the sum total of existence according to the three positions [53]. For instance, from the presentist perspective, the eternalist is committed to a strict superset of entities compared to their commitment, and from the eternalist perspective, the growing block’s sum total of existence is a strict subset of theirs. More could be said in an attempt to make this more rigorous, but I trust the idea is sufficiently clear for us to proceed on this understanding.

要理解这场争论，或许有一个实用的思路: 我们可以认清三种立场对应的存在总和之间清晰的子集和超集关系 [53]。例如，从现在论的视角看，永恒论承诺的实体是现在论所承诺实体的严格超集；从永恒论的视角看，成长块理论的存在总和是永恒论存在总和的严格子集。要让这个说法更严谨还可以补充很多内容，但我相信这个思路已经足够清晰，我们可以基于这个理解继续往下谈。

The Situation Before Causal Set Theory

因果集理论提出之前的情况

Before the advent of relativistic physics, when physics was thought to describe what happens in a Newtonian setting, any of our three metaphysical positions could straightforwardly be combined with our best physics. Although Newtonian physics did not invoke a distinction between past, present, and future, it is easily seen as being compatible with it. However, once we move to relativistic physics, this symmetry is broken in favor of eternalism. The dynamicist theories of presentism and the growing block run into the problem of depending on a fundamental distinction between what is present and what is not in a relativistic setting where simultaneity between spacelike-related events is relative to a frame of reference. Consequently, in relativity, there is no global, objective, frame-independent, and thus absolute notion of present available. And it seems as if existence ought to be a global, objective, and frame-independent affair. Therefore, existence cannot depend on a notion of present, as presentism and the growing block theory demand. It thus seems as if eternalism is the only game in town once we accept relativity (Although the argument is fairly direct, it seems as if a version of it is first found in Rietdijk [41] and Putnam [37]. It has been repeated many times since (for instance, in [45] or [43]). For a more general assessment of the prospects of presentism in modern physics, see [54].).

在相对论物理学诞生之前，物理学被认为是在牛顿框架下描述事件，我们的三种形而上学立场都可以直接与当时最优的物理学相容。尽管牛顿物理学本身没有引入过去、现在和未来的区分，但人们很容易发现它与这种区分并不冲突。然而，当我们进入相对论物理学后，这种对称性被打破，支持了永恒论。现在论和增长块理论这类动态论遇到了问题: 它们依赖于对“何为现在”与“何为非现在”的根本区分，但在相对论框架中，类空关联事件的同时性是相对于参考系的。因此，在相对论中不存在全局、客观、不依赖于参考系，因而绝对的“现在”概念。而存在本身应当是一件全局、客观、不依赖于参考系的事。因此，存在不能像现在论和增长块理论要求的那样，依赖于“现在”这个概念。所以一旦我们接受相对论，似乎只有永恒论成立 (尽管这个论证相当直接，但它的雏形最早可见于里特迪克 [41] 和普特南 [37] 的著作。此后该论证被反复引用 (例如 [45] 或 [43])。关于现在论在现代物理学中发展前景的更全面评估，参见 [54]。)。

The above argument implicitly depends on the ”present” being defined by an equivalence relation of co-presentness which is naturally satisfied by events on a spacelike hyperplane. A foliation of spacetime into a (totally) ordered set of spacelike hypersurfaces is unique in Newtonian (or neo-Newtonian) spacetime, but is relative to the frame of reference and so non-unique in special relativity's Minkowski spacetime. However, as Stein [49] has proved, there exists a (unique) frame-independent absolute and non-trivial relation of co-presentness which may underwrite an objective notion of becoming. In particular, given an event in Minkowski spacetime as vantage point, we can identify all events on its past light cone as being ”co-present” with it. Such a relation of co-presentness permits the definition of versions of presentism (only an event and events on its past light cone exist) or the growing block theory (which also admits events inside the event's past light cone).

上述论证隐含地依赖于“现在”由共存等价关系定义，类空超平面上的事件自然满足该关系。将时空分层为全序的类空超曲面集合在牛顿 (或新牛顿) 时空中是唯一的，但在狭义相对论的闵可夫斯基时空中，分层依赖于参考系，因此不唯一。然而，正如斯坦 [49] 所证明的，存在一种 (唯一的) 不依赖于参考系的绝对、非平凡的共存关系，可以为客观的生成概念提供基础。具体来说，以闵可夫斯基时空中的一个事件作为有利视角，我们可以将其过去光锥上的所有事件识别为与它“共存”。这种共存关系允许我们定义版本的现在论 (仅该事件及其过去光锥上的事件存在) 或增长块理论 (也承认该事件过去光锥内部的事件存在)。

However, saving presentism or the growing block from the relativity of simultaneity comes at a price. First, since the new relation of co-presentness is nontransitive and antisymmetric and so clearly not an equivalence relation, the usual intuitions invoked to motivate presentism seem to become more removed from what is supposed to be the form of the present. Defending such a light cone presentism would generally require giving up rather natural intuitions about time. For example, it would have to be denied that the causal ordering of events along null geodesics, such as of the creation and detection of a photon, implies a temporal ordering - lightlike-related events like this would be co-present. More of interest for present purposes is a second point: although absolute in the sense of frame independence, the present is relative to a particular reference event, the ”given” event. To be sure, presentism in Newtonian spacetime also picked one of the spacelike hypersurfaces as the present. But this happened not at the expense of the other hypersurfaces: those would all take turns in sequentially becoming the ”present.” In this way, every event in Newtonian spacetime would exist at some point in time. However, on the present proposal, it is not clear (a) how a particular event is chosen as the ”given” event and (b) how the dynamical updating is supposed to work. What exists appears to depend on the arbitrary choice of an event as reference, unless something is said about the dynamics of the ”present.”

然而，把现在论或增长块从同时性相对性的困境中挽救出来是有代价的。首先，由于新的共存关系是非传递且反对称的，显然不是等价关系，用来支撑现在论的通常直觉和现在应有的形式之间的偏离已经相当明显。为这种光锥现在论辩护通常要求放弃关于时间相当自然的直觉。例如，我们必须否认: 沿类光测地线的事件因果序 (比如光子的产生与探测) 蕴含时间序——此类类空关联事件会被认为是共存的。就本文当前目的而言，更值得关注的是第二点: 尽管现在在不依赖参考系的意义上是绝对的，但它相对于特定的参考事件，即那个“给定”事件。诚然，牛顿时空中的现在论也会选出一个类空超平面作为现在，但这并不以牺牲其他超平面为代价: 它们都会依次轮流成为“现在”。通过这种方式，牛顿时空中的每个事件都会在某个时间点存在。然而，在当前的提议下，我们不清楚 (a) 特定事件是如何被选为“给定”事件的，也不清楚 (b) 动态更新应当如何运作。存在似乎依赖于任意选择一个事件作为参考，除非我们对“现在”的动力学做出额外说明。

A natural way to generalize the view emerging from Stein's proposal, and suggested in [11], is to relativize becoming to a given (infinite) worldline and then state that the dynamical sequence of nows is given by the totally ordered past light cones of events along that worldline. In this way, every event in Minkowski spacetime will be said to exist at some point in time (namely, when it is ”swept over” by the past light cone of events on the worldline). The worldline needs to extend from past to future infinity and ought to be the worldline of a possible observer. Call this ”worldline-dependent becoming,” and note that it is certainly available already in Minkowski spacetime.

斯坦的提议衍生出了一种自然的推广观点 (也在文献 [11] 中被提出): 将生成相对化到给定的 (无穷长) 世界线，然后主张动态的现在序列由该世界线上各事件的全序过去光锥给出。通过这种方式，闵可夫斯基时空中的每个事件都会被认为在某个时间点存在 (即当它被世界线上事件的过去光锥“扫过”时)。该世界线需要从过去无穷远延伸到未来无穷远，并且应当是一个可能观察者的世界线。我们将这称之为“依赖世界线的生成”，需要注意的是，这种观点在闵可夫斯基时空中就已经成立。

Worldline-dependent becoming is objective in that it only relies on the geometry of Minkowski spacetime. Furthermore, it is absolute in that it is frame-independent, i.e., is based only on Lorentz-invariant structures. However, it is relative in that it depends on a particular given worldline. Thus, even though it does not privilege a particular frame of reference, it sanctions one particular worldline or observer. I will call this feature of worldline-dependent becoming local.

依赖世界线的生成是客观的，因为它仅依赖于闵可夫斯基时空的几何结构。此外，它是绝对的，因为它不依赖于参考系，即仅基于洛伦兹不变结构。但它同时也是相对的，因为它依赖于某条给定的特定世界线。因此，即使它不偏好某个特定参考系，它也会认可某一条特定世界线或观察者。我将依赖世界线的生成的这一特性称为局域性。

Apart from this form of localism, there are other unattractive features of worldline-dependent becoming. ”Being co-present” is no longer an equivalence relation, as both transitivity and symmetry no longer hold. Although this loss of equivalence may not be fatal for the view, it has clearly unpalatable metaphysical consequences: if we tie existence to co-presentness, then an entity a may exist for another entity b , while b does not exist as far as a is concerned. Furthermore, events which on some intuitive notion of global time lie in the distant past will be copresent if they are spatially sufficiently far removed. This is certainly odd, but since in Minkowski spacetime nothing answers to this intuitive notion of global time, there may simply not be enough structure to make the worry stick.

除了这种局域性之外，依赖世界线的生成还有其他不太吸引人的特性。“共存于当前”不再是等价关系，因为传递性和对称性都不再成立。尽管这种等价性的丧失对该观点来说不一定是致命的，但它确实会带来令人难以接受的形而上学后果: 如果我们将存在性与共存于当前绑定，那么对于实体 b 而言，实体 a 可能存在，但就 a 而言，b 并不存在。此外，根据全局时间的直观概念，那些位于遥远过去的事件，如果它们在空间上相距足够远，也会成为共存于当前的事件。这当然很奇怪，但由于在闵可夫斯基时空中，没有任何结构符合这种直观的全局时间概念，这个担忧可能根本就没有足够的结构支撑。

These unwelcome consequences can be mitigated if we either base our metaphysics on some non-Lorentz-invariant structure or accept a relativization of existence to frames of reference. The former would amount to an unscientific hypostatization of an undetectable structure. Perhaps surprisingly, the latter has been defended in the literature: Fine [18] defends ”fragmentalism,” i.e., the view which accepts that our commitment to presentism and special relativity forces us to accept that existence simpliciter is relativized to frames of reference such that different inertial observers will in general disagree as to what exists, not merely as to what is simultaneous.

如果我们要么将形而上学建立在某种非洛伦兹不变结构之上，要么接受存在相对于参考系的相对化，这些不受欢迎的后果就可以得到缓解。前者相当于对一种不可探测的结构进行非科学的实体化。或许令人惊讶的是，后者已经在文献中得到辩护: 法因 [18] 捍卫了“碎片化主义”，即该观点认为我们对现在主义和狭义相对论的承诺迫使我们承认，绝对存在是相对于参考系而言的，因此不同惯性观察者通常会对何物存在产生分歧，而不仅仅是对何为同时产生分歧。

In light of special relativity, advocates of dynamical theories such as presentism or the growing block view thus face the following dilemma: either their metaphysics answers to their initial motivation and explanatory requests or is compatible with the structure of Minkowski spacetime, but not both [10,54]. They must thus either give up their original ambition or go against very well-established physics.

因此，鉴于狭义相对论，现在主义或增长块理论等动态理论的支持者面临着如下两难困境: 他们的形而上学要么符合其最初的动机和解释要求，要么与闵可夫斯基时空结构相容，但二者不可兼得 [10,54]。因此，他们必须要么放弃最初的抱负，要么违背已经非常成熟的物理学。

Is this uncomfortable position ameliorated as we go beyond special relativity to more fundamental theories? The dilemma stays essentially the same as we move to GR, even though the debate is enriched by two new factors, pulling in opposite directions. The good news for the presentist first: as it turns out, in spacetimes of an important family of models in GR, there exists a physically privileged foliation. These spacetimes admit an objective cosmic time, thus grounding an objective and in principle observable distinction of events into past, present, and future. The Friedmann-Lemaître-Robertson-Walker (FLRW) spacetimes, which form the backbone of the cosmological standard model, belong to this family. Given that cosmologists have good evidence for thinking that these models describe the spacetime structure of our actual world with a surprisingly high accuracy at sufficiently large scales and at sufficiently late times, the presentist might be tempted to draw (premature!) hope. Although the FLRW spacetimes appear to correctly capture the large-scale structure of spacetime, they assume a perfectly uniform distribution of matter-energy across the universe. The rather significant local deviations from such a global average distribution thwart the local validity of a partition into past, present, and future - most crassly in black holes. Moreover, it is not clear how the global average distribution of the universe’s matter-energy content could be causally connected to the intuitions which drive presentism.

当我们从狭义相对论走向更基础的理论时，这种令人不安的处境会得到改善吗？当我们转向广义相对论，这一两难困境本质上并没有改变，尽管辩论因两个作用方向相反的新因素而变得更丰富。首先，对现在主义者来说的好消息: 事实证明，在广义相对论中一个重要模型族的时空里，存在一种物理上优先的叶状结构。这些时空允许存在一个客观的宇宙时间，从而为将事件划分为过去、现在和未来的客观且原则上可观察的区分提供基础。作为宇宙学标准模型支柱的弗里德曼-勒梅特-罗伯逊-沃尔克 (FLRW) 时空就属于这一族。鉴于宇宙学家有充分证据表明，这些模型在足够大的尺度和足够晚的时间上，以极高的精度描述了我们现实世界的时空结构，现在主义者可能会忍不住从中 (过早地！) 汲取希望。尽管 FLRW 时空似乎正确捕捉了时空的大尺度结构，但它们假设宇宙中的质能分布是完全均匀的。局部对全局平均分布的相当显著的偏差阻碍了过去、现在、未来划分的局部有效性——最明显的就是黑洞内部。此外，目前尚不清楚宇宙质能内容的全局平均分布如何能与驱动现在主义的直觉产生因果关联。

Although the presentist may find ways to finesse these difficulties, they will have to content themselves with a metaphysics of time, which can at best be contingently true: many models of GR, and thus many ways in which GR deems the world could have been, do not admit any foliation at all. This is the bad news: rather than an embarrassment of riches as in Minkowski spacetime and other relativistic spacetimes where foliations into spacelike hypersurfaces were highly non-unique, in these cases, there is no way at all to partition spacetime into past, present, and future. If we restrict ourselves to naturalism, it seems as if the presentist has two main strategies available: either they forgo the idea of global present in favor of a more local notion, or else they make the case that those unfoliable spacetimes are, although formally models of GR, not physically reasonable possibilities. The latter option, while prima facie reasonable, will involve the stubborn challenge to deliver quite general reasons why unfoliable spacetimes should not be considered physically reasonable, lest we have to articulate specific reasons spacetime by spacetime. We will return to the former strategy in the next subsection.

尽管当前论者可能找到方法巧妙处理这些难题，但他们仍需满足于一种充其量仅为偶然为真的时间形而上学: 广义相对论的诸多模型，即广义相对论所认定的世界的诸多可能形态，根本不允许任何分层 foliations。这就是坏消息: 在闵可夫斯基时空及其他将时空分层为类空超曲面的相对论时空中，分层方式高度不唯一，是过于丰富带来的难题，而在这些模型中，根本没有任何方法能把时空划分成过去、现在和未来。如果我们坚持自然主义立场，当前论者似乎主要有两种可用策略: 要么放弃全局现在的概念，转而支持更局部的概念，要么论证那些无法分层的时空虽然是广义相对论的形式模型，但并非物理上合理的可能性。后一种选择乍看合理，却面临一个棘手挑战: 必须给出充分的一般性理由，说明为何无法分层的时空不能被视为物理上合理，否则我们就得逐个时空地给出具体理由。我们会在下一小节回到前一种策略的讨论。

Philosophy of Time in Causal Set Theory

因果集理论中的时间哲学

As we have seen in the previous subsection, the central principles of relativistic physics seriously limit the scope for theories of time which include a fundamental notion of ”becoming,” although they fall short of ruling them out altogether. Causal set theory promises to broaden that scope and to brighten the prospects of a dynamical metaphysics of time. The basis of that promise is that on its standard formulation, which includes a dynamics such as ”classical sequential growth” dynamics [40], causal set theory can be interpreted to postulate an ”active process of growth in which ’things really happen”’ [46], a ”birthing” of elements of a causal set, without violating any of the central tenets of relativity, such as general covariance, the general principle ultimately responsible for the difficulties for ”becoming” in relativistic physics. In order for such an active process of becoming to be compatible with relativistic principles, a global form of becoming is replaced by a local version, in line with the first strategy in the last paragraph of the previous subsection.

> 正如我们在前一小节所看到的，相对论物理学的核心原则严重限制了包含“生成”这一基础概念的时间理论的适用范围，但并未将其完全排除。因果集理论有望拓宽这一范围，并为时间的动态形而上学带来更光明的前景。这一期望的基础在于，在其标准表述 (包含“经典顺序生长”动力学这类动力学 [40]) 中，因果集理论可以被解读为假定了一种“‘事情真实发生’的主动生长过程”[46]，即因果集元素的“生成”，同时不违反任何相对论核心原则——比如广义协变性，正是这一总原则导致了相对论物理学中“生成”概念面临诸多困难。为了让这种主动的生成过程符合相对论原则，全域形式的生成被局域版本取代，这与前一小节最后一段提出的第一种策略一致。

Following the structure in Wüthrich and Callender [56], let us consider the fate of dynamical theories of time first at the kinematical level of causal set theory, before turning to classical sequential growth dynamics. A growing causal set closely resembles a discrete version of a growing spacetime block, and so I will often just speak of the growing block theory. However, a presentist position can easily be gleaned from dynamical causal set theory: the present consists of all and only the maximal elements of a dynamically growing causal set. In this way, each dynamical addition of another element, which can only happen to the future of previously added elements, ”updates” the present, i.e., the set of maximal elements at that ”moment.” Although the growing block view may give us a more natural template for interpreting the dynamically growing causal set due to the asymmetry between the presence of a ”birthing” process and the absence of an ”annihilating” process, it is easy enough to modify the interpretation to suit presentist needs. The reader is invited to keep this in mind when I will speak only of the growing block in the remainder of the section.

> 按照 Wüthrich 和 Callender[56] 的结构，在讨论经典顺序生长动力学之前，我们先来考察动态时间理论在因果集运动学层面的命运。生长中的因果集非常接近生长时空块的离散版本，因此我通常直接称其为生长块理论。不过，当下主义立场也可以很容易地从动态因果集理论中得出: 当下恰好由动态生长的因果集中所有极大元素构成。按照这种方式，每一次新元素的动态添加 (新元素只能添加在已有元素的未来) 都会“更新”当下，即那一“时刻”的极大元素集合。尽管由于存在“生成”过程但不存在“湮灭”过程的不对称性，生长块观点为解读动态生长的因果集提供了更自然的框架，但也很容易修改这一解读以适配当下主义的需求。请读者在我本节余下内容仅讨论生长块时记住这一点。

Let’s start at the kinematic level. The advocate of a dynamical theory will seek to foliate causal sets into slices of subsequent ”nows.” We can identify a maximal antichain, i.e., a maximal set of events which are pairwise incomparable with respect to the fundamental relation $\prec$ of causal precedence, as the universe at a ”moment of time.” Any finite causal set admits a partition of the entire structure into maximal antichains and is thus foliable. For infinite causal sets, the question of foliability involves some subtleties which preclude a fully general answer. Suffice it to say that the past-finite causal sets grown by classical sequential dynamics are foliable in our sense. We can thus safely assume that the physically relevant class of causal sets admits a foliation of the entire structure into a sequence of subsequent presents.

我们先从运动学层面开始。动态理论的支持者会寻求将因果集叶状分解为连续的“现在”切片。我们可以将极大反链——即一组关于因果优先的基础关系 $\prec$ 两两不可比的极大事件集合——认定为某一“时刻”的宇宙。任何有限因果集都可以将整个结构划分为极大反链，因此是可叶状分解的。对于无限因果集，可叶状分解性问题存在一些微妙之处，无法给出完全通用的答案。只需说: 由经典顺序动力学生成的过去有限因果集在我们的定义下是可叶状分解的就足够了。因此我们可以放心地假设，物理上相关的因果集合类允许将整个结构叶状分解为一系列连续的当下。

There are some parallels to the situation in GR and a few notable differences between the continuum relativistic spacetimes and the discrete causal sets. First are the parallels. In both cases, foliations are highly non-unique, although there is a sense in which the cardinality of the non-uniqueness is higher in the continuum case of GR. The partition of the base structure into a sequence of subsequent presents is extraneous to the physical theory in both cases (just as SR or GR did not single out a particular foliation, causal set theory also does not). That this addition is extraneous can also be seen from the fact that in both cases, the partitions are not invariant under automorphisms of the base structure.

这种情况与广义相对论中的情况有一些相似之处, 同时连续相对论时空与离散因果集之间也存在几处显著差异。首先来看相似之处: 两种情况下，叶状分解都高度不唯一，尽管在广义相对论的连续情况下，不唯一性的基数更高。将基础结构划分为一系列连续当下，在两种理论中都是额外添加到物理理论中的内容 (就像狭义相对论或广义相对论不会选出特定的叶状分解一样，因果集理论也不会)。这种添加是额外的，也体现在两种情况下，划分都不满足基础结构自同构下的不变性。

As for the differences, there are good reasons to think that the physically relevant causal sets afford such a partition, whereas in GR, there exist numerous non-foliable spacetimes. If we can state good reasons for excluding those, then this difference will disappear. As for a definite difference, a maximal antichain in causal set theory, which is supposed to represent the universe at a ”moment of time,” has absolutely no intrinsic structure. This is radically different from the situation in GR, where we will find a rich induced spatial geometry and topology in a spacelike hypersurface. Finally, there is no analogue of Stein’s special-relativistic theorem in causal set theory, due to the existence of ”non-Hegelian subsets,” to be discussed in section ”Structuralism”. The failure of Stein’s theorem means that we can generally hope for more freedom in trying to identify a relation appropriate for becoming. However, as [56, §3] argue, the defender of a dynamical theory cannot find much traction in this failure, which means that the original dilemma for this position between acceptance of the physics and maintaining an attractive position still stands.

至于差异，我们有充分的理由认为物理上相关的因果集允许这样的划分，而在广义相对论中，存在大量不可叶状分解的时空。如果我们能给出排除这些时空的充分理由，这个差异就会消失。就确定的差异而言，因果集理论中本应代表某一“时刻”宇宙的极大反链完全没有内禀结构。这和广义相对论的情况截然不同——在广义相对论中, 类空超曲面上会诱导出丰富的空间几何与拓扑。最后, 由于存在“非黑格尔子集”(我们会在“结构主义”一节讨论)，因果集理论中不存在对应斯坦因狭义相对论定理的结果。斯坦因定理不成立意味着我们通常有更多自由来寻找适配生成概念的关系。然而，正如文献 [56, §3] 所论证的，动态理论的支持者无法从这一失效中获得多少支持，这意味着该立场原本面临的“接受现有物理”和“维持自身立场吸引力”之间的两难仍然存在。

Still at the level of kinematics, if we seek a ”becoming” interpretation beyond the narrow confines of imposing a foliation into something like spacelike hyper-surfaces or maximal antichains, we can straightforwardly identify causal set theory analogues of worldline or light cone becoming: a worldline is a chain of events connected by $\prec$, and the past light cone of an event is the set of all events which causally precede that event in terms of $\prec$. This straightforward identification arguably reinforces the original dilemma [56]. And of course, the alternative block interpretation is equally available in causal set theory as it is in relativity.

> 仍在运动学层面，如果我们想要寻求一种“生成”诠释，而不局限于将时空叶理化为类空超曲面或极大反链这类框架，我们可以直接找出因果集理论中对应世界线生成或光锥生成的类比: 一条世界线就是由 $\prec$ 连接的事件链，一个事件的过去光锥就是所有根据 $\prec$ 在因果关系上先于该事件的事件集合。可以说，这种直接的对应强化了原有的二难困境 [56]。当然，和相对论一样，块状宇宙诠释在因果集理论中也同样成立。

The kinematics of causal set theory are thus most naturally interpreted to be devoid of real becoming, just as standard GR. Claims of real becoming in causal set theory are all based on the dynamics, which is added to the kinematics in order to restrict the models of the theory to physically reasonable ones. The standard (though classical) dynamics is a law of sequential growth (more specifically, of ”generalized percolation”) such that a causal set grows by a sequential addition of new elements to the causal future of existing ones, where the elements to which the new element is causally related are a matter of probability [40]. Although not yet quantum, classical sequential growth dynamics is a natural and useful stepping stone toward a path-integral formulation of an eventual quantum theory of causal sets. In this dynamics, ”becoming” appears to be embodied in this sequential addition of new elements, a process which is interpreted by Rideout and Sorkin [40, 024002-2] to be constitutive of time:

> 因此，和广义相对论一样，因果集理论的运动学最自然的诠释就是不存在真实的生成，因果集理论中所有关于真实生成的主张都建立在动力学之上——动力学是附加在运动学之上的，用于将理论模型限制为物理上合理的模型。标准 (尽管是经典的) 动力学是顺序增长定律 (更具体来说是“广义渗流”): 因果集通过向已有元素的因果未来依次添加新元素增长，新元素和哪些元素存在因果关联由概率决定 [40]。尽管经典顺序增长动力学还不是量子理论，但它是通往最终量子因果集理论路径积分表述的自然且有用的垫脚石。在该动力学中，“生成”似乎就体现在新元素的依次添加过程中，里德奥特和索金 [40, 024002-2] 认为这个过程构成了时间:

The phenomenological passage of time is taken to be a manifestation of this continuing growth of the causet. Thus, we do not think of the process as happening ’in time’ but rather as ’constituting time’ [...]

> 现象层面的时间流逝被认为是因果集持续增长的体现。因此，我们不认为这个过程是“在时间中发生”，而是认为它“构成了时间”[⋯]

Before I proceed to discuss the prospects of becoming in a fully dynamical causal set theory, let me emphasize that a ”block universe” interpretation remains very much a live option, as Huggett [20] also remarks (This is his first interpretive option (page 16); the second augments the kinematical causal structure with a gauge-invariant dynamics, to be discussed below.). Under this interpretation, the dynamics just offers a space of possible full histories with a probability measure defined on them. It is thus clear that dynamical causal set theory remains fully compatible with a metaphysics of non-dynamical being, a block universe without becoming.

在我讨论完整动力学因果集理论中生成的前景之前，我要先强调，“块状宇宙”诠释仍然是十分可行的选项，赫格特 [20] 也认可这一点 (这是他提出的第一个诠释选项，见第 16 页；第二个选项是在运动学因果结构基础上补充规范不变动力学，我们会在下文讨论)。在该诠释下，动力学只是给出了所有可能完整历史的空间，并在其上定义了概率测度。因此很明显，动力学因果集理论仍然完全兼容非动态存在的形而上学，也就是不包含生成的块状宇宙。

Let us consider the viability of a metaphysics of becoming in causal set theory augmented by a dynamics of classical sequential growth. The most obvious path to such an interpretation is by turning the ”now” into a localized, observer-dependent matter, i.e., a form of worldline (or light cone) becoming: individual observers experience local becoming as they inch up on their worldlines toward the future (That local, asynchronous becoming is closely analogous to worldline or light cone becoming is also noted by Arageorgis [1].). In the words of Sorkin [47], rather than ”super-observers,” we have an ”asynchronous multiplicity of ’nows’.”

我们来考察，在补充了经典顺序增长动力学的因果集理论中，生成形而上学是否成立。得到这种诠释最直接的路径，是将“现在”转化为局域的、依赖观测者的概念，也就是世界线 (或光锥) 生成的一种形式: 单个观测者沿着自身世界线向未来移动时，会体验到局域生成 (阿拉佐吉斯 [1] 也指出，这种局域异步生成和世界线生成或光锥生成高度类似)。用索金 [47] 的话来说，我们拥有的不是“超级观测者”，而是“‘现在’的异步多样性”。

Although there thus exist analogues of localized, ”asynchronous” becoming in GR in the form of worldline or light cone becoming which are just as covariant as asynchronous becoming in dynamical causal set theory, Dowker [14, 15] wants to drive a wedge between asynchronous becoming in causal set theory and its analogues in GR. What is missing in GR for the analogy to hold, it seems, is any valid reason to think of spacetime events as not merely existing, or ”having happened” or ”will have happened,” but instead as ”happening” as the result of a dynamical process of ”occurrence.” In GR, according to Dowker, events are just there without ever being born or undergoing (or having undergone) a process of occurrence. Although the result of the birthing occurrences of spacetime events in dynamical causal set theory is the same - that the event is there and exists - the path that leads to the result is essentially different: whereas in the case of birthing occurrences, we have true becoming, in the block universe, we find just static ”being.”

尽管广义相对论中本来就存在局域“异步”生成的类比，即以世界线生成或光锥生成的形式存在，其协变性和动力学因果集理论中的异步生成一样，但道克 [14, 15] 想要区分因果集理论的异步生成和广义相对论中的对应类比。该类比要成立，广义相对论中似乎缺了一点: 没有合理的理由将时空事件视作不是仅仅存在、不是“已经发生”或“将会发生”，而是作为动态“发生”过程的结果“正在发生”。道克认为，在广义相对论中，事件仅仅是存在着，从来不会被“诞生”，也不会经历 (或已经经历) 发生过程。尽管动力学因果集理论中时空事件诞生发生的最终结果和广义相对论一样——事件都存在于此——但得到这个结果的路径本质上完全不同: 诞生发生的过程中我们拥有真正的生成，而块状宇宙中只有静态的“存在”。

I believe that the analogy between asynchronous becoming in causal set theory and light cone becoming in GR is much tighter than Dowker seems to think, for two reasons (Huggett [20] argues that unless the background ”time” relative to which events are born can somehow be shown to be physical, i.e., not mere gauge, the dynamics is fully analogous to what we find in GR and so not hospitable to a substantive notion of passage. Showing background time to be physical is Huggett’s second option.). First, it should be noted that light cone becoming in GR does not require the introduction of global forms of time and thus is fully covariant in any way one might demand. It just needs the local causal structure, very much like asynchronous becoming in causal set theory.

> 我认为，因果集论中的异步生成与广义相对论中的光锥生成，二者的类比远比道克所认为的更紧密，这其中有两点原因 (赫格特 [20] 提出: 除非能证明事件生成所参照的背景“时间”本身是物理实在的——即并非仅是规范——否则该动力学就和广义相对论中的动力学完全类似，因而无法容纳实体化的流逝概念。证明背景时间是物理实在的，正是赫格特的第二种方案)。首先，需要指出，广义相对论中的光锥生成不需要引入全局形式的时间，因此完全满足任何可能要求的协变性。它仅需要局部因果结构，这一点和因果集论中的异步生成非常相似。

Second, it seems difficult to maintain that the asynchronous becoming in causal set theory - the ”birthing” of events - is a physical process. If it were, then it would be rather unusual for such a process to not occur in (or constitute) physical time. Let me explain. The discrete form of general covariance imposed on the growth dynamics in causal set theory - necessary to keep the theory properly relativistic - and the consequent absence of any facts of the matter which of two unrelated (and so ”spacelike-related”) events ”occurred” or was ”born” first, there is no physical background time in which the births occur. This was precisely why there was no global time and that the resulting becoming is asynchronous. As a consequence, in both GR and causal set theory, there is no room for a global notion of becoming, but clearly scope for a localized, asynchronous form of it, rendering the analogy rather tight.

> 其次，认为因果集论中的异步生成——即事件的“诞生”——是物理过程，这一观点站不住脚。如果它真的是物理过程，那么这个过程不发生在 (或不构成) 物理时间中，就会十分反常。容我解释: 因果集论的增长动力学施加了离散形式的广义协变性——这是保证理论符合相对论的必要条件——其结果是，对于任何两个无关 (即“类空关联”) 的事件，不存在关于哪一个“先发生”或哪一个“先诞生”的客观事实，诞生过程也不存在物理背景时间。这正是因果集论没有全局时间、生成过程是异步的根本原因。因此，无论是广义相对论还是因果集论，都没有容纳全局生成概念的空间，但显然都存在局域化异步生成的空间，这使得二者的类比相当紧密。

However, Wüthrich and Callender [56] have identified two novel ways in which becoming can become more global in causal set theory than it ever could in GR, both of which are ultimately due to the discreteness of the fundamental structure.

> 然而，维特里希与卡伦德 [56] 指出，因果集论中生成可以实现比广义相对论中任何可能都更全局化，这是两条全新的路径，二者都根本上源于基础结构的离散性。

The first is that there appears to be a global physical fact about the size of the universe at any stage of the birthing of events. Although the order in which unrelated events occur must remain indeterminate due to the required covariance, the cardinality of the causal set at any stage of the sequential growth is an objective, global, gauge-invariant fact (For the related concept of ”covtree,” see - Chap. 71, ”Covariant Growth Dynamics”). First, the causal set has zero events, then one, then two, then three, etc. At any stage n of the growth process, we can thus affirm that the causal set consists of n elements and so has a determinate size; we cannot, in general, assert which events have occurred by stage n . Consequently, there is a sense in which we have ontological indeterminacy as to which events have already occurred by a given stage, but without any indeterminacy in the cardinality of the structure representing the sum total of existence at that stage.

第一点是，在事件诞生的任何阶段，宇宙的大小都存在一个全局物理事实。尽管由于协变性要求，无关事件的发生顺序必然是不确定的，但序贯增长过程任意阶段的因果集基数都是一个客观、全局、规范不变的事实 (相关概念“协变树”参见第 71 章“协变增长动力学”)。最初，因果集有 0 个事件，之后是 1 个，再之后是 2 个、3 个，依此类推。因此，在增长过程的任意阶段 n，我们都可以确认因果集包含 n 个元素，因而具有确定的大小；但一般而言，我们无法断言到阶段 n 为止哪些事件已经发生。其结果是，在这种情况下，对于给定阶段哪些事件已经发生存在本体论上的不确定性，但在该阶段，代表存在总体的结构，其基数不存在任何不确定性。

The second novel feature is truly exotic, and I am not aware of any other context in which something similar can be found. One might expect, on the basis of the first feature, that no particular event in a future-infinite causal set is ever going to enjoy determinate existence until the asymptotic future, as it were, when the infinite growth process has been completed. Once the growth of the causal set has been completed, and all births have happened (which will of course not be the case at any finite stage), then all events will snap into determinate existence from their prior indefinite state. Even for future-finite causal sets, there is the analogous worry that events will not come into determinate being until the growth has been completed, which will occur after a finite number of steps.

第二个新特征非常特别，据我所知，其他语境下都不存在类似的情况。基于第一个特征，人们可能会认为，未来无限的因果集中，任何特定事件都不会获得确定存在性，直到渐进未来——也就是无限增长过程完成之时。一旦因果集的增长完成，所有事件都已诞生 (当然这在任何有限阶段都不会发生)，所有事件就会从先前的不确定状态一跃获得确定存在性。即使是未来有限的因果集，也存在类似的问题: 事件要直到增长完成后才会进入确定存在状态，而增长完成发生在有限步之后。

However, this is in general not the case, at least for future-infinite causal sets growing by transitive percolation. In order to see this, let us introduce the concept of a ”post”: a post is an event that either is causally preceded by or causally precedes any other event in the causal set. A post can be interpreted as an event where the universe undergoes a transition from a sharply contracting to an expanding phase, perhaps a ”big bang” of sorts. As it turns out [40], causal sets grown by transitive percolation in general have many such posts. Suppose that the event born at stage n of such a causal set is a post. In this case, all events in the causal past of the post and the post itself will snap into determinate existence, leaving no ontological indeterminacy at that stage. At the next stage, however, there will again be ontological indeterminacy, unless the next event is also a post (See Wüthrich and Callender [56, §4, particularly figure 3] for a fuller explanation and a figure illustrating the point.).

然而，一般而言情况并非如此，至少对于通过传递渗析增长的未来无限因果集来说不是这样。要理解这一点，我们先来引入“柱事件”的概念: 柱事件是指因果集中，和其他所有事件都存在因果先后关系的事件 (要么在因果上先于其他所有事件，要么被其他所有事件在因果上先于)。柱事件可以解释为宇宙从急剧收缩转向膨胀的过渡事件，或许可以理解为某种“大爆炸”。研究表明 [40]，一般而言通过传递渗析增长的因果集会存在许多这样的柱事件。假设该因果集中，在阶段 n 诞生的事件是一个柱事件。在这种情况下，该柱事件因果过去中的所有事件，以及柱事件本身，都会一跃获得确定存在性，在该阶段不存在任何本体论上的不确定性。不过下一阶段又会重新出现本体论不确定性，除非下一事件也是一个柱事件 (更完整的解释和说明该观点的图示参见维特里希与卡伦德 [56, §4，尤其是图 3])。

Unfortunately, it is unclear whether the supposition that a particular event is a post can be legitimately posited. The problem is the following: whether or not a given event is a post remains itself indeterminate until the causal set has fully grown. As long as the growth process is ongoing, it remains possible that an event is added at some later stage which is causally unrelated to an event we might have thought of as a post; if that happens, then the original event is of course no longer a post, and the ontological determinacy of its past cannot be assumed.

遗憾的是，将某一特定事件假定为终点事件是否合理目前尚不明确。问题在于: 在因果集完全生长完成前，任意给定事件是否为终点事件本身始终是不确定的。只要生长过程还在继续，后续就仍有可能添加一个事件，而该事件与我们原本认定为终点的事件并无因果关联；一旦这种情况发生，原事件当然就不再是终点事件，因此不能假定其过去存在本体确定性。

Note just how exotic this new form of becoming is. While it is of course quite natural on a dynamic metaphysics of time to consider the future indeterminate, we have here a literal sense in which the past is indeterminate also or at least what would be a natural analogue of the past in a causal set. In GR, there is a sense in which the past changes from indeterminate to determinate in light cone becoming as the light cone grows and encompasses larger parts of the ”past.” However, in causal set theory, all of the ”past” is generally indeterminate until the end, when the entire causal set becomes determinate at once.

注意这种新形式生成有多么奇特。虽然在动态时间形而上学中认为未来是不确定的，这一点非常自然，但在此理论中，过去——至少是因果集里对应过去的自然类似物——本身也确实是不确定的。在广义相对论中，随着光锥生长、覆盖更大范围的“过去”区域，光锥生成过程会让过去从不确定转变为确定。然而在因果集理论中，几乎所有“过去”通常直到整个过程结束前都是不确定的，直到终点整个因果集才会同时变得确定。

In conclusion, it thus seems as if all events in a dynamically growing causal set, including ”past” ones, remain ontologically indeterminate until the growth process is completed. At that stage, finite or not, we have the full causal set, and the resulting ontology is indistinguishable from one based on the block universe metaphysics. Thus, we either accept a block interpretation, or else we purchase a foreign form of becoming in the coin of a rather complete ontological indeterminacy. Events may become, but only indeterminately so. It should thus be clear that becoming in dynamical causal set theory assumes a novel, exotic form.

综上，在动态生长的因果集中，包括“过去”事件在内的所有事件，直到生长过程完成前，本体论层面始终是不确定的。生长完成后，无论因果集是否有限，我们都会得到完整的因果集，其最终本体论与块宇宙形而上学的本体论无法区分。因此，我们要么接受块宇宙解释，要么以相当彻底的本体论不确定性为代价，换取一种异于传统的生成形式。事件可以生成，但只能是不确定地生成。由此可见，动态因果集理论中的生成呈现出一种全新、奇特的形式。

Structuralism

结构主义

In philosophy of science, ”structural realism” is offered to the realist as a means to evade the strictures of the pessimistic metainduction [51]. The pessimistic metain-duction strikes the realist with the repeated embarrassment of having committed to obsolete ontologies whenever a scientific theory gets replaced with a successor theory. The structuralist analysis of the pessimistic metainduction identifies the problem in pre-structuralist realism in its assumption that we ought to commit to an ontology of "things." If instead of reading off of theories a surface ontology of objects, we committed to their underlying structures, the pessimistic argument is avoided because the structures the structural realist commits to survive scientific revolutions. At the same time, it is these same structures which are responsible for the predictive success of theories and not their surface ontologies. Consequently, structural realism commits to the structures described by the mathematical formulations of the pertinent theories, and only to these structures, and thus hopes to maintain the explanatory and predictive power of the theory. Structural realism as a general strategy to respond to the pessimistic metainduction offers a wholesale recipe, a general template of how to think about scientific theories.

> 在科学哲学中,“结构实在论”是为实在论者提供的、用以规避悲观元归纳严格约束的方案 [51]。悲观元归纳对实在论者提出质疑: 每当新科学理论取代旧理论，实在论者都曾信奉过时的本体论，一再陷入窘境。对悲观元归纳的结构主义分析指出，前结构实在论的问题在于其预设: 我们应当信奉“事物”本体论。如果我们不从理论中提取表层的对象本体论，而是信奉理论的底层结构，悲观元归纳的质疑就能被规避——因为结构实在论者所信奉的结构能在科学革命中留存下来。同时，对理论预测成功负责的恰恰是这些结构，而非理论的表层本体论。因此，结构实在论只信奉相关理论数学表述所描述的结构，并寄希望于以此保留理论的解释力与预测力。作为回应悲观元归纳的通用策略，结构实在论提供了一套整体方案，一套思考科学理论的通用框架。

However, structural realism can be bought into also as a retail product, rather than as a wholesale good. In this case, it serves as an interpretive tool, which may or may not fit the theory under consideration. Its application is only justified to the extent to which it fits the case at hand. Such justification must thus be given for each case separately. For instance, it can be argued that since in the presence of quantum entanglement, the total state of a bipartite system does not supervene on the states of the individual subsystems, an ontological commitment to these subsystems must be augmented by the admission of something else into the ontology, such as perhaps the wave function. If instead of choosing such individualism, we approach the interpretation of quantum physics with the structuralist template, then our reconceptualization of individuals in structural terms - and thus our commitment only to the structure of the total system - solves the problem of non-supervenience that the individualist faces. Furthermore, as summarized in Ladyman and Ross [24, §3.1], the structuralist can argue that they escape a form of metaphysical underdetermination that arises from the apparent possibility of permuting indistinguishable elementary particles which the individualist must interpret as resulting in metaphysically distinct situations which remain indiscernible by quantum physics. The individualist must thus accept, it seems, that the individuality of the particles which are indiscernible according to quantum theory transcends what is a complete description of the physical properties of the particles involved and so conclude that quantum physics must remain incomplete.

然而，结构实在论也可以作为零售商品而非整体商品被接受。在这种情况下，它是一种解释工具，未必适用于所有被考察的理论。只有当它适配当下研究的问题时，应用它才是合理的，因此必须针对每个问题单独给出合理性证明。例如，有观点认为，由于量子纠缠中，二分系统的总状态不随各子系统的状态随附，对这些子系统的本体论承诺必须要在本体论中加入其他内容，比如波函数。如果我们不选择这种个体论，而是用结构主义模板来解释量子物理学，那么我们将个体重构为结构性概念，因此仅承诺总系统的结构，就能解决个体论面临的非随附性问题。此外，正如莱德曼与罗斯 [24, §3.1] 总结的，结构主义者可以主张，他们避开了一种形而上学非充分决定论问题: 不可区分的基本粒子可被置换，这对个体论来说意味着会产生量子物理学无法区分的形而上学不同情境，从而催生该问题。因此个体论者似乎必须承认，量子理论认为不可区分的粒子，其个体性超越了对这些粒子所有物理性质的完整描述，由此得出量子物理学必定不完备的结论。

Similarly, as contended in Ladyman and Ross [24, §3.2], a structuralist interpretation of general relativity resolves the impasse between traditional substantivalist and relationalist interpretations of relativistic spacetime and, importantly, removes their respective inadequacies. In a nutshell, (manifold) substantivalists seem to confer to the points of the manifold M of a spacetime $\langle M, g_{ab}\rangle$ with metric g_{ab} an individual existence, which leads to a form of unobservable and physically doubtful form of indeterminism, as exhibited in the so-called hole argument. In contrast, relationalists are struck with the problem of the purely ”gravitational” degrees of freedom of the metric field: the matter-energy content of the universe as captured by the stress-energy tensor T_{ab} fails to determine the metric g_{ab} of spacetime. As a consequence, it seems impossible to carry through a relationalist reduction of spacetime to matter. Structural realism steps in as a via media with a reasonable claim that it can deal with both problems. Since it does not commit to the existence of individual spacetime points but only to the spacetime structure as a whole, it evades the pressures from the hole argument. As it posits a relational structure which also includes the gravitational degrees of freedom, it does not fall prey of the relationalist's struggle.

类似地，正如莱德曼与罗斯 [24, §3.2] 主张的，对广义相对论的结构主义解释解决了相对论时空传统实体论解释与关系论解释之间的僵局，重要的是，它消除了两种解释各自的缺陷。简而言之，(流形) 实体论者似乎赋予了时空 $\langle M, g_{ab}\rangle$ (度量为 g_{ab}) 中流形 M 的点以独立存在性，这就导致了一种不可观测、物理上存疑的非决定论，这就是所谓的孔洞论证。而关系论者则面临度量场纯“引力”自由度的问题: 应力能张量 T_{ab} 所刻画的宇宙质能内容无法确定时空的度量 g_{ab} 。因此，似乎不可能将时空关系论还原为物质。结构实在论以合理主张作为中间道路介入，能够同时处理这两个问题。由于它不承诺独立时空点的存在，仅承诺整体的时空结构，因此它避开了孔洞论证的压力。由于它设定的关系结构也包含引力自由度，因此不会陷入关系论的困境。

Although much more could be said about each of the two cases and much more has of course been said, they illustrate how structural realism may serve as a useful interpretive template at least for theories in fundamental physics. The retail approach to structural realism differs from the wholesale one that it could have been the case for the former, but not the latter, that a structuralist interpretation would have worked, e.g., only for quantum physics, but not for general relativity, or vice versa. The central thesis of this section is that causal set theory is naturally amenable to a structuralist reading in the sense of the retail approach, but that this fact has at best mild implications for the wider viability of wholesale structural realism. The rest of this section is primarily concerned with motivating the first part of the thesis, but will remain silent on the latter part.

尽管关于这两个案例中的每一个都还能展开更多论述，学界当然也已有诸多讨论，但它们足以说明，结构实在论至少可以作为基础物理学理论的一个有用解释模板。零售进路的结构实在论与批发进路的区别在于: 对前者而非后者而言，结构主义解释本就可能只适用于量子力学却不适用于广义相对论，反之亦然。本节核心论题是: 因果集理论自然适合零售进路意义上的结构主义解读，但这一事实对批发结构实在论的整体可行性最多只有微弱影响。本节余下内容主要是为该论题的第一部分提供理据，对第二部分暂不做讨论。

An obvious and central task for the structural realist is to articulate the notion of a "structure." Unfortunately, in much of the literature on structural realism, this important task is neglected. Whenever the notion is explicated, the assumed concept is typically that of a relational structure. Although category-theoretic notions of structure may ultimately be more general and thus more suitable to fully capture the notion of structure particularly as it is operational in mathematics, another central domain of structural realist ambitions, the concept of relational structure based on set theory is fully adequate for our purposes (Alternative conceptions include, for example, the graph-theoretic notion of structure in Leitgeb and Ladyman [29], the group-theoretic one in Roberts [42], and the category-theoretic one in Bain [2]. There is a discussion to be had to what degree these apparently distinct notions may nevertheless be equivalent.).

结构实在论者一个明确且核心的任务是阐明“结构”这一概念。遗憾的是，在多数关于结构实在论的文献中，这项重要任务都被忽略了。每当这一概念得到阐释，默认的概念通常都是关系结构。尽管范畴论的结构概念最终更具一般性，因此更适合完全捕捉结构这一概念——尤其是它在数学 (结构实在论抱负的另一核心领域) 中的运作方式，但基于集合论的关系结构概念完全满足我们的研究需求 (替代概念举例来说，包括莱特格布和莱德曼 [29] 提出的图论结构概念、罗伯茨 [42] 的群论概念，以及贝恩 [2] 的范畴论概念。这些看似不同的概念究竟在多大程度上其实是等价的，还有待讨论。)

Roughly (For a more rigorous development of the following, see Wüthrich [52].), a relational structure $\mathcal{S}$ is an ordered pair $\langle O, R\rangle$ of a non-empty set of relations R defined on a non-empty set of relata O , the domain of $\mathcal{S}$. An n -ary relation defined on the domain O is a subset of the n -fold Cartesian product $O \times \cdots \times O$, where the n -fold Cartesian product of O is defined as the set of all ordered n -tuples $\langle x_1, \ldots, x_n\rangle$ with $x_i \in O$ (More generally, a Cartesian product (and hence a relation) is defined as of different, in general distinct sets. As this will be irrelevant in what follows, I will ignore this complication.).

大致来说 (下文更严谨的阐述可见 Wüthrich [52])，一个关系结构 $\mathcal{S}$ 是有序对 $\langle O, R\rangle$ ，由定义域在非空关系项集 O (即 $\mathcal{S}$ 的论域) 上的非空关系集 R 构成。定义域 O 上的一个 n 元关系是 n 重笛卡尔积 $O\times\cdots\times O$ 的子集，而 O 的 n 重笛卡尔积被定义为所有满足 $x_i \in O$ 的有序 n 元组 $\langle x_1, \ldots, x_n\rangle$ 构成的集合 (更一般来说，笛卡尔积 (以及由此衍生的关系) 被定义在多个一般而言互不相同的集合上。由于这一点在下文讨论中无关紧要，我将忽略这一复杂情况。)

In order to satisfy structuralist demands, the elements of the domain O must not possess any intrinsic nature beyond their structural properties. In other words, they are fully defined by their relational profile, i.e., their set of relations to other elements of O . Structural realists sometimes insist that fundamentally, there are no "objects" [19]. The best way to make sense of such structuralist claims is precisely to take them to assert that the identity of the elements in the domain is exhausted by their relational profile.

为满足结构主义的要求，论域 O 的元素除结构性质外，不能拥有任何 intrinsic 本质，换句话说，它们完全由其关系轮廓 (即它们与 O 其他元素的关系集合) 定义。结构实在论者有时会坚持，从根本上讲不存在“对象”[19]。要理解这类结构主义主张，最佳方式恰恰就是将其解读为: 论域中元素的同一性完全由其关系轮廓穷尽。

In addition to the characterization of relational structures, we will need a notion of structural identity: what does it mean to say that two structures are the same? We are interested here in physical structures (rather than in merely mathematical ones), in the sense that the physical systems which exemplify certain structures are ontologically prior to the abstract mathematical structure that may be used to describe them. Thus, under what circumstances can two physical system either in the same physically possible world or in two distinct worlds have the ”same” structure?

除了刻画关系结构，我们还需要结构同一性的概念: 说两个结构相同究竟是什么意思？我们此处关注的是物理结构 (而非单纯的数学结构)，具体而言，我们认为例示特定结构的物理系统在本体论上优先于可用来描述它们的抽象数学结构。那么，两个处于同一个物理可能世界、或分属两个不同世界的物理系统，在什么情况下会拥有“相同”的结构呢?

The rough idea is that two structures $\mathcal{A}$ and $\mathcal{B}$ are structurally identical in case they have the same relations over their domains A and B , which in general will be distinct. This idea is captured by ”isomorphisms” between the concerned structures. A homomorphism from $\mathcal{A}$ to $\mathcal{B}$ is a map ϕ from A to B which preserves the relations in the sense that for any $a_i \in A$, if $\langle a_1, \ldots, a_n \rangle \in R_A$, then $\langle \phi(a_1), \ldots, \phi(a_n) \rangle \in R_B$. A bijective map $\phi : A \to B$ is an isomorphism just in case both ϕ and its inverse ϕ^{-1} are homomorphisms. Two structures $\mathcal{A}$ and $\mathcal{B}$ are then structurally identical, or isomorphic, symbolically $\mathcal{A} \simeq \mathcal{B}$, just in case there exists an isomorphism from A to B . Finally, two structures $\mathcal{A}$ and $\mathcal{B}$ are automorphic just in case $\mathcal{A} \simeq \mathcal{B}$ and $A = B$, in which case the corresponding isomorphism is an automorphism.

大致思路是: 若两个结构 $\mathcal{A}$ 和 $\mathcal{B}$ 在各自论域 A 和 B (通常这两个论域并不相同) 上具有相同的关系，则二者结构相同。这一思想由相关结构之间的“同构”概念刻画。从 $\mathcal{A}$ 到 $\mathcal{B}$ 的同态是一个从 A 到 B 的映射 ϕ ，该映射保持关系: 对任意 $a_i \in A$ ，若 $\langle a_1, \ldots, a_n \rangle \in R_A$ 成立，则 $\langle \phi(a_1), \ldots, \phi(a_n) \rangle \in R_B$ 成立。双射 $\phi : A \to B$ 成为同构，当且仅当 ϕ 及其逆映射 ϕ^{-1} 都是同态。此时，两个结构 $\mathcal{A}$ 和 $\mathcal{B}$ 结构相同 (即同构)，记作 $\mathcal{A} \simeq \mathcal{B}$ ，当且仅当存在一个从 A 到 B 的同构。最后，两个结构 $\mathcal{A}$ 和 $\mathcal{B}$ 自同构当且仅当 $\mathcal{A} \simeq \mathcal{B}$ 且 $A = B$ ，此时对应的同构就是自同构。

An interpretation of a physical theory T is structuralist if it asserts that what fundamentally exists according to T just is structural in the sense that it can be fully characterized by automorphism classes of structures. In particular, the elements of the domain of the structures possess no intrinsic nature beyond their function as ”carriers” of relational structures identified by their automorphism class. Structural realism pairs such structuralist interpretations with realism.

对物理理论 T 的结构主义解释主张: 根据 T ，根本存在的事物本质上都是结构的，即可以完全通过结构的自同构类刻画，该解释就是结构主义的。具体而言，结构论域中的元素除了作为由自同构类确定的关系结构的“承载者”发挥作用外，不具有任何内在本质。结构实在论将这类结构主义解释与实在论结合起来。

With the terminology fixed, it is straightforward to see that causal set theory fits naturally with the concept of a relational structure and is thus amenable to a structuralist interpretation. The domain of the structure just is the set C of basic, featureless events in a causal set, and the single relation fundamentally defined on that domain is the relation of causal precedence $\prec$, which partially orders the set of events. Of course, not all such discrete partial orders are in fact causal sets; as we have seen in subsection ”The Basics of Causal Set Theory”, additional conditions are imposed for these orders to qualify as proper candidates for physical causal sets. However, whatever these additional conditions may be, they do not change the fact that physical causal sets are relational structures $\langle C, \prec\rangle$.

> 明确术语后，不难发现因果集合论自然契合关系结构的概念，因此适合做结构主义解释。该结构的论域就是因果集中基本的、无特征的事件构成的集合 C ，论域上定义的根本关系就是因果在先关系 $\prec$，它给事件集赋予了偏序结构。当然，并非所有这类离散偏序都是因果集；正如“因果集合论基础”小节所述，额外条件会限定这些偏序能否成为合格的物理因果集候选。但无论这些额外条件是什么，都无法改变物理因果集本身就是关系结构 $\langle C, \prec\rangle$ 这一事实。

An important part of a structuralist interpretation, to repeat, is that the elements of C do not have any fundamental intrinsic properties apart from their relational profile. As such, it has direct implications for the metaphysics of causal set theory. If basal events are identified merely be their relational profile, then how can two or more events with the same relational profile be distinguished? Connected with the question is the issue of how to interpret highly symmetric structures.

> 重申一下，结构主义解释的核心要点是，C 的元素除了关系属性外，不具有任何基本内在性质。因此，它对因果集合论的形而上学有直接影响。如果基础事件仅仅通过其关系属性被识别，那么怎么区分两个或多个拥有相同关系属性的事件呢？与之相关的问题就是如何解释高对称结构。

In order to make this discussion more rigorous, let us introduce the notion of ”non-Hegelian” pairs or sets. A non-Hegelian subset $H \subseteq C$ of events in a causal set $\langle C, \prec\rangle$ is a set of distinct events $x_1, \ldots, x_k$ in C with the same relational profile, i.e., a set $\{x_1, \ldots, x_k \mid \forall x_i, x_j, z \in C$ such that $z \neq x_i$ and $z \neq x_j, \neg(x_i \prec x_j)$ and $z \prec x_i \leftrightarrow z \prec x_j$ and $x_i \prec z \leftrightarrow x_j \prec z$, where $i, j = 1, \ldots, k\}$. Any elements of a non-Hegelian set are pairwise unrelated - due to the antisymmetry of $\prec$, they could not have the same relational profile otherwise.

> 为了让本次讨论更严谨，我们先引入“非黑格尔”对或集合的概念。因果集 $\langle C, \prec\rangle$ 中事件的非黑格尔子集 $H \subseteq C$ 是 C 中具有相同关系构型的不同事件 $x_1, \ldots, x_k$ 构成的集合，即满足 $z \neq x_i$ 、$z \neq x_j, \neg(x_i \prec x_j)$ 、$z \prec x_i \leftrightarrow z \prec x_j$ 、$x_i \prec z \leftrightarrow x_j \prec z$ 的集合 $\{x_1, \ldots, x_k \mid \forall x_i, x_j, z \in C$ ，其中 $i, j = 1, \ldots, k\}$ 。非黑格尔集合的任意元素两两不相关——由于 $\prec$ 的反对称性，若非如此它们不可能拥有相同的关系构型。

Although results regarding how generic non-Hegelian sets are in physical causal sets are few and far between, there are reasons to think that they are quite generic in causal sets of sufficient size and with any hope of giving rise to realistic physical structures (David Meyer, private communication). If they do occur, we face a metaphysical conundrum, as those elements will all have an identical relational profile. If the basal events are truly featureless apart from their relational profile, it seems as if these events ought to be considered one and the same: this is Leibniz’s principle of the identity of indiscernibles (PII), according to which whatever cannot be discerned is identical. In other words, two numerically distinct entities must be discernible at least by some of their properties. This raises the well-rehearsed discussion of which properties we quantify over in the PII. In fact, we can distinguish different PIIs with different logical strength, depending on which kinds of properties we consider.

> 尽管目前关于非黑格尔集合在物理因果集中的普遍性的研究成果寥寥，但有理由认为，在尺寸足够大、有望生成真实物理结构的因果集中，非黑格尔集合是相当普遍的 (David Meyer，私人交流)。如果这类集合确实存在，我们就会遇到一个形而上学难题: 这些元素都拥有完全相同的关系构型。如果基础事件除关系构型外确实不具备其他特征，那么这些事件似乎就应当被视为同一个: 这就是莱布尼茨的不可分辨物同一性原理 (PII)，该原理认为无法被分辨的事物就是同一的。换句话说，两个数值不同的实体至少必须能通过某些性质被区分开来。这就引发了一个老生常谈的讨论: 我们在 PII 中量化的究竟是哪些性质。实际上，根据我们考虑的性质种类不同，可以区分出逻辑强度不同的多个 PII 版本。

Whatever the choice, however, given causal set theory's stipulation that the identity of the basal events is exhausted by their relational profile, the only way to keep elements of non-Hegelian sets distinct is by endowing them with a ”primitive thisness” or ”haecceities.” The idea here is that it is part of the essence of a basal event to be that particular event and no other. Thus, two elements of a non-Hegelian set are distinct by virtue of possessing a distinct essential haecceities. Many philosophers of physics feel queasy in the face of haecceities, as these are essential and fundamental yet completely intangible properties. From a philosophical perspective, many would thus prefer not to have to rely on haecceities and so to identify the elements of non-Hegelian sets. Physicists often have practical reasons to do the same, for instance, because the matrix encoding the causal structure is otherwise degenerate and so not invertible or because non-standard set theory would have to be used instead of the standard one.

> 但无论如何选择，鉴于因果集理论规定基础事件的同一性完全由其关系构型决定，要保留非黑格尔集合中各元素的差异性，唯一的方法就是赋予它们“原始此在性”或“此性”。其核心观点是，成为某个特定事件而非其他事件，是一个基础事件的本质组成部分。因此，非黑格尔集合中的两个元素之所以不同，是因为它们拥有不同的本质此性。许多物理哲学家都对此性感到不安，因为它是本质的、基础的，却又是完全不可捉摸的性质。从哲学角度看，多数人因此更不愿依赖此性，而更愿意将非黑格尔集合的元素等同起来。物理学家也常出于实际原因持同样观点，比如若非如此，编码因果结构的矩阵会退化、无法求逆，或是不得不使用非标准集合论而非标准集合论。

However, at least at the level of general relativity, many of the most important spacetimes have a high degree of internal symmetry, such as spatial homogeneity or isotropy or invariance under time translations. Given that classes of events in those cases cannot be discerned by means of fundamental physical properties and yet it would be absurd to identify, for instance, all events on a spacelike hypersurface of Friedmann-Lemaître-Robertson-Walker spacetimes or all events of Minkowski spacetime, one might worry that more tolerance for non-Hegelian sets in causal set theory is called for.

> 但至少在广义相对论层面，许多最重要的时空都具备高度内对称性，比如空间均匀性、各向同性或是时间平移不变性。在这些情况下，一类事件无法通过基础物理性质被区分，可如果因此就比如把弗里德曼-勒梅特-罗伯逊-沃尔克度规时空类空超曲面上的所有事件、或是闵可夫斯基时空的所有事件都等同起来，显然是不合理的，因此可能有人会担忧，因果集理论需要对非黑格尔集合给出更大包容度。

Perhaps such worry is unnecessary. Consider Minkowski spacetime. In order to give rise to Lorentz symmetry, the fundamental causal set cannot be too regular or symmetric; if it were, then there would be a physically privileged foliation at the emergent level [7]. Thus, in order to give rise to a highly symmetric continuum spacetime, the fundamental discrete structure cannot be too symmetric. This mechanism ascertains that non-Hegelian sets cannot play too much of a role for physically relevant models of causal set theory.

或许这种担忧是多余的。以闵可夫斯基时空为例: 要生成洛伦兹对称性，基础因果集不能过于规则或对称；如果它过于对称，那么在突现层面就会出现物理上的优先叶状结构 [7]。因此，要生成高度对称的连续时空，基础离散结构本身不能过于对称。这一机制表明，在具有物理相关性的因果集理论模型中，非黑格尔集合无法发挥太大作用。

In sum, the consideration of structural realism in the context of causal set theory is fruitful in both directions. On the one hand, structural realism suggests a very natural interpretation of causal set theory and arguably helps in clarifying the metaphysics of causal sets in ways that may have implications in the technical formulation of the theory. On the other hand, causal set theory offers a particularly elegant exemplar for the structural realist to develop and articulate their position.

总而言之，在因果集理论的语境下探讨结构实在论是双向有益的。一方面，结构实在论为因果集理论提供了一种非常自然的解释，并且可以说它有助于厘清因果集的形而上学，这种厘清还可能会对该理论的技术表述产生影响。另一方面，对于结构实在论者而言，因果集理论提供了一个格外雅致的范例，可供他们发展与阐明自身立场。

Conclusions

结论

Causal set theory offers a very rich field for philosophical study, due to different aspects: the suggestion that causal relations may be more fundamental than temporal ones, the functionalist emergence particularly of all spatial structures, the proposed (still classical) dynamics evoking a relativistically kosher, ”asynchronous” form of becoming, and its straightforwardly structuralist interpretation. At least the first three remain unsettled as their discussion continues. I hope to have presented the state of these debates in an engaging way and to have shown their fruitful connections to larger issues in the foundations of physics, the philosophy of time, and the metaphysics of science.

因果集理论为哲学研究提供了十分丰富的领域，这源于其多个不同特点: 它提出因果关系可能比时间关系更根本，尤其主张所有空间结构都是功能主义突现的，其提出的 (仍是经典层面的) 动力学催生了符合相对论要求的“异步”生成形式，且它可被直接解读为结构主义。至少前三个观点至今仍未有定论，相关讨论仍在持续。我希望本文能生动呈现这些争论的研究现状，并展现它们与物理学基础、时间哲学以及科学形而上学领域更宏大议题之间富有价值的关联。

Cross-References

交叉引用

Emergence of Riemannian Quantum Geometry

黎曼量子几何的涌现

Philosophical Foundations of Loop Quantum Gravity

圈量子引力的哲学基础

- Toward the Emergence of Continuum Spacetime in Causal Set Theory

- 因果集理论中连续时空的涌现研究

References

参考文献

1. A. Arageorgis, Spacetime as a causal set: universe as a growing block? Belgrade Philos. Annu. 29, 33-55 (2016)
2. J. Bain, Category-theoretic structure and radical ontic structural realism. Synthese 190, 1621- 1635 (2013)
3. S. Baron, B. Le Bihan, Quantum gravity and mereology: not so simple. Philos. Q. 72, 19-40 (2022)
4. S. Baron, B. Le Bihan, Causal theories of spacetime. Noûs (forthcoming)
5. J.S. Bell, Speakable and Unspeakable in Quantum Mechanics (Cambridge University Press, Cambridge, 1987)
6. L. Bombelli, J. Lee, D. Meyer, R. Sorkin, Spacetime as a causal set. Phys. Rev. Lett. 59, 521-524 (1987)
7. L. Bombelli, J. Henson, R.D. Sorkin, Discreteness without symmetry breaking: a theorem. Modern Phys. Lett. A 24, 2579-2587 (2009)
8. G. Brightwell, Partial orders, in Graph Connections: Relationships Between Graph Theory and Other Areas of Mathematics, ed. by L.W. Beineke, R.J. Wilson (Clarendon Press, Oxford, 1997), pp. 52-69
9. J. Butterfield, Stochastic Einstein locality revisited. Br. J. Philos. Sci. 58, 805-867 (2007)
10. C. Callender, Shedding light on time. Philos. Sci. 67, S587-S599 (2000)
11. R. Clifton, M. Hogarth, The definability of objective becoming in Minkowski spacetime. Synthese 103, 355-287 (1995)
12. F. Dowker, Real time. New Sci. 36-39 (2003)
13. F. Dowker, Introduction to causal sets and their phenomenology. Gen. Relat. Grav. 45, 1651- 1667 (2013)
14. F. Dowker, The birth of spacetime atoms as the passage of time. Ann. N. Y. Acad. Sci. 1326, 18-25 (2014)
15. F. Dowker, Being and becoming on the road to quantum gravity: or, the birth of a baby is not a baby, in Beyond Spacetime: The Foundations of Quantum Gravity, ed. by N. Huggett, K. Matsubara, C. Wüthrich (Cambridge University Press, Cambridge, 2020), pp. 133-142
16. J. Earman, Reassessing the prospects for a growing block model of the universe. Int. Stud. Philos. Sci. 22, 135-164 (2008)
17. N. Emery, N. Markosian, M. Sullivan, Time, in Stanford Encyclopedia of Philosophy (2020). https://plato.stanford.edu/
18. K. Fine, Tense and reality, in Modality and Tense: Philosophical Papers, ed. by K. Fine (Oxford University Press, Oxford, 2005), pp. 259-320
19. S. French, The interdependence of structure, objects, and dependence. Synthese 175(supplement), 89-109 (2010)
20. N. Huggett, Skeptical notes on a physics of passage. Ann. N. Y. Acad. Sci. 1326, 9-17 (2014)

21. N. Huggett, C. Wüthrich, Emergent spacetime and empirical (in)coherence. Stud. Hist. Philos. Mod. Phys. 44, 276-285 (2013)

22. N. Huggett, C. Wüthrich, Out of Nowhere: The Emergence of Spacetime in Quantum Theories of Gravity (Oxford University Press, Oxford, Under contract)

23. D.J. Kleitman, B.L. Rothschild, Asymptotic enumeration of partial orders on a finite set. Trans. Am. Math. Soc. 205, 205-220 (1975)

24. J. Ladyman, D. Ross, Every Thing Must Go: Metaphysics Naturalized (Oxford University Press, Oxford, 2007)

25. V. Lam, C. Wüthrich, Spacetime is as spacetime does. Stud. Hist. Philos. Mod. Phys. 64, 39-51 (2018)

26. V. Lam, C. Wüthrich, Spacetime functionalism from a realist perspective. Synthese 199, 335- 353 (2021)

27. B. Le Bihan, Spacetime emergence in quantum gravity: functionalism and the hard problem. Synthese 199(2), 371-393 (2021)

28. B. Le Bihan, N. Linnemann, Have we lost spacetime on the way? Narrowing the gap between general relativity and quantum gravity. Stud. Hist. Philos. Mod. Phys. 65, 112-121 (2019)

29. H. Leitgeb, J. Ladyman, Criteria of identity and structuralist ontology. Philos. Math. 16, 388-396 (2008)

30. J. Levin, Functionalism, in Stanford Encyclopedia of Philosophy (2021). https://plato.stanford.edu/archives/win2021/e

31. L. Lombard, On the alleged incompatibility of presentism and temporal parts. Philosophia 27, 253-260 (1999)

32. S. Major, D. Rideout, S. Surya, Spatial hypersurfaces in causal set cosmology. Class. Quantum Grav. 23, 4743-4752 (2006)

33. S. Major, D. Rideout, S. Surya, On recovering continuum topology from a causal set. J. Math. Phys. 48, 032501 (2007)

34. D.B. Malament, The class of continuous timelike curves determines the topology of spacetime. J. Math. Phys. 18, 1399-1404 (1977)

35. U. Meyer, The presentist's dilemma. Philos. Stud. 122, 213-225 (2005)

36. A. Ney, Fundamental physical ontologies and the constraint of empirical coherence. Synthese 192, 3105-3124 (2015)

37. H. Putnam, Time and physical geometry. J. Philos. 64, 240-247 (1967)

38. D. Rideout, P. Wallden, Emergence of spatial structure from causal sets. J. Phys.: Conf. Ser. 174, 012017 (2009)

39. D. Rideout, P. Wallden, Spacelike distance from discrete causal order. Class. Quantum Grav. 26, 155013 (2009)

40. D.P. Rideout, R.D. Sorkin, Classical sequential growth dynamics for causal sets. Phys. Rev. D 61, 024002 (1999)

41. C.W. Rietdijk, A rigorous proof of determinsim derived from the special theory of relativity. Philos. Sci. 33, 341-344 (1966)

42. B. Roberts, Group structural realism. Br. J. Philos. Sci. 62, 47-69 (2011)

43. S. Saunders, How relativity contradicts presentism, in Time, Reality and Experience, ed. by C. Callender (Cambridge University Press, Cambridge, 2002), pp. 277-292

44. S. Savitt, Presentism and eternalism in perspective, in The Ontology of Spacetime, ed. by D. Dieks (Elsevier, Amsterdam, 2006), pp. 111-127

45. L. Sklar, Time, reality, and relativity, in Reduction, Time, and Reality, ed. by R. Healey (Cambridge University Press, Cambridge, 1981), pp. 129-142

46. R.D. Sorkin, Geometry from order: causal sets. Einstein Online 2, 1007 (2006)

47. R.D. Sorkin, Relativity theory does not imply that the future already exists: a counterexample, in Relativity and the Dimensionality of the World, ed. by V. Petkov (Springer, Dordrecht, 2007), pp. 153-161

48. R.D. Sorkin, Does locality fail at intermediate length-scales? in Approaches to Quantum Gravity: Toward a New Understanding of Space, Time and Matter, ed. by D. Oriti, chapter 3 (Cambridge University Press, Cambridge, 2009), pp. 26-43

49. H. Stein, On relativity theory and openness of the future. Philos. Sci. 58, 147-167 (1991)

50. S. Surya, The causal set approach to quantum gravity. Living Rev. Relat. 22(5) (2019). https://link.springer.com/article/10.1007/s41114-019-0023-1

51. J. Worrall, Structural realism: the best of both worlds? Dialectica 43, 99-124 (1989)

52. C. Wüthrich, The structure of causal sets. J. Gen. Philos. Sci. 43, 223-241 (2012)

53. C. Wüthrich, Demarcating presentism, in EPSA Philosophy of Science: Amsterdam 2009, ed. by H. de Regt, S. Okasha, S. Hartmann (Springer, Dordrecht, 2012), pp. 439-448

54. C. Wüthrich, The fate of presentism in modern physics, in New Papers on the Present: Focus on Presentism, ed. by R. Ciuni, K. Miller, G. Torrengo (Philosophia Verlag, Munich, 2013), pp. 91-131

55. C. Wüthrich, Time travelling in emergent spacetime, in Hajnal Andréka and István Németi on the Unity of Science: From Computing to Relativity Theory Through Algebraic Logic, ed. by J. Madarász, G. Székely. Outstanding Contributions to Logic, vol. 19 (Springer, Cham, 2021), pp. 453-474

56. C. Wüthrich, C. Callender, What becomes of a causal set. Br. J. Philos. Sci. 68, 907-925 (2017)

57. D. Yates, Thinking about spacetime, in Philosophy Beyond Spacetime: Implications from Quantum Gravity, ed. by C. Wüthrich, B. Le Bihan, N. Huggett (Oxford University Press, Oxford, 2020), pp. 129-153