Chapter 4
On the Foundational Assumptions of Modern Physics

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Abstract General relativity and the standard model of particle physics remain our most fundamental physical theories enjoying robust experimental confirmation. The foundational assumptions of physics changed rapidly during the early development of these theories, but the subsequent challenges of their refinement and the exploitation of their explanatory power turned attention away from foundational issues. Deep problems and anomalous observations remain unaddressed. New theories such as string theory seek to resolve these issues, but are presently untested. In this essay, I evaluate the foundational assumptions of modern physics and propose new physical principles. I reject the notion that spacetime is a manifold, the existence of static background structure in the universe, the symmetry interpretation of covariance, and a number of related assumptions. The central new principle I propose is the *causal metric hypothesis,* which characterizes the observed properties of the physical universe as manifestations of causal structure. More precisely, the *classical causal metric hypothesis* states that the metric properties of classical spacetime arise from a binary relation on a set, representing direct influences between pairs of events. Rafael Sorkin's maxim, "order plus number equals geometry" is a special case. The *quantum causal metric hypothesis* states that the phases associated with directed paths in causal configuration space, under Feynman's sum-over-histories approach to quantum theory, are determined by the causal structures of their constituent universes. The resulting approach to fundamental physics is called *quantum causal theory.*

Introduction

Relativity and Quantum Theory. Relativity and quantum theory emerged from mathematical and philosophical seeds in the works of Gauss, Riemann, Cayley, Hilbert, and others; were incorporated as physical theories by Einstein, Heisenberg, Schrödinger, Weyl, and their contemporaries; and matured as definitive predictive systems in the form of modern general relativity and the standard model of particle

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physics in the second half of the twentieth century. Among theories enjoying robust experimental confirmation, these two theories represent our deepest understanding of fundamental physics. The rapid alteration of foundational assumptions characterizing the early development of these theories later diminished as their fruit was harvested. Satisfactory unification of relativity and quantum theory proved to be an immense and forbidding challenge, resisting numerous optimistic early attempts, and an abundance of new experimental results amenable to description within the developing framework of quantum field theory decreased motivation for radical new departures.

Foundational Problems; New Theories. Recently the triumphs of quantum field theory have slowed, and unexplained phenomena such as dark matter and dark energy hint at new physics. In this environment, long-acknowledged foundational problems have gained new urgency. The fundamental structure of spacetime, the nature and significance of causality, the quantum-theoretic description of gravity, and unified understanding of physical law, have all attracted increased scrutiny. Untested new theories seek to address these issues, often incorporating new assumptions as alien to established physics as the assumptions of relativity and quantum theory were to the Newtonian paradigm. Among these new theories, string theory [1] abolishes point particles and introduces new dimensions, symmetries, and dualities; loop quantum gravity [2] undertakes the quantization of relativistic spacetime; noncommutative geometry [3] interprets spacetime as a noncommutative space; entropic gravity [4] attributes gravitation to the second law of thermodynamics; and causal set theory [5] discards manifold models of classical spacetime in favor of discrete partially ordered sets. While limited, this list represents a reasonable cross-section of the general approaches to new physics under active investigation.

Overview and Organization of This Essay. In this essay, I evaluate the foundational assumptions of modern physics and offer *speculative* new principles, partially overlapping some of the new theories mentioned above. These principles cannot, to my present knowledge, claim definitive experimental confirmation, but their consideration is reasonable alongside other untested theories. Among the assumptions I reject are the manifold structure of spacetime, the evolution of physical systems with respect to a universal time parameter, the existence of a static background structure serving as an "arena" for dynamical processes, the symmetry interpretation of covariance, the transitivity of the binary relation encoding causal structure, and the commutativity of spacetime. The central new principle I propose is the *causal metric hypothesis*, which characterizes the observed properties of the physical universe as manifestations of causal structure. For purposes of precision, it is convenient to formulate classical and quantum versions of the causal metric hypothesis. The classical version states that the properties of classical spacetime are manifestations of a binary relation on a set. Rafael Sorkin's maxim, "order plus number equals geometry," is a special case. The quantum version states that the phases associated with directed paths in causal configuration space are determined by the causal structures of their constituent universes. These ideas are explained in more detail below. The resulting approach to fundamental physics is called *quantum causal theory.*

This essay is organized as follows: in the section "Identifying the Foundational Assumptions," I identify and discuss the foundational assumptions of modern physics, focusing on assumptions enjoying wide recognition in the mainstream scientific community. I introduce three different classes of assumptions: general principles, formal postulates, and ancillary assumptions. I isolate six general principles of particular importance, and briefly cite a few others worthy of mention. I then discuss assumptions specific to relativity, nonrelativistic quantum theory, and quantum field theory. In the section "Vignette of Unexplained Phenomena," I briefly mention some empirical phenomena unexplained by these theories. In the section "Rejected Assumptions," I reject several existing assumptions, with motivation provided by the previous two sections. In the section "New Principles," I propose new physical principles, with particular focus on the *fundamental structure of spacetime*. In the section "Practical Considerations," I remark on the status of these assumptions and principles in light of the current state of experimental and theoretical physics, and suggest how the ideas presented in this essay might find their way into the laboratory.

Identifying the Foundational Assumptions

Three Classes of Assumptions. In the world of scientific thought, ideas from mathematics, philosophy, and the empirical realm converge in the form of *general physical principles*, which further crystallize into *formal postulates* of specific physical theories, while remaining colored and often distorted by *ancillary assumptions* involving issues of interpretation and biases from the prevailing intellectual environment. These principles, postulates, and ancilla are all *foundational assumptions* in the sense that basic science depends critically, and to some degree independently, on each. However, they also possess important distinguishing characteristics.

General physical principles represent attempts to capture deep physical truths that are often difficult to quantify. As a result, such principles often survive, via an evolutionary process of refinement and reinterpretation, through multiple scientific revolutions, while formal postulates and ancillary assumptions often die along with the specific theories built around them. For example, the general principle of *covariance*, which at its root involves an assertion of the observer-independence of physical law, has motivated a succession of mutually contradictory formal *invariance postulates*, such as Galilean invariance and Lorentz invariance, along the historical path from Newtonian physics through special relativity to general relativity and beyond. Parallel to these invariance postulates have followed a succession of mutually contradictory ancillary assumptions regarding the interpretation of time and related issues. Covariance itself, meanwhile, remains relevant even to nonmanifold models of spacetime.

Formal postulates of dubious aspect sometimes persist due to a lack of suitable alternatives, even when they contradict widely acknowledged general principles. For example, the general principle of *background independence* is usually taken for granted, at a philosophical level, in the modern physics community; yet the formal postulates underlying the standard model of particle physics, as well as many newer theories, fail to satisfy this principle. Ancillary assumptions can be particularly troublesome because of their tendency to escape serious scrutiny. Examples include the *luminiferous aether* in pre-relativistic physics, and some of the assumptions related to *Bell's inequalities* in the foundations of quantum theory. General principles and formal postulates are safer in this regard, since they attract the conscious focus of theorists.

Six General Physical Principles. Six crucial general principles of modern physics are *symmetry*, *conservation*, *covariance*, the *second law of thermodynamics*, *background independence*, and *causality*. These principles are intimately interrelated. Results such as *Noether's theorem* tie symmetries to conservation laws, and relativistic covariance is understood in terms of symmetry, at least locally. More generally, covariance may be interpreted in terms of *generalized order theory*. Both viewpoints involve isolating privileged information; either that fixed by a particular group action, or that contained in a distinguished suborder. Entropy, and thence the second law of thermodynamics, may also be expressed via partitioning of information: in ordinary statistical thermodynamics, entropy involves "microscopic refinements of macroscopic states;" while in discrete causal theory, it may be measured in terms of the cardinality of certain *Galois groups* of generalized order morphisms.

Background independence is usually understood as a statement about spacetime; that it is a dynamical entity subject to physical laws, such as Einstein's field equations, rather than a static object. Philosophically, background independence provides an example of the use of *parsimony* to achieve explanatory and predictive power; the less a theory assumes, the more it can potentially reveal. Background independence is one of the strengths of general relativity; relativistic spacetime geometry is determined via dynamics, not taken for granted. Improvement beyond relativity is conceivable. For example, Einstein's equations do not predict the *dimension* of spacetime; a theory providing a dynamical explanation of dimension would be superior in important ways. Causality is of central importance to physics, and to science in general, principally because *prediction* relies upon the discovery of causal relationships, together with the assumption of *reproducibility.* Classically, causality is often formalized as an *irreflexive, acyclic, transitive binary relation* on the set of spacetime events. It is related to covariance via order theory, to the second law of thermodynamics via the arrow of time, and to background independence via the general criteria of explanatory and predictive power. However, the deep meaning of causality, and its appropriate role in quantum theory, remain controversial.

Other General Principles. Other general principles deserving mention include *symmetry breaking*, physical versions of *superposition* including Feynman's *sum over histories*, *action principles*, *cluster decomposition* and other versions of *locality*, Einstein's *equivalence principle*, *scale-dependence* and *independence*, the *holographic principle*, *dualities* such as *S-duality*, and various principles involved in the interpretation of quantum theory. Untested modern theories rely on further principles, or refinements of principles already mentioned, whose importance is tied to their success. For example, Maldacena's *AdS/CFT correspondence* [6] is much more important if string theory is physically relevant than it would be otherwise. Pure mathematics, such as number theory, also offers general principles, and conjectured principles, with deep connections to physics. For example, *zeta functions*, and hence the *Riemann hypothesis*, are connected to quantum field theory via noncommutative geometry and the theory of *motives* [7]. The *Langlands program* is connected to physical symmetry and duality via *representation theory* and *conformal field theory*, and thence also to string theory [8].

Assumptions of Relativity and Quantum Theory. The following formal postulates and ancillary assumptions apply to general relativity and quantum theory, although some of them also survive in newer theories. General relativity postulates a four-dimensional pseudo-Riemannian manifold of Lorentz signature, interpreted as spacetime, whose curvature, interpreted as gravitation, is determined dynamically via interaction with matter and energy according to Einstein's field equations, and whose metric properties govern its causal structure. Singularities arise in the generic case, as noted by Penrose, Hawking and Ellis, and others.

Multiple approaches to nonrelativistic quantum theory exist. I will describe two, equivalent under suitable restrictions. The *Hilbert space approach* postulates complex Hilbert spaces whose elements represent probability amplitudes, self-adjoint operators whose eigenvalues represent the possible values of measurements, and time evolution according to Schrödinger's equation. In the simplest context, these amplitudes, operators, et cetera, represent the behavior of point particles. Feynman's *sum-over-histories approach* [9] postulates probability amplitudes given by complex sums over spaces of paths, interpreted as spacetime trajectories of point particles in the simplest context. In a path sum, each path contributes equally in magnitude, with phase determined by the *classical action*, given by integrating the *Lagrangian* along the path with respect to time. This version generalizes easily to relativistic and post-relativistic contexts.

Quantum field theory postulates operator fields that create and annihilate state vectors in complex Hilbert spaces. States corresponding to particular particle species are associated with particular representations of symmetry groups. The properties of Minkowski spacetime impose *external symmetries* encoded by the Poincaré group. *Internal symmetries*, such as those encoded by *gauge groups*, also play a critical role. The standard model of particle physics is expressed via the nonabelian *Yang-Mills* gauge theory, and includes particles, fields, and symmetry groups in remarkable accord with the observations of particle physicists over the last century.

Vignette of Unexplained Phenomena

Overview. Since the ascendancy of general relativity and the standard model, a variety of unexplained physical phenomena have been recognized. The large-scale dynamical anomalies attributed to *dark matter* and *dark energy*, the absence of a large *cosmological constant* arising from vacuum energy, and the apparent asymmetry between matter and antimatter in the observable universe, are a few of the most prominent examples. These phenomena suggest the promise of physical models that naturally incorporate *scale-dependence*, and that offer statistical or entropic explanations of small nonzero constants and inexact symmetries. Discrete order-theoretic and graph-theoretic models tend to perform well by these criteria.

Dark Matter. The *dark matter hypothesis* is based on the failure of astrophysical systems on the scale of galaxies to obey relativistic dynamics, assuming only the matter content detectable by non-gravitational means. In contrast, objects near the stellar scale seem to verify relativistic predictions remarkably well. The dark matter hypothesis has been compared unfavorably to the luminiferous aether, and various new dynamical laws have been proposed to account for observed behavior without invoking missing mass. However, this phenomenon does behave like ordinary matter in many respects, as observed in the collision of galaxies and in certain examples of *gravitational lensing*. If the dark matter hypothesis is valid, the matter involved seems unlikely to be accounted for by the standard model. Claims have been made of laboratory observations of new particles consistent with dark matter, but these are not broadly accepted at present.

Dark Energy. Dark energy is the entity invoked to explain the phenomenon interpreted as *acceleration of the expansion of the universe*. The cosmological constant appearing in the modified form of Einstein's equations is one possible type of dark energy. Predictions based on quantum field theory and the Planck scale yield a value for the cosmological constant roughly 120 orders of magnitude greater than observation implies. Interestingly, causal set theory suggests a fluctuating cosmological constant close to the observed value, based on a simple argument involving discreteness and the size of the Hubble radius in Planck units. Nonconstant models of dark energy, such as *quintessence*, have also been proposed, but any fluctuations in dark energy appear to occur on scales much larger than those of dark matter or ordinary matter and energy. Apparent anomalies in the motion of certain large galactic clusters, called *dark flow*, might reflect such fluctuations. Dark matter and dark energy extend the scale-dependence of phenomena already observed in conventional physics. Strong and weak interactions, electromagnetism, ordinary gravity, dark matter, and dark energy all dominate on different scales, each covering roughly equivalent ranges in a logarithmic sense. The extent of this scale-dependence was unknown during the development of relativity and quantum theory, and should command significant attention in the development of new models.

Matter-Antimatter Asymmetry. Our present understanding of antimatter comes almost entirely from quantum field theory, and it is reasonable to ask if matter-antimatter asymmetry in the observable universe might indicate a problem with quantum field theory itself, or at least with the standard model. Unexpected asymmetries have been successfully handled by quantum field theory in the past; the prototypical example is *CP violation*, which is itself related to the matter-antimatter problem. However, potential sources of matter-antimatter asymmetry in the standard model seem either too weak, or too strong, to account for observation. Interesting experimental issues regarding antimatter remain to be resolved. Until recently, little direct evidence existed to demonstrate that antimatter interacts *gravitationally* in the same way as matter, and it had even been suggested that local matter-antimatter asymmetry might result from a type of gravitational segregation. More conventionally, experiments designed to investigate matter-antimatter asymmetry have recently produced data suggesting rates for certain decay processes different than those predicted by the standard model. It seems too early to render judgment on the significance or meaning of these results, however.

Rejected Assumptions

Structural Assumptions; Metric Emergence. Some of the physical assumptions I reject in this essay are already widely doubted, but survive in old and new theories alike due to the unfamiliarity or intractability of their principal alternatives. Among these are the basic structural assumptions that spacetime is a real manifold, that physical systems evolve with respect to a universal time parameter, and that the universe possesses a static background structure serving as an immutable "arena" for dynamical processes. This last assumption is, of course, merely the negation of the general principle of background independence. General relativity includes the first of these assumptions, and the standard model includes all three. Since these assumptions are retained largely for operational reasons, their rejection is not very revolutionary. However, a successful theory abstaining from them would be revolutionary indeed. I reject them partly on general mathematical and philosophical grounds, and partly for the specific physical reason that they are incompatible with discrete quantum causal theory.

Another basic structural assumption I reject is that spacetime is commutative. This statement should be understood in the sense of Connes' noncommutative geometry [3]. Though this assumption is less-widely doubted in mainstream physics than those mentioned above, it has recently become the subject of justified scrutiny. A number of existing proposals about fundamental spacetime structure lead naturally to noncommutative spaces. For example, such spaces arise via the *deformation theory of Hopf algebras*, and in certain category-theoretic approaches to physics. Even "classical spaces" such as Minkowski spacetime may be "recognized as possessing noncommutative structures" in useful ways.

Along with these assumptions perish a number of corollaries. Spacetime dimension becomes an emergent property, no longer assumed to be constant, static, or an integer. Properties previously ascribed to a metric, in the sense of differential geometry, must either be discarded or assigned different structural origins. For example, given a geodesic between two events in relativistic spacetime, there exist many other "near-geodesics" between them; however, a nonmanifold model of spacetime might admit a unique "short" path between two events, with every other path being much "longer." Such reflections prompt reconsideration of the notions of distance and locality. Other metric properties could be similarly reexamined, but most important is to investigate what mechanisms supply the *appearance* of a metric at ordinary scales. This may be called the *problem of metric emergence.*

Assumptions About Causality. The answer I will propose to the problem of metric emergence involves reinterpreting the general physical principles of causality and covariance. This requires rejection of some common ancillary assumptions about these specific principles. First, I reject the assumption that the apparent metric properties of classical spacetime involve any information other than a set of events and a binary relation, the *causal relation*, encoding causal structure. This rejection amounts to a "negative version" of the *classical causal metric hypothesis*; the corresponding "positive version" is stated below. Theorems of Stephen Hawking [10] and David Malament [11] in the late 1970s hinted at this conclusion in a relativistic context, by demonstrating that "most" of the metric properties of relativistic spacetime may be recovered from its causal structure. Causal set theory already incorporates a version of this idea.

Second, I reject the assumption that the causal relation is transitive. This odd-seeming statement merely acknowledges the physical relevance of information about *direct* versus *indirect* causation. The usual transitive "causal order" may be recovered by closing the causal relation under transitivity. Third, I reject the assumption that the causal relation is acyclic. This rejection permits the existence of *causal cycles*, which already arise as *closed timelike curves* in certain solutions of general relativity. Causal cycles need raise no paradoxes; if they exist, they are properties of a binary relation, not "self-contradictory inhabitants" of a background structure.

Assumptions About Covariance. Turning to covariance, I reject the assumption that it is an instance of group symmetry, even locally; rather, it should be viewed in order-theoretic terms. For example, different frames of reference in relativity assign different time-orders to events separated by spacelike intervals; these orders correspond to different classes of refinements of the causal relation. This rejection is notable because progress in physics has historically involved invoking new symmetry principles, rather than rejecting existing ones. Since the time of Weyl, *group representation theory* has permeated theoretical physics as the mathematical expression of symmetry, and remains perhaps the most promising technical vehicle for short-term progress beyond the standard model. Over the long term, however, analogous constructs from order theory, and perhaps other notions more primitive than groups, will likely replace much of group representation theory in this role. Alternative approaches to covariance involving category theory and noncommutative geometry have already been proposed.

New Principles

Overview: Quantum Causal Theory. New principles I propose in this essay include the *causal metric hypothesis, iteration of structure* as a quantization principle, and *co-relative histories*. These principles, explained in more detail below, form the backbone of *quantum causal theory*, which is a general term I use to describe approaches to quantum spacetime and quantum gravity that take causal structure to be fundamental. Technical tools necessary to implement these ideas include a synthesis of *multicategory theory* and *categorification* in abstract algebra, involving "interchangeability of objects, morphisms, elements, and relations;" a refined version of *random graph dynamics*; and the theory of *semicategory algebras*. In particular, *path alge-*

bras encode the properties of both individual causal universes and their configuration spaces, while providing convenient methods of computation. Details of many of these ideas appear in my paper [12]. Here I focus only on the basic concepts.

Causal Metric Hypothesis. Foremost among the new principles I propose is the *causal metric hypothesis.* The philosophical content of this hypothesis is that *the observed properties of the physical universe are manifestations of causal structure.* To crystallize this idea into a precise, quantitative approach to physics, it is convenient to first state a classical version of the hypothesis, which serves as a precursor to the corresponding quantum version, just as classical notions form the building blocks of quantum theory in Feynman's sum-over-histories approach. The *classical causal metric hypothesis* may be stated as follows:

> The properties of classical spacetime arise from a binary relation $\prec$ on a set S, where elements of S represent spacetime events, and elements of $\prec$ represent direct influences; i.e., causal relations, between pairs of events.

Figure 4.1 illustrates the classical causal metric hypothesis, and demonstrates how it differs from the paradigm of general relativity. Figure 4.1a shows a region of relativistic spacetime, with distinguished events marked by nodes. In general relativity, the geometry of spacetime governs the scope of causal influence. For example, event *x may have been influenced by* all events in its geometric "past," shown in dark gray, and *may influence* all events in its geometric "future," shown in light gray. The classical causal metric hypothesis turns this picture on its head, taking "spacetime geometry" to be nothing more than a *way of describing actual influences*. Figure 4.1b shows a family of events, with direct influences indicated by edges running up the page. Under the classical causal metric hypothesis, the geometric "past" and "future" are *a posteriori* constructions. Rafael Sorkin's causal set maxim, "order plus number equals geometry," is a special case of the classical causal metric hypothesis.

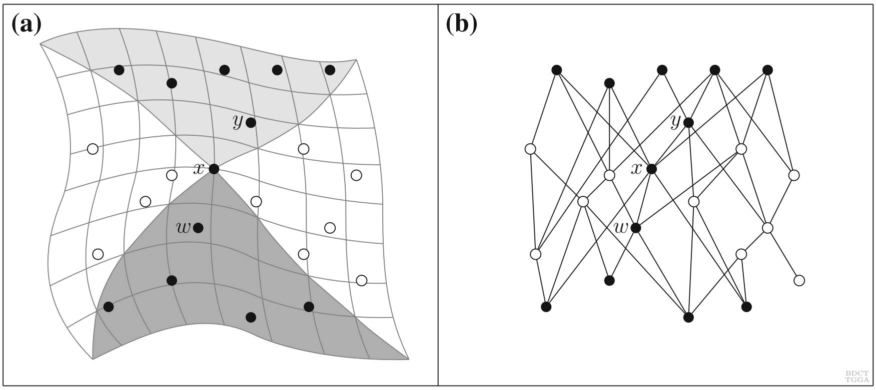

Fig. 4.1 **a** In general relativity, spacetime geometry governs the scope of causal influence; **b** under the classical causal metric hypothesis, "spacetime geometry" is merely a way of describing actual influences

The Causal Relation. The *binary relation* referenced in the classical causal metric hypothesis is a mathematical way of encoding direct influences between pairs of events, represented by edges in Fig. 4.1b. Such a relation, which I will call the *causal relation* in this context, may be viewed as a *generalized partial order,* with the word "order" indicating precedence and succession. For example, event x in Fig. 4.1b precedes event y; this is written $x \prec y$. In Sorkin's causal set theory, the causal relation is a partial order in the technical sense, but there are good reasons to generalize this picture; for example, by abstaining from transitivity and acyclicity, as already indicated above. However, the most interesting versions of causal theory I know of do impose "reasonable assumptions" on the causal relation; for example, *local finiteness*. More generally, assumptions about local structure are usually more reasonable to impose than their nonlocal counterparts, due to our ignorance of the global structure of the universe.

Recovery of Lorentzian manifold structure from the causal relation is necessary at some level of approximation, owing to the large-scale success of general relativity. The metric recovery theorems of Hawking and Malament, mentioned above, demonstrate that specifying appropriate *volume* data, as well as order data, is sufficient to recover continuum geometry. According to the classical causal metric hypothesis, this volume data should derive in some way from the pair $(S, \prec)$. The simplest dependence is the "trivial" one, in which a single unit of volume is assigned to each element of S, irrespective of $\prec$; this is the causal set approach, as encapsulated by Sorkin. However, the causal metric hypothesis allows for alternative methods of specifying volume data that depend on the causal relation $\prec$ in more complicated ways.

Iteration of Structure as a Quantization Principle. Feynman's *sum-over-histories* approach to quantum theory [9] is perhaps the most promising general approach under the causal metric hypothesis. Significant efforts have already been made to adapt this approach to causal set theory, although technical problems such as the *permeability of maximal antichains* complicate the picture. For this reason, and many others, it is preferable to work in *relation space*, as described in section 5 of my paper *On the Axioms of Causal Set Theory* [12]. Sums in this context involve paths in a "configuration space of classical universes," each represented by a pair $(S, \prec)$. I refer to such a space as a *causal configuration space.* For example, the causal configuration space of causal set theory is the space of all acyclic, transitive, interval-finite universes admitting an order embedding into the natural numbers. Causal configuration space inherits a *directed structure* induced by special morphisms between pairs of universes, called *transitions*. This directed structure may be viewed as a "higher-level analogue" of the directed structures on the individual universes $(S, \prec)$, encoded by the causal relations $\prec$. This emergence of higher-level directed structure on causal configuration space is a prototypical example of a recurring principle in quantum causal theory that I refer to as *iteration of structure.* In particular, *quantization* consists of passage from individual universes to causal configuration space. Mathematically, this may be viewed in terms of a generalized version of *categorification/decategorification*, in which structure is added or ignored by promoting elements or demoting objects.

Co-relative Histories; Kinematic Schemes. For technical reasons, transitions are *too specific* to be physically fundamental; they carry "gauge-like information."

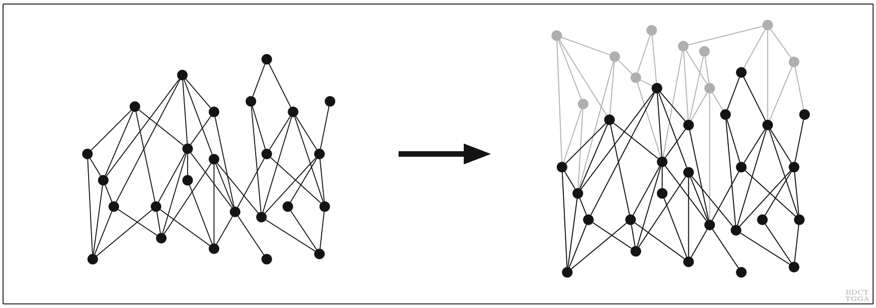

Fig. 4.2 A co-relative history. *Gray* indicates “new structure” in the target universe

Appropriate equivalence classes of transitions, which I call *co-relative histories*, are the physically significant building blocks of higher-level structure in causal configuration space, providing a refined version of iteration of structure. Figure 4.2 illustrates a co-relative history.

Co-relative histories replace the notion of *time evolution* in quantum causal theory. The target universe of a co-relative history may be viewed as a “later stage of development of its source universe.” A suitable choice of co-relative histories, providing “evolutionary pathways for every possible universe,” yields a special substructure of causal configuration space that I call a *kinematic scheme.*

Figure 4.3 modified from a similar figure in my paper [12], shows a portion of a kinematic scheme $\mathcal{S}$ that I refer to as the *positive sequential kinematic scheme.* The word “sequential” means that each co-relative history in $\mathcal{S}$ “adds a single element” to its source universe. The word “positive” means that the elements of each universe in $\mathcal{S}$ may be labeled by positive integers. The “generations” indicated by the large numbers 0, 1, 2, 3, 4 in Fig. 4.3 correspond to such labeling. The inset in Fig. 4.3 shows a portion of the abstract underlying directed graph corresponding to $\mathcal{S}$; comparison of this graph to $\mathcal{S}$ itself illustrates iteration of structure. Each upward-directed path in $\mathcal{S}$ represents a “kinematic account” of the evolution of its terminal universe. The path terminating at the universe U in Fig. 4.3 is an example. Note that the “spacelike hypersurface;” i.e., maximal antichain, in $\mathcal{S}$, represented by the three universes in double circles, is *permeated* by the path from $\oslash$ to U. This indicates that the relation space over $\mathcal{S}$; i.e., the corresponding space of co-relative histories, provides a “superior viewpoint” in a structural sense. This is an example of the *relative viewpoint* advocated by Alexander Grothendieck, in which one studies *relationships between mathematical objects*, rather than studying each object individually. Gray indicates universes whose causal relations are intransitive. These universes distinguish $\mathcal{S}$ from the configuration spaces arising in causal set theory [13].

The theory of kinematic schemes provides a precise realization of the principle advocated by Robert Spekkens in his essay *The paradigm of kinematics and dynamics must yield to causal structure,* also appearing Chap. 2. Different kinematic schemes lead to different dynamical equations, all equally valid. For example, kinematic

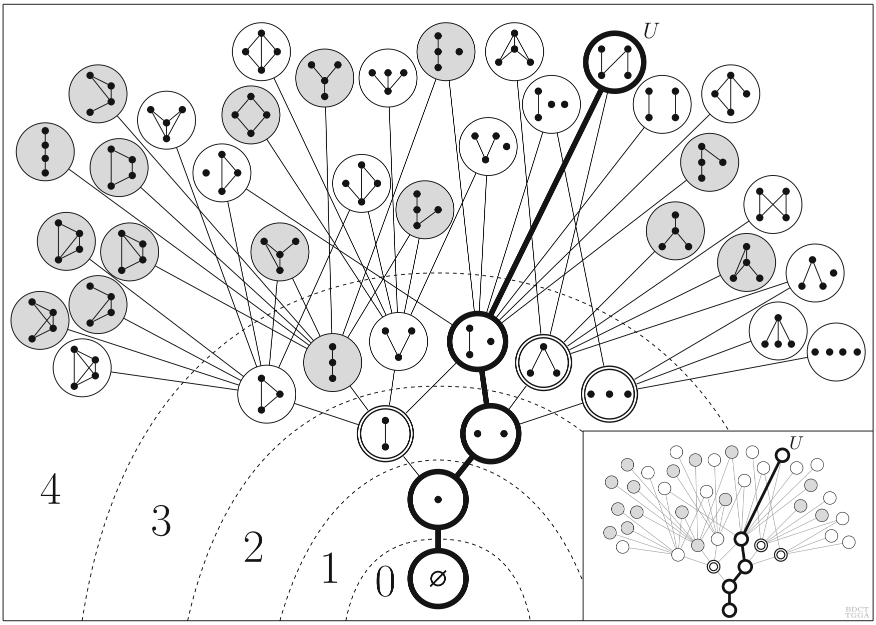

Fig. 4.3 Portion of the positive sequential kinematic scheme $\mathcal{S}$; *inset* shows the underlying directed structure; *large-font* numbers indicate generations; *double circles* represent a maximal antichain; *dark path* represents a permeating chain; *gray* indicates intransitive universes

schemes in which sources and targets differ by entire generations of elements govern discrete causal analogues of relativistic dynamics.

Dynamics; Quantum Causal Metric Hypothesis. The sum-over-histories approach to quantum theory, suitably adapted, assigns amplitudes to families of co-relative histories in a kinematic scheme. The sources of these co-relative histories are viewed as "initial universes," and the corresponding targets are viewed as "terminal universes." In ordinary quantum theory, such amplitudes are complex-valued, but the complex numbers cannot be taken for granted in the discrete causal context. Finite algebraic structures provide interesting alternatives. These amplitudes may be interpreted as encoding "probabilities" of reaching given families of terminal universes from given families of initial universes. They are computed by summing quantities called *phases* over paths between pairs of families of universes. The values of these phases are of great interest; they supply the specific physical content of the theory, just as choosing a Lagrangian supplies the physical content of a typical "conventional theory," via the corresponding action principle. The *quantum causal metric hypothesis* states that these phases "arise from causal structure" in an appropriate sense:

> The properties of quantum spacetime arise from a kinematic scheme $\mathcal{S}$. In particular, the phases associated with directed paths in $\mathcal{S}$, under the sum-over-histories approach to quantum theory, arise from the causal relations on the constituent universes of $\mathcal{S}$.

As mentioned above, technical advantages result from working in terms of the relation space over $\mathcal{S}$; i.e., the corresponding space of co-relative histories.

Causal Schrödinger-type Equations. Given a suitable choice of phases, adapting and generalizing Feynman's reasoning to the quantum causal context enables the derivation of dynamical equations, which I refer to as *causal Schrödinger-type equations*. A special case of such an equation is

$$\psi^{-}_{R;\theta}(r) = \theta(r) \sum_{r^{-} \prec r} \psi^{-}_{R;\theta}(r^{-}),$$

where R is a subspace of the space of co-relative histories over a kinematic scheme, r^{-} and r are "consecutive" co-relative histories in R, $\prec$ is the binary relation on R induced by iteration of structure, θ is the *phase map*, and $\psi^{-}_{R;\theta}$ is the *past causal wave function*, defined by summing phases over the set of maximal irreducible directed paths in R terminating at r.

Practical Considerations

Current Status of Rejected Assumptions and New Principles. The rejected assumptions and new principles discussed in this essay occupy a variety of positions with respect to theory and experiment, some more precarious than others. Manifold structure of spacetime remains tenable, but the existence of a universal time parameter and static background structure have been doubtful ever since the first observations supporting general relativity. The idea that noncommutative geometry is essential to quantum spacetime is still conjectural. Consideration of the "negative version" of the causal metric hypothesis may be omitted in favor of the stronger "positive version," to which I return below. Intransitivity of the causal relation is obvious at large scales; for example, it is uncommon to be *directly* related to one's grandparents. At the fundamental scale, the issue may be treated technically by examining whether or not physical predictions depend on including intransitive universes in the sum over histories. *A priori*, the answer is yes, but special choices of phase maps might annul this. Regarding causal cycles, I know of no solid evidence of their existence; however, certain interesting interpretations of well-known phenomena do incorporate them. Inadequacy of the symmetry interpretation of covariance might be demonstrated only in conjunction with breakdown of manifold structure.

Turning to new principles, the causal metric hypothesis is most compelling in the discrete setting, due to the metric recovery theorems. There is at present no convincing experimental evidence of spacetime discreteness, but it is thus far infeasible to experimentally probe most regimes where such evidence might present itself. In this regard at least, the plausibility of the causal metric hypothesis must be judged indirectly at this time. The theory of co-relative histories can be neither "right" nor "wrong;" it represents a *viewpoint*, more useful in some contexts than others. The idea itself is quite general, but since "relationships" in category-like settings generally involve directed structure, the theory is most natural in the causal context. The same is true of iteration of structure; moreover, the conceptual utility of this idea seems greatest in the *discrete* causal setting. To demonstrate the contrast, *Einstein manifolds* possess directed structure, but configuration spaces of Einstein manifolds are generally nothing like Einstein manifolds themselves.

Recovery of Established Physics at Appropriate Scales. The parsimony of the new principles proposed in this essay renders recovery of established physics from these principles a substantial challenge, with a correspondingly great compensation if this challenge can be met. The metric emergence problem for flat Minkowski spacetime is the obvious first step toward both relativity and the standard model in this context, since along with it will emerge the usual algebraic notions regarding coordinate transformations and particle states. Note, however, that while the standard model adds particle states as *separate ingredients* to Minkowski spacetime, *both must emerge together* in the quantum causal context. Treating matter and energy as auxiliary data would defeat the purpose of the program by violating the causal metric hypothesis, as well as the principle of background independence. Based on our best guesses about the fundamental scale, the simplest "elementary particle" interactions currently accessible to observation might easily involve Avogadro's number of fundamental causal elements, or its square, or its cube. This is encouraging in the sense that such magnitudes allow for familiar mechanisms such as entropy, and novel ones such as graph-dynamical phase transitions, to produce sharp behavior and select for precise quantities. However, it is discouraging in the sense that interactions large enough to observe might be difficult to model.

Implications of Recent Observations. Last year, the Large Hadron Collider (LHC) at CERN detected a new particle with energy near 125 GeV and properties similar to the predicted properties of the standard model Higgs boson. Work is ongoing to analyze possible deviations from these predictions, but concern exists that the observed particle may match the standard model Higgs so precisely that the results will provide little or no help in pointing to new physics. Whether or not this is true, new high-energy particle physics may soon become technologically or economically infeasible in laboratory settings. This sharpens the need for creative ideas regarding the general problem of what experimental phenomena to search for and how to search for them. In the context of quantum causal theory, results one might look for experimentally include inexactness of symmetries, variation or small nonzero values of physical constants, and new kinds of scale-dependence. Quantities such as the emergent dimension of spacetime might vary with "energy density," though such effects might be extremely small.

Opportunities for observational physics exist beyond those afforded by traditional laboratory experiments, particularly in cosmological contexts. Shortly before publication of this volume, the BICEP experiment, which measures polarization in the cosmic microwave background, reported detection of so-called *B-modes of primordial gravitational waves.* This observation has been widely regarded as evidence in favor of the *inflationary hypothesis* in cosmology, which is based primarily on the apparent communication in the early universe of regions now widely separated. Inflation is thus rooted in *causal* considerations. In my paper [12], I propose a quantum-causal alternative to inflation, in which causal structure grew abruptly "sparser" in the early universe, due to a graph-dynamical phase transition. I am presently trying to connect this idea to experiment.

Connections to Quantum Information Theory. An intriguing possibility is that *quantum circuits* might provide relatively large-scale "windows" into fundamental-scale physics. Such circuits may be represented by small "causal universes" whose relations are weighted by *single-qubit unitary transformations.* In traditional quantum theory, important restrictions on such universes arise from results such as the *no-cloning theorem.* Such circuits are small at ordinary scales, but they are many orders of magnitude larger than the Planck scale. Only very simple quantum circuits have been constructed to date, but complex circuits may be built in the near future.

The behavior of quantum circuits might be related to fundamental-scale behavior in at least two different ways. First, and most optimistically, if spacetime possesses a sufficiently simple structure, appropriate quantum circuits might serve as *virtual fundamental-scale laboratories* easily accessible to future technology. Computations involving such circuits might then suggest unforeseen phenomena that could be detected independently at reasonable scales. Alternatively, breakdown of manifold structure at the fundamental scale might lead to detectable deviations from "ideal behavior" in quantum circuits. In particular, in the discrete context, the algebraic objects involved in standard quantum information theory, such as complex Lie groups, would require replacement by complicated discrete objects. Due to the information-theoretic sensitivity involved in the physical implementation of quantum circuits, quantum computing might provide an ideal setting in which to detect the deviations associated with such objects.

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