Imperial College
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THEORETICAL PHYSICS GROUP

DEPARTMENT OF PHYSICS

TIME FROM TOP TO BOTTOM:

Smolin's Temporal Relationalism and its discontents

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Submitted in partial fulfilment of the requirements for the degree of
Master of Science of Imperial College London
QUANTUM FIELDS AND FUNDAMENTAL FORCES

SEPTEMBER 2022

Abstract

In this paper I will present Smolin's temporal relationalism programme then argue against a number of conceptual points. Temporal relationalism argues that causative time, energy and momentum should be fundamental in physics, while space and spacetime are emergent. Smolin presents his causal theory of views as a discrete basis from which momentum space, and subsequently spacetime, can emerge. Spacetime emerges from momentum space and depends upon the doubly special relativity programme and its concept of relative locality. This serves to provide a unified metaphysical basis, realised in physical models, both with which to interpret quantum mechanics and general relativity, and from which these theories can arise from a more fundamental quantum theory of gravity. He grounds all this by arguing from Leibnizian principles in a way that I will argue is flawed, in particular in its use of the concept "background independence." I will also argue that Smolin's account of spacetime emergence requires some unaccounted for functionalism and question the ways in which "views" functions analogously to shore up his causal theory of views.[1]

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[1] Acknowledgements: I would first like to thank João Magueijo for his supervision in this dissertation. I would also like to thank Adélaïde Pratoussy for her support throughout this Master's without which I would have been lost. I would also like to thank my parents, Michael and Chrissy Bysh, for their love and support throughout my life and my studies.

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Chapter 1

Introduction

We have known since 1905 and Einstein's special theory of relativity that space and time are not entirely separate things. Contrary to the naïve 3-dimensional world of experience, in which time passes and things change, space and time according to special relativity are component parts of a 4-dimensional spacetime manifold. When you throw Einstein's general theory of relativity into the mix, in which this 4-dimensional spacetime manifold is dynamical and becomes curved in response to matter, things seem stranger still.

On the other hand, it is hoped that quantum mechanics, the other great pillar upon which modern physics rests, will be combined satisfactorily with general relativity at some point to give rise to a quantum theory of gravity, at a level of description more fundamental than either alone can afford. Yet time in quantum mechanics is something external to the system, something through which the system is evolved rather than a component dimension of dynamical spacetime as general relativity describes. Time in quantum mechanics, that is, seems to be quite conventionally Newtonian. So it seems that some quite serious questions about the nature of time will need to be addressed, implicitly or explicitly, by any successful quantum theory of gravity.

A couple of questions are helpful at this point to distinguish between different views about time in modern physics. First, is time fundamental and irreducible, or does it emerge from a more fundamental timeless reality? Second, is time absolute, defined with reference to some fixed event, or is time relational, defined by the relation *between* events?

Temporal relationalism will answer that time is fundamental and relational, and gives its name to the paper I will primarily be reviewing in this essay (Smolin 2020). The paper is the summary of a research programme undertaken by Lee Smolin and collaborators over the last 20 years or so.

Temporal relationalism aims to provide a unified metaphysical basis both with which to interpret quantum mechanics and general relativity, and from which these theories can arise from a more fundamental quantum theory of gravity. I will spend most of the rest of this paper explaining why temporal relationalism says time is fundamental and relational, and how this is instantiated, before finally offering some critiques of the conceptual foundations of the project. It is a project that touches upon a large number of foundational areas in modern physics that I will sketch in the rest of this chapter before embarking on describing temporal relationalism in detail. We begin with an overview of the temporal relationalist project.

1.1 Prolegomenon

Turning the usual framing of the search for quantum gravity on its head, Smolin argues we should "*gravitise* the quantum" rather than trying to quantise gravity (Smolin 2020, p.149, emphasis added). By gravitise, Smolin means we should try to generalise the *background independence* he finds to be characteristic of general relativity.

General relativity makes spacetime dynamical. In Newtonian physics, events unfold through time in a fixed, 3-dimensional background space. Special relativity takes a step forward and unites space and time, but the spacetime picked out by Lorentz transformations in special relativity is still fixed and undynamical. General relativity, on the other hand, describes why, when and how the geometry of that spacetime must change in response to energy and momentum. Eloquently summarised in the aphorism attributed to John Archibald Wheeler, general relativity states that "Spacetime tells matter how to move; matter tells spacetime how to curve" (Charles W Misner, Thorne, and Wheeler 1973, p. 5). By making spacetime dynamical, general relativity may therefore be described as demonstrating some degree of background independence.

Gravitising quantum theory, then, is to attempt to replicate this background independence in quantum theory. It is a process of "identifying and unfreezing those aspects of quantum theory that are arbitrary and fixed, making them subject to dynamical laws" (Smolin 2020, p. 149). It aims to solve "foundational issues in quantum mechanics in a way that also addresses the problem of quantum gravity" (ibid., p. 143).

In its standard form, Smolin argues quantum mechanics is incomplete and must be completed in a way that solves satisfactorily the *measurement problem*: roughly, how is it that when one wishes to extract empirical information from a state evolving according to deterministic dynamics one ends up with a probability for each of several possible outcomes after doing something called *measurement*? How can measurement be something that exists in the formalism of quantum mechanics, and how does it cause determinism to give rise to probability? Some have attempted to solve this problem by changing the metaphysics while other seek to resolve this problem by adding to or changing quantum mechanics in some way, to *complete* quantum mechanics. Smolin advocates one of the latter complete-the-theory version, specifically a *hidden variables* theory of a relationalist kind.

Relationalism holds that the properties and values of variables associated with the states of a physical system are only physically meaningful if defined relative to another system. That is to say, there are no absolute facts about the properties of a given system in the abstract; there are only facts relative to other systems with which a system is interacting. Holding such a view would seem to require quite a radical departure from metaphysical realism, the view that there is a mind-independent, or perhaps interaction-independent, world. What motivates such a view?

If we approach quantum gravity by trying to quantise general relativity, we need to find something to play the role of time, and it seems that relationalism may be a sensible way to achieve this. As we have seen, unlike in quantum mechanics in which a system is evolved through time, in general relativity spacetime *is* the system itself, there is no background space in which the system lives nor time through which the system can be evolved. Therefore, much as position and velocity are only physically meaningful relative to another position or velocity, it seems as though time, too, may find meaning relationally. As we will see, this is ultimately a reflection of the diffeomorphism invariance of general relativity and at the heart of *the problem of time in quantum gravity*. Hence, general relativity would seem to encourage a relationalist metaphysics, especially once considerations of quantum gravity are thrown into the mix, at least according to some schemes. Smolin goes so far as to describe relationalism as itself simply “a way to characterise general relativity” (ibid., p. 143).

Temporal relationalism distinguishes itself from other relationalist approaches to quantum gravity by treating time as fundamental, as existing irreducibly all the way from top to bottom, from the 4-dimensional world of experience down to the most fundamental level of reality. It is its causative role, “as the generator of novel events from present events” that Smolin argues is irreducible (ibid., p. 144). Opponents of this view, that Smolin dubs *timeless* relationists, argue instead that time is emergent. As well as time, Smolin argues that energy and momentum are fundamental while space and spacetime are emergent. This emergence takes place in fundamental momentum space, in accord with the view that energy and momentum are fundamental.

In making these arguments, Smolin argues for a form of *presentism*: the present is physically real, objective and universal, but the future and past are not real. In particular, he develops a view he calls the *thick present*, a present in which events can be causally connected but from which events fall into the past once they have exhausted their ability to give rise to future events (Smolin 2020, p. 158).

Presentism would appear to put temporal relationalism in tension with special relativity for, if the present moment is objective and universal, this would seem to define a preferred frame in violation of Lorentz invariance and, its consequence, the relativity of simultaneity. Smolin squares this circle by considering a theory known as *doubly* or *deformed* special relativity. In this, locality becomes relative and the relativity of simultaneity becomes approximate and energy dependent in such a way that purported relativity of simultaneity arises from our failure to construct locality effectively. Much more will be said about this in section 2.4. I think it's the most fascinating part of the whole temporal relationalism project, but the way it is used to solve the incompatibility of presentism and the relativity of simultaneity is also the part of the paper that is least clear, as far as I can understand it.

Finally, Smolin argues that there is a discrete relationalist substrata from which continuous momentum space emerges and, in turn, spacetime and relative locality. This is his *causal theory of views* and Smolin argues that locality in spacetime is an approximation for proximity or similarity in the fundamental causal network or space of views.

Perhaps surprisingly, Smolin argues for this project from first principles. He traces background independence, relationalism and other principles back to Leibniz's *principle of sufficient reason.* This states roughly that all questions of why something is one way rather than another have a rational answer. Simply put, in one formulation the principle states that "nothing happens without a reason" (Leibniz 1714). We will expand upon this and all of the above in the rest of this paper.

So, in summary, in the rest of this chapter we will see that temporal relationalism is a project that aims to solve the measurement problem of quantum mechanics (section 1.2) in a way that learns lessons from general relativity (section 1.3), in turn offering a suitable metaphysics for a quantum theory of gravity (section 1.4) and does all this in a relationalist way (section 1.5). Then in chapter 2, I explain how relationalism arises from consideration of Leibniz's principle of sufficient reason (section 2.1) and that paradigm shifts in the history of physics may be understood through the lens of increasing levels of relationalism (section 2.2). Then we will outline the consequences of choosing time, energy and momentum to be fundamental (section 2.3) and how space, spacetime and relative locality arise from doubly special relativity in momentum space (section 2.4). Finally I outline how Smolin's causal theory of views offers a discretisation of relative locality that he argues is suitable, via the energetic causal set framework, as the basis for a quantum theory of gravity (section 2.5). I finish chapter 2 with a bullet-pointed recap (section 2.6).

In chapter 3 I argue that temporal relationalism has some serious conceptual problems. First, I argue background independence is not a useful methodological tool by which to improve physical theories, contra Smolin, because there is no theory independent notion of; second, I argue that Smolin's account of background independence either seems to support timeless relationalism over temporal relationalism, or seems to make ineliminable reference to time in a way that seems deeply unhelpful in both for temporal relationalism and the concept of background independence.

Next I question whether momentum can really be described as non-spatiotemporal and argue that ultimately Smolin's account of spacetime emergence requires some sort of spacetime functionalism to carry through. Then I question Smolin's use of the word "view" in his causal theory of views and argue that he is relying too heavily on the colloquial sense of that word – as in human sight – and is ultimately either using the word "view" as an analogy, or he's anthropomorphising atoms and molecules.

Finally I argue that human experience of the passage of time is the fundamental basis upon which Smolin argues for the fundamentality of time and question whether that is really a good basis from which to argue. In chapter 4 I conclude.

We begin with a discussion of quantum mechanics and the measurement problem.

1.2 Quantum Mechanics and the measurement problem

The state of an abstract quantum mechanical system is specified by an equivalence class of normalised vectors in Hilbert space, known as *rays*. The structure specific to a given system is then added via a set of preferred, self-adjoint operators (or sets of basis vectors) associated with some *observable* quantity.[1] A unitary dynamics on that Hilbert space then takes the ray at

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[1] In this section I will neglect a few things that are immaterial to the rest this essay in order to simplify slightly the presentation. The two particular things I have in mind are needing more generally to use a density matrix rather than a ray to specify the state of

one time and evolves it into the state of the system at other times. This is usually generated by the *Hamiltonian* operator, $\hat{H}$, and given by the Schrödinger equation which, for a state labelled by $|\psi\rangle$, says

$$\frac{d}{dt}|\psi\rangle = -\frac{i}{\hbar}\hat{H}|\psi\rangle\,. \tag{1.1}$$

In order to extract empirical content from this formalism we might proceed to make some sort of *measurement* of the system and to do so we make reference to the *Born rule.* The possible measurement outcomes of an operator $\hat{O}$ acting on a state $|\psi\rangle$ are given by the operator's eigenvalues and the *probability* of obtaining one of those particular outcomes upon measurement is given by the expectation value,

$$\langle O\rangle = \langle\psi|\hat{O}|\psi\rangle\,. \tag{1.2}$$

This is the Born rule.

The trouble is, though, the system need not be in *one* of the eigenvalue states, $|o_i\rangle$, associated with $\hat{O}$, and will generically appear to be in multiple of those eigenvalue states at the same time. Indeed, due to the linearity of the Schrödinger equation and Hilbert space, the suitably normalised sum of any two or more states that are a solution to the Schrödinger equation will itself be a solution to the Schrödinger equation. Thus a general state will be a superposition of those possible outcomes,

$$|\psi\rangle = \alpha_1|o_1\rangle + \alpha_1|o_1\rangle + \ldots + \alpha_n|o_n\rangle\,, \tag{1.3}$$

and the Born rule means that the probability of acheiving any particular outcome *upon measurement* is equal to the modulus squared of the complex coefficient known as an amplitude, $|\alpha_i|^2$. The normalisation $\sum_i|\alpha_i|^2 = 1$ is required so that the total probability always sums to 1, in accordance with the usual laws of probability.

We might have thought that $|\psi\rangle$ *represents* the state of the system; this would seem a natural interpretation, thinking of a ray in Hilbert space as akin to a point in configuration space in Lagrangian mechanics. But, say, for example, our system is a single electron and the observable of interest is its spin in a particular basis. And say the electron is in one of these suitably normalised superpositions of spin up, $|\uparrow\rangle$, and down, $|\downarrow\rangle$, such as

$$|\psi_e\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle\,. \tag{1.4}$$

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a system; and the need to integrate continuous variables rather than sum discrete ones.

Then according to the Born rule we know that upon measurement there's a 50% chance we will find the electron in the $|\uparrow\rangle$ state and 50% chance we will find the electron in the $|\downarrow\rangle$ state. But what does it mean for $|\psi_e\rangle$ to represent the state of the system if, *upon measurement*, we only ever have one outcome from various possibilities? And how is it that something called "measurement" appears in the formalism of quantum mechanics? This, then, is the *measurement problem.*

Furthermore, if we had a pair of electrons rather than one, and say they had arisen from the decay of some spin-0 particle such that the electrons must have opposing spin states for spin to be conserved in this decay. Then this state might be expressed, in the case where the two possibilities have equal probability, as the so-called singlet state,

$$|\psi\rangle_{1,2} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2), \tag{1.5}$$

where subscripts arbitrarily label the electrons. In essence this means when we measure the spin of electron 1 in some basis we know with certainty the spin of electron 2: it's the opposite of the result we got for electron 1. We say this state is *entangled.* And this correlation persists regardless of the separation of the electrons and therefore demonstrates that non-locality is an essential feature of quantum mechanics. This will be relevant later.

There are number of conceivable routes to solve the measurement problem. The first is to accept $|\psi\rangle$ is a complete description of the system but there is some mechanism that selects one of the possible outcomes: this is roughly the route chosen by the Copenhagen interpretation. The second proposes that $|\psi\rangle$ is an *in*complete description and adds in some mechanism that selects one of the possible outcomes: dynamical collapse theories. The third proposes $|\psi\rangle$ is an incomplete description but that some further ontology, unacknowledged by the forgoing formalism, means there is in fact only one possible outcome: hidden-variables theories. Fourth, that $|\psi\rangle$ is a complete description and we must take seriously all outcomes despite only experiencing one: the Everett interpretation. Or, treat $|\psi\rangle$ instrumentally, or of epistemic rather than ontological import (so-called ψ-epistemic views), or purely informational (QBism), and so on. I won't examine these final routes but now expand upon the first four.

The so-called textbook, or Copenhagen, solution is that upon measurement the state "collapses" onto one of the various possible outcomes. This simply raises the further question of what counts as a measurement, what counts as something that "collapses" the state in the first place? Answers have included observation, consciousness and others and have been much criticised in the time since this was first proposed but all tend towards anti-realism.[2] Furthermore, we should expect our measuring devices themselves ultimately to be described by quantum mechanics. So if this interpretation holds, it would seem that when measuring a system we must make reference to measuring the measuring devices that measure the state of the initial system, in order for the state of the measurement of the measuring devices to have appropriately collapsed, and so on leading to a regress up to the macroscopic level. In practice, this interpretation usually amounts to using quantum mechanics as a calculational tool and ignoring the metaphysical quandries. The Copenhagen interpretation, then, would seem to be kicking the can down the road and then quickly shutting the door. One might say it's more of a shut-up-and-calculate quietism than an interpretation.

Perhaps, instead, we should take seriously the talk of "collapse" and add to the unitary dynamics a stochastic mechanism by which the state collapses onto one possible measurement outcome. This is the dynamical collapse approach, most famous among which is the eponymous Ghirardi-Rimini-Weber theory (1986).

Or, perhaps there are some variables, *be*ables as opposed to *observ*ables in John Bell's language, undescribed by ordinary quantum mechanics that need to be described to fully account for what the partial description given by the quantum state. These are the hidden-variables approaches, most prominent among which is Bohmian mechanics (aka de Broglie-Bohm or pilot wave theory). In this, an actual configuration of particles exists, in addition to the quantum state, that evolves according to the *guiding equation*. This expresses the velocities of the particles via the quantum state that, in turn, evolves according to the Schrödinger equation. The so-called hidden variables are thus, somewhat confusingly, the actually existing particles. As a result the theory is deterministic and thereby sidesteps the measurement problem. Finally, we note that though the wavefunction acts on the particles, the particles do not act on the wavefunction; the wavefunction determines the dynamics of the particles, not the particles themselves (Goldstein 2021).

Another approach leaves the formalism of quantum mechanics as it is but, instead, attempts to achieve realism by taking seriously all the states in a given superposition: this is the Everett interpretation. The idea here is that upon a certain kind of interaction between a system in a superposition state and a measuring device (or observer), the system becomes

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[2] An memorable example of taking seriously one version of this view: "I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it" (Pais 1979, p. 907).

entangled with the measuring device (or observer) and the reason we see only one outcome upon measurement is that the universe has branched in some meaningful way such that there are several independent observers, each with a different measurement outcome. That is: all measurement outcomes are obtained and although we only experience one, there is another of us in each of another of various worlds in which a different outcome was obtained. The modern proponents of this theory propose that decoherence is the mechanism by which this objective universe splitting happens and more details of this along with discussion of various problems and proposed solutions to this approach can be found in (Wallace 2012; Wallace 2010). We return to one final interpretation, relational quantum mechanics, in section 1.5.

1.3 General Relativity

As discussed in section 1.1, in general relativity the energy and momentum of matter act as sources of spacetime curvature and the spacetime curvature tells that matter how to move. Mathematically, this is expressed in Einstein's equations as,[3]

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi\, T_{\mu\nu}. \tag{1.6}$$

Here, the energy momentum tensor, $T_{\mu\nu}$, describes the matter content acting as a source for curvature that is described by the Ricci curvature tensor, $R_{\mu\nu}$, and Ricci scalar, R. The geometry and causal structure of the manifold that becomes curved is encapsulated in the metric tensor, $g_{\mu\nu}$, which is a (0,2) tensor field on the manifold. This means both that as a function the metric takes as its argument two vectors at a point and returns a scalar—defining the inner product on the tangent space at each point on the manifold—and also that the metric describes the distance from each point to neighbouring points. In this latter guise, the metric tensor in a particular coordinate basis provides the invariant line element,

$$ds = g_{\mu\nu}dx^{\mu}dx^{\nu}. \tag{1.7}$$

Furthermore, general relativity generalises the relativity principle of special relativity, doing very much what it says on the tin. In special relativity,

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[3] From now on we use natural units in which Newton's constant and the speed of light are both set equal to 1 ($G = c = 1$) such that, in this case, the prefactor of $T_{\mu\nu}$ is greatly simplified as written ($\frac{8\pi G}{c^4}$ in SI Units). Furthermore, we suppress a term involving the cosmological constant, $\Lambda g_{\mu\nu}$, that may be added to the Einstein tensor, $G_{\mu\nu}$, as it is not relevant in what follows.

and Newtonian physics, there is an equivalence between all inertial frames. Inertial frames are those that are unaccelerated, in which force-free bodies move uniformly in straight lines, and in which the laws of physics take a particularly simple form (Knox 2013, p. 6). This equivalence means that whether an object is at rest or moving with a constant velocity is a matter of description rather than anything absolute. That is, inertial frames are a *special* class of frames, distinguished from those moving in a non-uniform way. In contrast, in general relativity we have diffeomorphism invariance (aka general covariance) under which any and all reference frames are treated equally, with the caveat that it must be possible to transform smoothly from one frame to the other, a transformation that is part of the group $GL(4,\mathbb{R})$. The effect of this is that coordinates have no physical meaning in general relativity. Coordinates are simply labels, and a point on the manifold may simply be relabelled, provided this is done so in a smooth, invertible way.

A solution to Einstein's equations Equation 1.6 is a spacetime denoted by $(\mathcal{M}, g_{\mu\nu}, f)$, where $\mathcal{M}$ denotes the manifold which in turn specifies the dimension, topology, differential structure and signature of the spacetime; $g_{\mu\nu}$ denotes the metric; and f denotes all other fields. Diffeomorphism invariance is then given by the (smooth, invertible) map, ϕ, from the manifold to itself

$$\phi(\mathcal{M}, g_{\mu\nu}, f) \mapsto \big(\mathcal{M}', g'_{\mu\nu}, f'\big). \tag{1.8}$$

This map takes a point on the manifold to another point on the manifold,

$$p \mapsto p' = \phi \cdot p, \tag{1.9}$$

and drags the fields along for the ride according to,

$$(\phi \cdot f)(p) = f\big(\phi^{-1} \cdot p\big). \tag{1.10}$$

This is the statement that the value of the transformed field, $(\phi \cdot f)$, at a point p is equal to the value of the field, f, at the transformed point, $(\phi^{-1} \cdot p)$. So diffeomorphism invariance means there are many ways to describe the same spacetime.

Hence, a *physical* spacetime is an *equivalence class* of manifolds, metrics and fields $(\mathcal{M}, g_{\mu\nu}, f)$ under the action of the diffeomorphism group of that manifold, Diff($\mathcal{M}$); we may denote this equivalence class using curly brackets, $\{\mathcal{M}, g_{\mu\nu}, f\}$ (Smolin 2006, p. 206). So, given a solution to Einstein's equations (1.6), diffeomorphism invariance means we are free to drag that solution around the manifold and if we do so we will end up with a solution that is mathematically distinct but physically identical.

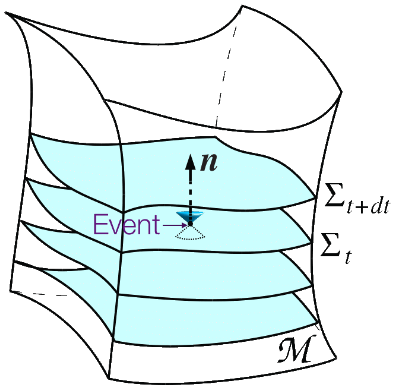

Figure 1.1: An illustration of the ADM formulation with one spatial dimension suppressed.

One particular way of splitting the full 4-dimensional diffeomorphism invariance that will be relevant later is according to the ADM formalism, named after Arnowitt, Deser and Misner by whom it was proposed (1959). According to this scheme, spacetime is foliated into spacelike hypersurfaces, Σ_t, each of which is labelled by its time coordinate, t. On each spatial hypersurface a point is specified by coordinates, x^i, and there exists a three-dimensional spatial metric, γ_{ij}, where $i, j = 1, 2, 3$. The way these hypersurfaces are separated is described by the *lapse function*, N, and the subsidiary three-dimensional diffeomorphism invariance is given by the *shift function*, N^i, such that a general parametrisation metric according to these coordinates is

$$ds^2 = -N^2 dt^2 + \gamma_{ij}(dx^i + N^i dt)(dx^j + N^j dt). \tag{1.11}$$

A graphical illustration of this formalism is given in Figure 1.1. One spatial dimension is suppressed – it's quite difficult to print a four-dimensional figure.

1.4 The need for a Quantum Theory of Gravity

> *A good student following a general relativity class in the morning and a quantum-field-theory class in the afternoon must think her teachers are chumps, or haven't been talking to one another for decades. They teach two totally different worlds. In the morning, spacetime is curved and everything is smooth and deterministic. In the afternoon, the world is formed by discrete quanta jumping over a flat spacetime ... that the morning teacher has carefully explained not to be features of our world.*
>
> — Rovelli and Vidotto*, 2015, p. 5*[4]

So far, so good. Yet if we stop to think about it for a moment, something profoundly odd is going on in Equation 1.6. We've known for a hundred years that matter is quantum in nature, yet matter is described on the right

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[4] As quoted in (Rickles 2021, p. 340).

hand side of Equation 1.6 by the classical energy-momentum tensor. The quotation above makes the point: general relativity and quantum mechanics cannot be treated completely independently; at the very least general relativity must treat matter in a quantum way.

Perhaps we can promote $T_{\mu\nu}$ to the status of an operator in some suitably defined quantum field theory so that we could calculate the expectation value of finding it in some physically appropriate state $|\psi\rangle$ according to $\langle\psi|\, \hat{T}_{\mu\nu}\, |\psi\rangle$. Then Equation 1.6 becomes simply

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi \, \langle\psi|\, \hat{T}_{\mu\nu}\, |\psi\rangle \, . \tag{1.12}$$

This is known as *semi-classical quantum gravity*: matter is treated in a quantum way while spacetime is still treated classically. This approach is able to handle linear quantum fields in curved spacetime and has been worked out in a mathematically rigorous way since at least 1994 (Wald 1994). However, there are ambiguities in the way $\langle\psi|\, \hat{T}_{\mu\nu}\, |\psi\rangle$ is defined, and it contains terms of fourth order in derivatives of the metric (as opposed to the classical equation that is second order) meaning there will be "runaway" solutions where the curvature blows up (ibid., p. 99)[5]. Even aside from these more mathematical problems, in such an approach the measurement problem rears its ugly head once more: either measurement induces some sort of discontinuity in the metric field, or the geometry of spacetime ends up in a superposition (Rickles 2021, p. 344). So to solve these problems and be able to treat quantum fields more generally we need to move beyond semi-classical to some fully fledged quantum theory of gravity, and doing so, at least according to the most prominent approaches, will require a radical reexamination of space and time. We may distinguish between two classes of approaches by their proposed method of quantisation: covariant or canonical.[6]

Covariant quantum gravity

Most covariant approaches split the metric into background terms and perturbations and, so doing, keep the symmetries of four-dimensional space-

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[5] Further shortcomings are laid out in (Wüthrich 2021, §24.2) and references therein.

[6] Of course, other approaches also exist. Those in which general relativity is fundamental and contains quantum mechanics (such as Einstein's proposed *unified field theory*); or those in which neither general relativity or quantum mechanics are fundamental and both are emergent from some other theory. Nonetheless, the main approaches may all be characterised as finding general relativity in some way contained within quantum mechanics, in which gravity is quantised, so to speak. I therefore focus on those theories. This way of dividing up the various approaches mirrors that in (Rickles 2021).

time intact. They treat the general relativistic curvature of spacetime as a modification to an otherwise flat, fixed geometry by a spin-2 field. This takes place using the linear approximation to the full Einstein equations and the gravitational interaction is mediated by a particle known as the *graviton*. However, treating the metric perturbatively, presupposing some sort of classical background from which curvature is a deviation, arguably undermines the sense that the curvature or flatness of spacetime is determined dynamically and independently in general relativity. And in framing the gravitational interaction in a way that it may be quantised, treating it like electromagnetism and the nuclear forces, might be seen as hacking out that profound insight of general relativity and the equivalence principle: that general relativity is a theory as much about the dynamical structure of spacetime as it is simply about the gravitational interaction (ibid., p. 342). The most prominent instantiation of this approach to quantum gravity is superstring theory, in which the graviton arises in the spectrum of closed strings.

Another type of covariant approach follows instead Feynman's path integral formulation, summing over all four-dimensional metric tensors. It does thereby avoid the perturbativity of other covariant approaches but does so at the cost of landing itself with a *measure problem*, "in which it isn't clear how to assign probabilities to outcomes in the path integral" and essentially requires the solving of "one of the most pressing problems in topology" (ibid., Footnote 9).

Canonical quantum gravity

On the other hand, canonical approaches involve re-expressing general relativity as a constrained Hamiltonian problem, attempting to quantise spacetime more directly and thereby retaining its dynamical character. Earlier geometrodynamical models assigned the metric the role of canonical variable but more recently the Ashtekar connection and its conjugate have been used as the canonical variables: this is Loop quantum gravity, the most prominent canonical approach. Formulating general relativity canonically in any form, however, requires a split between space and time in which spacetime is foliated into spacelike hypersurfaces, just as in the ADM formalism we saw in section 1.3. The lapse and shift functions become constraints on the Hamiltonian: the shift functions become the 'supermomentum' constraints, while the lapse function becomes the 'super-Hamiltonian' constraint (ibid., §3.2.1). However, the Hamiltonian generates the dynamics but at the same time is also a constraint of the theory as the super-Hamiltonian, we are left with a Schrödinger-like dynamics for a physical state $|\psi\rangle$ where

$$\hat{H}\,|\psi\rangle = 0. \tag{1.13}$$

That is, it would appear that the genuine physical properties of the system *do not change over time.* This is a reflection of the diffeomorphism invariance of general relativity: time translation is a diffeomorphism of the theory and hence will leave the system unchanged.

This, then, is *the problem of time.* The heart of this problem is contained in a number of questions, as posed by Chris Isham (1993, p. 5): how should time be reintroduced in a quantum theory of gravity? Should it be introduced before or subsequent to quantisation? Can time be regarded as a fundamental concept or an emergent, phenomenological one? And if time is truly only an approximate concept, how reliable is quantum mechanics in the regime where time is not applicable?

We will see in the reminder of this paper how temporal relationalism's answer to these questions, that time is fundamental and must be introduced prior to quantisation, seeks to solve the problem of time. Before finishing this section, though, there is one final approach we must outline: causal set theory.

Causal set theory

Causal set theory seeks to recover spacetime from causation, and takes causal structure to be central to the way in which general relativity determines spacetime geometry, up to a conformal factor (Wüthrich 2021, p. 366). Causal sets are discrete sets of events along with a relation of "causal precedence," denoted $\prec$, that partially order the set.[7] The events are themselves sub-Planckian chunks of spacetime whose size is fixed by the conformal factor.

By foregrounding causation, the causal set theory approach will be very well suited to instantiating models along the lines advocated by temporal relationalism. Indeed, Smolin's energetic causal sets approach underpins much of this project, as set out in (Cortes and Smolin 2014) among other papers.

So, we need a quantum theory of gravity. Covariant quantisation, canonical quantisation and causal set theory are the most popular approaches to

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[7] Only a *partial* order is possible due to there being no frame-independent fact of the matter as to the causal order of spacelike-separated events due to the relativity of simultaneity in special relativity mean (Huggett, Vistarini, and Wuthrich 2012, p. 4).

finding such a theory. But what is relationalism and why should we aspire that our fundamental physics to reflect it?

1.5 Relationalism

Relationalism is defined in opposition to another view about spacetime, substantivalism, and is an idea that traces its history back to Leibniz and a disagreement with Newton over what *space* — and from the early twentieth century *spacetime* — actually is. Substantivalism, Newton's view, maintains that space(time) exists in its own right, and is a meaningful sort of thing that persists in the absence of matter, and somehow underlies the matter in that space(time). Relationalism, by contrast, will say that what we *mean* when we talk about spacetime is possible and actual spatiotemporal relations between matter that matter may instantiate (Pooley 2012, p. 2). Spacetime is not the cosmic canvas upon which matter is daubed; rather, the presence of matter, and spatiotemporal relations between matter, *is* spacetime.

The relationalism-substantivalism debate is a vast topic in its own right, and going into it in more detail is beyond the scope of this essay.[8] Temporal relationalism is making a more specific, metaphysically stronger claim. The relationalism of temporal relationalism, instead, is metaphysically similar to the relational interpretation of quantum mechanics to which we now turn.

Relational quantum mechanics

Relational quantum mechanics states roughly that the variables associated with quantum mechanical systems take values only in interactions with other systems. Variables do not have values that persist through time or in the abstract; variables only take values at certain times, only through interaction, and only relative to the second system with which the first interacted. Furthermore, in much the way that the velocity of one system may only be defined relative to another, *all* physical variables are relational in relational quantum mechanics. These aspects of relational quantum mechanics are encoded in the physical assumption that Carlo Rovelli and Federico Laudisa say is central to the interpretation:

> The probability distribution for (future) values of variables relative to S' depend on (past) values of variables relative to S'

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[8] See (Pooley 2012) for a recent and thoroughgoing account.

> but not on (past) values of variables relative to another system S''. (2021, §0.1)

The ontology of relational quantum mechanics, then, is "an evolving network of sparse relative *events*, described by punctual relative values of physical variables" (ibid., §0.1). These events are statements of fact such as "the particle is at x at time t," (ibid., §1.1). Furthermore, given a particular 'observer' we may define its *perspective* as the ensemble of events relative to that observer together with the usual probability rules associated with quantum mechanics. In a sense, then, relational quantum mechanics is like the Copenhagen interpretation, except any physical system can play the role of observer. It is these two ways in which relational quantum mechanics resembles Smolin's temporal relationalism: both describe a network of relational events, and both attempt to generalise the unreconstructed notion of 'observer' found in the Copenhagen interpretation of quantum mechanics.We will see these aspects of temporal relationalism in section 2.5, in the causal theory of views. The latter point is necessitated by the radical relationalism the views share; it is only the perspective or view of an event that is physically meaningful.

However, temporal relationalism and relational quantum mechanics are different and, in their attitudes to time, incompatible views. In relational quantum mechanics time, like any other contingent variable, is purely relational and worldline dependent. Therefore, there can exist no universal time, no "universal flow of becoming" in relational quantum mechanics (ibid., §3.2); Smolin calls this *timeless* relationalism. Temporal relationalism, on the other hand, treats time in a preferential way, placing time and causation at the fundamental level such that a universal, objective time does in fact exist.

So, now we have outlined quantum mechanics, general relativity, the need for and approaches to quantum gravity, and relationalism, we can see how they fit together in temporal relationalism. Following Smolin, we begin with Leibniz.

Chapter 2

Temporal relationalism

2.1 The Principle of Sufficient Reason

In grounding his own relationalist views, Smolin appeals to Leibniz's *principle of sufficient reason.*[1] Smolin quotes the following version of this principle,[2] (Leibniz 1714):

> §31 Our reasonings are based on two great principles, that of contradiction, in virtue of which we judge that which involves a contradiction to be false, and that which is opposed or contradictory to the false to be true.
>
> §32 And that of sufficient reason, by virtue of which we consider that we can find no true or existent fact, no true assertion, without there being a sufficient reason why it is thus and not otherwise, although most of the time these reasons cannot be known to us.

Smolin also quotes another version of the principle of sufficient reason from the letters to Samuel Clarke in which Leibniz puts it more succinctly (Leibniz 1717), "nothing happens without a reason." With direct reference to happening, Smolin reads this latter version as pertaining to events and thus more directly applicable to questions of spacetime.

In essence the principle of sufficient reason means that every fact about the world can be explained; phrased negatively, there are no facts about the world about which no explanation can be given. Smolin's own rendering

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[1] More accurately, Smolin is appealing to both the principles of *contradiction* and of sufficient reason, which Leibniz stated explicitly both are basic and fundamental (Rodriguez-Pereyra 2018, p. 4).

[2] Many inequivalent versions exist in Leibniz's writings (ibid., p. 2).

is that "every time we identify some aspect of the universe that seemingly may have been different, we will discover, on further examination, a rational reason why it is so and not otherwise" (Smolin 2020, p. 146).

He argues we should take seriously Leibniz's principles, though as methodological advice for physicists rather than as metaphysics. This advice he dubs the principle of *increasingly sufficient reason*: "seek to progress by making discoveries and inventing hypotheses and theories that lessen the arbitrary elements of our theories" (ibid., p. 146). This has often been the case in physics, Smolin argues. Why is the speed of light c, for example? Because of the electrical permittivity, ε_0, and magnetic permeability, μ_0, of the vacuum according to $\frac{1}{\sqrt{\varepsilon_0 \mu_0}}$. And there are further physical facts that may yet be given an explanation, for example a physical theory that requires three macroscopic spatial dimensions, as yet a brute fact about the world.

Smolin argues that taking seriously the principle of increasingly sufficient reason pushes one towards a relationalist interpretation of physics and has five consequences that may, in turn, be methodologically useful in seeking to make progress in physics. Each of these is a route to lessen the arbitrariness of our theories and therefore increase sufficient reason, in Smolin's language. These are the principles,

1. of increased background independence;
2. of the relationality of space and time; [3]
3. of causal completeness;
4. of reciprocity; and
5. of the identity of the indiscernible.

We take each in turn, explaining what it means and how it is supposed to follow from the principle of increasingly sufficient reason. I'm presenting Smolin's views here unless explicitly stated otherwise.

Background independence

A background independent theory does not require us to divide a system in two, into a dynamical part and an undynamical background, and instead treats the entire system as dynamical. Because the geometry of spacetime

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[3] Or, in Smolin's verbiage, "The principle that properties that comprise or give rise to space, time, and motion are relational," (Smolin 2020, p. 147).

is dynamically determined in general relativity, it may be said to exhibit a high degree of background independence. In contrast all other physical theories to date "depend upon structures fixed in time and have no justification" and, further, that these structures "are evidence that the theory in question is incomplete" (ibid., pp. 147–148). Hence Smolin's principle of increased background independence states:

> a physical theory should depend on no structures that are fixed and do not evolve dynamically in interaction with other quantities. (ibid., p. 148)

Background independent theories have fewer arbitrary elements than background dependent ones, hence increasing background independence increases sufficient reason.

Increasing background independence will often be *gradual* and must ultimately lead to a cosmological theory. It must be gradual as it requires the unfreezing of background elements, of elements that it comes to be noticed have been simply assumed or non-dynamically imposed, and only when such elements are identified can the attempt to unfreeze them begin. There's an acquisitiveness to this process: elements of background structure are eliminated, elements external made internal, and this will scale inevitably outwards until there are no longer any elements external to the system. This process must terminate at the point where there are no external elements: a theory of the whole universe.

Smolin argues at this point that a theory of the universe must not be the same as a theory of parts of the universe. I'm not sure why. I don't see how it follows from the discussion, especially given we've just argued that a cosmological theory is reached by the gradual but repeated process of unfreezing background elements: what makes the final step different from those that precede it other than the process finishes? The only way I can make sense of the claim is if we must impose a split between system and observer in the manner of the Copenhagen interpretation. If, on the other hand, we aim to describe quantum mechanics on the basis of interactions such that a system and its environment, and everything else for that matter, are treated on an equal footing then I cannot see why a system of all must differ from a system of parts. This I take to be the case in the Everett interpretation as well as in relational quantum mechanics, albeit it is not clear in the latter that a state of the universe is possible given such a state would seem to be constructed by everything interacting with everything else in the universe simultaneously.

However, quantum mechanics has fixed elements, Smolin continues, and therefore cannot be a theory of the whole universe, regardless of the preceding part-whole argument. These fixed elements include the geometry of Hilbert space and the algebra of observables. Following the principle of increasing background independence, we should seek to unfreeze background elements of quantum mechanics, make these elements dynamical and thereby complete the theory. This is the sense, discussed in section 1.1, in which Smolin's project aims to gravitise the quantum rather than quantise gravity.

We will return to this theme in section 3.1, however, as beyond the intuitive level the notion of background independence (as something like relational and dynamical) is not generally well defined, not defined in a way that is agreeable between different approaches to quantum gravity, and therefore I will argue is of limited use a methodological tool. Furthermore, the basis upon which non-radically relational interpretations of quantum mechanics are ruled out become less secure. Nonetheless, I park those concerns for the moment and rather than writing "background independent" each time, or *background independence in Smolin's terms*, for the sake of brevity I will continue to write background independent without scare-quotes, though the reader should keep in mind I will problematize the utility of the term later.

Relational space and time

As we saw in section 1.5, general relativity and the problem of time encourage a relational view of spacetime, but this view may also be grounded from the principle of increasingly sufficient reason because a relational theory has fewer arbitrary elements as it requires no absolute referent from which other things are defined.

Nonetheless, Smolin allows that a relational theory may have *some* "beables that are intrinsic to individual events and processes", (Smolin 2020, p. 149). In temporal relationalism this exception is made for energy and Smolin argues that physics necessitates this.

Causal completeness

Everything that happens in the universe has a cause, which here is simply one or more prior events, that can never be traced back to something outside the universe. Consequently, a theory constructed on the basis of the principle of increasingly sufficient reason "can contemplate only a single, causally connected universe", Smolin says (ibid., p. 150), because a causally complete theory has fewer arbitrary elements than a causally incomplete theory.

I would argue this point is half-made, however, as there is a directionality to causation in the way this is presented which does not preclude branching into the future.[4] In the Everett interpretation, for example, events are always traceable to prior events. If one wishes to exclude the many worlds of the Everett interpretation, one would be require something akin to causal completeness but running into the future rather than the past. In the absence of such an idea, it is too quick to declare only a single universe is possible. I note this here as causal completeness does not appear obviously in the rest of his account of temporal relationalism.

Reciprocity

The principle of reciprocity states simply that for objects A and B, if A acts on B then B acts back on A. Smolin says this appears in one of Einstein's original papers on general relativity. It is less arbitrary for two objects to interact than there to be unilateral action from one on the other, hence reciprocity increases sufficient reason.

Including the principle of reciprocity means that Smolin's hidden-variables approach differs from the metaphysics of Bohm's pilot wave theory, though Smolin recovers Bohmian dynamics from within his real ensemble formulation of quantum mechanics as we will see later. In pilot wave theory the pilot wave influences the wavefunction but the wavefunction does not influence the pilot wave.

Identity of the Indiscernible

The principle of the identity of the indiscernible states that "any two objects that have exactly the same properties are in fact the same object" (ibid., p. 150) and is arguably another Leibnizian principle in its own right. If two indistinguishable objects were *not* identical, there would have to be some arbitrariness in their differentiation. Therefore it follows that the identity of the indiscernible reduces arbitrary elements and thus increases sufficient reason.

Arguably this principle arises from relationalism for, if all contingent properties are relational and our fundamental beables are a network of relations, it follows that indistinguishable objects must be identical. Relationally, if two objects stand in exactly the same relation to all the other objects with which they are related then they are the same object..

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[4] Smolin would undoubtedly agree that causation has such a directionality, as reestablishing the irreversibility of time in fundamental physics is one of the motivations for choosing time to be fundamental in temporal relationalism.

Consequently, there can be no global symmetries. If there were global symmetries, it would be possible for one object to be transformed via a symmetry to create a second object identical but distinguishable from the first. Apparent global symmetries arise, Smolin argues, as a result of background dependence, when simplified situations are modelled in which the background is artificially decoupled; unfreezing the background and making it dynamical eliminates global symmetries (Smolin 2020, p. 150). The most obvious example of this is the Lorentz symmetry of special relativity and QFT: when we unfreeze background spacetime and move from special to general relativity we find Lorentz symmetry to be only locally true. This is not true of gauge symmetries, of course, which may be parsed as redescriptions rather than symmetries, proper.

It follows that we should expect more fundamental theories of physics to exhibit fewer and fewer global symmetries. This runs contrary to the received wisdom of grand unification in which larger global symmetry groups accompany the larger gauge groups. On the other hand, it may be shown that general relativity has no global symmetries and hence is something that the theory has in its favour (ibid., p. 150).

2.2 Physics recounted relationally

With the fervour of the convert, one may retell the history of physics as a series of relational refinements to previous paradigms in which background structure is eliminated. Smolin suggests that doing so may better enable us to ascertain the process of reasoning by which arbitrary structure was identified and hence aid further progress.

Aristotlean dynamics is first order in time because velocity and rest have absolute meanings such that a force induces a velocity. More abstractly we may say that given a configuration space, $\mathcal{C}$, the dynamics is given by a fixed vector field on $\mathcal{C}$, $v^a[x]$, dependent upon some variable x^a,

$$\frac{dx^a}{dt} = v^a[x(t)]. \tag{2.1}$$

Newton defined velocity with respect to an absolute frame of reference centred on the Sun and in doing so made velocity relative, thereby unfreezing the background structure of absolute velocity. The vector field $v^a(x)$, frozen in Aristotle, is hence dynamical and itself evolves in time,

$$\frac{d^2x^a(t)}{dt^2} = G\left[x(t), \frac{dx(t)}{dt}\right], \tag{2.2}$$

such that we have dynamics that is second order in time, accelerations taking as their arguments positions and velocities (or momenta).

Stationed somewhere on the road from Newton to Einstein we find Mach from whom we find a quite explicitly relational picture, in which "the response to an acceleration or rotation of a body, measured against 'the fixed stars' must be the same as if that body were fixed and the universe accelerated or rotated in the opposite sense", (ibid., p. 153).

Once the laws of motion are second-order in time we must compare velocity vectors at different times, so we need to be able to compare vectors at different points in spacetime. Such a comparison means the two vectors must be parallel transported to the same point which requires, in general, a *connection.* Without a connection we must presuppose a flat, fixed background spacetime and thereby violate background independence. Hence a connection is a manifestation of background independence.

General relativity can be made an even more relational theory of spacetime if we choose to restrict it to compact spatial slices.[5] This restriction is necessary for two reasons. The first is that a relational theory of a non-compact manifold would require boundary conditions of some kind and this implies there is some non-dynamical fixed region outside the dynamical region of study. In doing so we would be reintroducing background dependency such that the theory would no longer be fully relational. Hence, compactness.

The second reason, for the restriction to spatial slices, is to build in the causal structure at the heart of temporal relationalism. These slices are essentially the spatial hypersurfaces of the ADM formalism we saw in section 1.3. The idea here is that if we understand general relativity relationally it is a theory of events which are equivalence classes of points on the manifold under the action of Diff$(\mathcal{M})$. Then, the information characterising a given physical spacetime, $\{\mathcal{M}, g_{\mu\nu}, f\}$, may be specified completely by the causal structure (typified by the lightcone structure, specifying the causal order of events) and the measure (which determines spacetime volume (Smolin 2006, p. 206), much as we saw when discussing Causal Set theory, section 1.4). Hence by restricting to compact spatial slices we make general relativity into a *temporally* relational theory.

The restriction to spatial slices is also the fork in the road for temporal and timeless relationists. For, though both parties would agree that time (and space, and all other 'contingent' variables) are relational in character, they would disagree about whether time is fundamental or emergent, and

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[5] In order to be *fully* relational we would also need to specify topology, differential structure and dimension on top of the present considerations (Smolin 2006, p. 207).

a preferred slicing of spacetime amounts to designating that time is fundamental. If time is emergent, the full 4-dimensional diffeomorphism group may be preserved. But if time is fundamental it must be separated in some way from space. By choosing spatially compact *feuilles* we are reducing from the full diffeomorphism group, Diff($\mathcal{M}$), to a 3-dimensional diffeomorphism group, Diff(Σ), that mods out elements of the equivalence class of spatial hypersurfaces.

Throughout *temporal relationalism* Smolin is keen to demonstrate that the principles he advocates are realised in theoretical models of various kinds despite arguing for them *ab initio.* If one advocates a reformulation of general relativity as just outlined there's a model for that: shape dynamics. Relational approaches to quantum gravity that are background independent? Try causal set models, causal dynamical triangulations, group field theory, and loop quantum gravity both in Hamiltonian and path integral/spin foam formulations. Relational approaches to quantum gravity that are background dependent? There's perturbative string theory, asymptotic safety and other perturbative approaches. And so on. I mention these for completeness but will not develop them further. One relational model is worth mentioning more fully as it underpins Smolin's real ensemble formulation of quantum mechanics.

A relational hidden variables theory is one that centres entanglement as the key relational feature of quantum mechanics from which a completion of the theory can arise. As entanglement means that a pair of quantum systems can exhibit features as a pair that they do not exhibit as individual systems, these features may be described as relational. "A completely relational description of quantum systems," Smolin says, "would be one that constructed all its properties from such shared properties" (Smolin 2020, p. 155). If a degree of freedom pertaining to their shared property is then assigned to each pair of ordinary degrees of freedom, one could arrange these additional degrees of freedom as a matrix or graph and form the basis of a relational hidden variables model upon which dynamics can be defined. If our pair of systems are a pair of electrons, each with a spin degree of freedom, the additional degree of freedom describes their nonlocal entanglement, such that upon discovering the spin of one the other is determined.

2.3 The fundamentals and their consequences

So far we've explored the relational part of Smolin's project, but we've also stated that time, energy and momentum are chosen to be fundamental. We now turn to the consequences of these choices.

A contemporary history of time

I think its safe to say that we *experience* the flow and passage of time. Yet most physicists and philosophers don't believe the passage of time is a physical phenomenon. Instead, they believe it is an illusion of human experience. Time is a dimension of spacetime, after all. As we exist in space, so we exist in time. We do not think of space coming into being as we move into it, neither should we believe time comes into being as we move into it. Kensington is just as real as Wednesday morning. A so-called *block universe* is considered by many to be entailed by general relativity, in which events are points and histories are worldlines in the 4-dimensional block. This view about time is often called *eternalism.*

We can point to various physicists to corroborate this point,[6] from moderns Paul Davies – "the flow of time is an illusion" (2013) – and Sean Carroll – "modern physics suggests that we can look at the entire history of the universe as a single four-dimensional thing" (2011) – to luminaries Hermann Weyl

> "the objective world simply *is*, it does not *happen.* Only to the gaze of my consciousness, crawling upward along the life line of my body, does a section of this world come to life as a fleeting image in space which continuously changes in time" (1949, p. 116),

and Albert Einstein himself

> "People like us, who believe in physics, know that the distinction between past, present and future is only a stubbornly persistent illusion." (1955)

Thick presentism: how soon is now?

Smolin disagrees. Smolin argues that we should treat time and causation as fundamental and irreducible, and the fact that our best physical theories say otherwise, suggesting that the present moment is an illusion and physics is fundamentally time reversible, demonstrates a fault with those theories. More fool them. Our experience is innately temporal, inherently structured by time, and central to that experience is an objective present. Properly described, Smolin says, the present moment is present at the deepest and most fundamental level of description of the physical universe. The reason

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[6] Several of these are helpfully collected and shamelessly borrowed from (Dowker 2020).

our experience is structured as a flow of such moments from the future to the past is that this is the fundamental nature of things. Time is causative, it generates novel events from present ones (Smolin 2020, p. 144). This present moment is objective and universal although events may be causally related in what Smolin calls the *thick* present, bringing into the present novel events from ones already present. An event falls out of this thick present once it has "given rise to all the future events it is ever going to, it has used up its whole capability to influence the future" (ibid., p. 157).

Furthermore, neither the past nor the future are real, Smolin argues. The unreality of the future seems intuitive if we deny the block universe view – future events are as yet uncaused, ungenerated by present events, the future is a book that is yet unwritten, to borrow a metaphor. Smolin also denies the past is real: "the past was real and is no longer real" (ibid., p. 157). In a footnote Smolin writes "an event is real and present by virtue of its capacity to directly influence the future," (ibid., Fn 4). Therefore it seems as though real and present are equated in Smolin's view.

Denying the past is real distinguishes Smolin's view as presentist rather than *possiblist*. This is often known as the growing block view, in which the present continually brings into being events that fall into the past but continue to be real. All three views are represented in Figure 2.1.

Presentism is generally understood to be incompatible with the special theory of relativity. In special relativity, whether two spacelike separated events are simultaneous or not depends upon the inertial frame of the observer of those events. Thus two observers with non-zero relative velocity to one another may disagree about the chronology of a pair of events. This would seem incompatible with an objective present which would seem to require a preferred frame to pick out the present, thereby making simultaneity absolute. We will see in section 2.4 that Smolin attempts to avoid this charge using doubly special relativity.

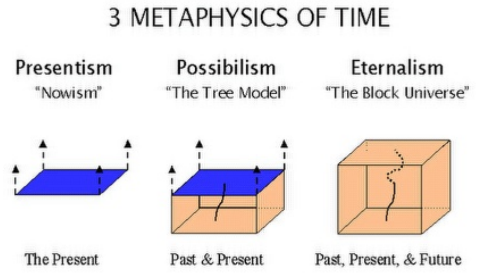

Figure 2.1: Three views on the metaphysics of time. From (Savitt 2021).

Energy and momentum

Energy and momentum, too, are relational and fundamental in Smolin's account. Their conservation laws are then "posited *ab initio*" (Smolin 2020, p. 161), or we might say that the laws themselves are taken to be irreducible and fundamental. Furthermore, Noether's theorem tells us spacetime translation symmetry gives rise to these conservation laws. Therefore, if they are fundamental then it looks as if the conservation of these laws may imply the emergence of continuum spacetime, in some sort of inversion of Noether's theorem.

Although Smolin does not make this argument, I would go further to suggest there is something inherently temporal about energy and momentum. In some sense once it has been proposed that time is fundamental it seems logical that energy and momentum are fundamental, too. For energy in physics is the ability of something to do work, and doing work is a time-y sort of thing. [7] Or, to phrase it negatively, energy and doing work do not makes sense atemporally. Energy is the property of a moment in time, a store of potentiality that becomes actuality by the passage of time. If time marches unstoppably on, if time causes continuously the generation of novel from present events then work is continuously being done and it seems as though fundamental time entails fundamental energy and momentum.

Nonetheless, this is a far from self-evident point and Smolin is more interested to demonstrate via models that *if* one chooses time, causation, energy and momentum to be fundamental, *then* one may recover spacetime, emergently.

Emergent space: how near is here?

Space is relational and emergent, like spacetime. Smolin argues this is for two reasons. First, this is reflective of the status of space in the prominent approaches to quantum gravity Smolin lists and are mentioned in section 2.2, background independent (and background dependent): spatial relations (or spatial geometry) are emergent in those theories. Therefore an account in which space is emergent is in keeping with other programmes in quantum gravity. Second, he argues there are general indications that space and time cannot both be fundamental and this is for two further reasons.

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[7] To digress etymologically for a moment, the English word 'energy' ultimately derives from the Greek *energeia* (ενέργεια) meaning 'activity' or 'actuality', the latter translation specific to Aristotelian philosophy – Aristotle himself having coined the word *energeia* (Olshewsky 1997). This is derived in turn from *ergon* (εργον) itself meaning 'work'. So work, or 'being-at-work' as *energeia* is sometimes translated, is inextricably linked to the concept of energy.

First, models of classical spacetime from which quantum geometry emerges dynamically have either fixed boundary conditions, or assume a temporal or causal order. So these take either space *or* time to be fundamental but not both. Second, Bohmian mechanics and dynamical collapse models both require a preferred position basis in Hilbert space (respectively the frame that picks out the positions of the particles or the frame in which the state collapses spontaneously) rather than taking all complete orthonormal bases to be equal and are therefore in conflict with the relativity of simultaneity in special relativity. And this may be taken to imply there should be a global temporal order picking out these preferred frames, moment by moment. So Smolin takes the need to have a preferred position basis as reflective of the fact that time is fundamental and space is emergent.

In summary, temporal relationalism takes space to be emergent because there are reasons to believe only one of space and time are fundamental and having chosen time to be fundamental this means space should be emergent; and because models of quantum gravity all tend to take space to be emergent. It then remains to be shown how space and spacetime are emergent from some considerations of time, energy and momentum.

However, it would seem as though simultaneity cannot be relative at *any* level at which there is an objective present. Smolin claims that the primacy of time avoids the charge of incompatibility with the relativity of simultaneity in special relativity because Lorentz invariance is a symmetry only at the emergent level, “which comes into effect only when space emerges” but not at the level of the fundamental laws that “govern a domain of events with causal relations, but no space” (Smolin 2020, p. 145). But I’m not sure that makes sense. For, if relativity of simultaneity is totally incompatible with presentism, this implies presentism is false at the emergent level where Lorentz symmetry holds. But that is incompatible with Smolin’s account which has a global present moment, from top to bottom. So it seems as though there are three possible options, if we want to maintain that time is fundamental. Either an account in which presentism disappears at the emergent level is needed, somewhat undermining the thrust of Smolin’s account; or some reason must be proposed as to why the two are not in fact incompatible; or we must give up or modify the relativity of simultaneity and Lorentz invariance as usually understood.

Smolin chooses option number three. Enter, doubly special relativity and relative locality.

2.4 Doubly special relativity and relative locality

It is expected that the Planck length and energy are the scale at which quantum gravitational effects will arise. But the length contraction predicted by standard, singly special relativity implies different inertial observers may disagree over the scale at which these phenomena arise (Magueijo and Smolin 2002, p. 1). Therefore, we might choose to modify special relativity so that all observers agree upon the Planck energy, E_p, by making it an invariant maximum energy in addition to the invariant maximum velocity, c, already present in singly special relativity.[8] This theory, with an invariant maximum energy and velocity is known as doubly, or deformed, special relativity.

In practice, this invariant energy scale is realised by modifying the geometry of momentum space by using a non-linear representation of the Lorentz group that gives a non-associative composition rule for momenta (Freidel and Smolin 2011, p. 4). As we want also to show that space and spacetime are emergent from fundamental time, energy and momentum, momentum space would seem to be a fitting arena from which spacetime may emerge. Finally, if space and spacetime are themselves emergent, so must locality be. And if we wish to preserve the relativity of inertial frames when adding an invariant energy scale to special relativity, we will see that locality must become relative, too. We begin with a sketch of the emergence of spacetime from momentum space.[9]

Spacetime emergence

We may describe the dynamics of a series of interacting particles by via an action by considering separately the free and interacting parts according to

$$S_{\text{tot}} \quad = \sum_{\text{worldlines, } I} S^I_{\text{free}} \quad + \sum_{\text{interaction, } \alpha} S^\alpha_{\text{int}}. \tag{2.3}$$

Then the free action is

$$S^I_{\text{free}} = \int ds \left(x^a_I \dot{p}^I_a + \mathcal{N}_I \mathcal{C}^I(p^I) \right), \tag{2.4}$$

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[8] We may take this maximum energy to be E_p albeit it is proposed that the actual scale is to be determined experimentally. Furthermore, in the original formulation of doubly special relativity a minimum (Planck-)length rather than energy is used (Amelino-Camelia 2002), but we will focus on the maximum energy version, first presented in (Magueijo and Smolin 2002).

[9] The following is an amalgamation of the presentations in (Freidel and Smolin 2011), (Smolin 2020) and (Amelino-Camelia et al. 2011).

where $\mathcal{N}$ is a Lagrange multiplier by which the mass-shell condition is imposed,

$$\mathcal{C} = \eta^{ab} p_a p_b + m^2 = 0. \tag{2.5}$$

Here m is the mass of each particle and the integration is from the initial to final event on each worldline. Note the system so described is in momentum space, with x^a appearing as conjugate to the coordinate in momentum space, p_a, in order to formulate canonical dynamics. Therefore, x^a lives in the cotangent space of the point p_a in momentum space, as "a momentum to the momentum" to use slightly clunky phrasing (Smolin 2020, p. 162).

Then, the interaction part of the action imposes energy-momentum conservation at interaction vertices by a further Lagrange multiplier, z^a, at each vertex according to

$$S^{\alpha}_{\text{int}} = -\mathcal{P}^{(\alpha)}_a z^a_{(\alpha)}, \tag{2.6}$$

where the minus sign results from the Lorentzian signature. This energy-momentum conservation means that for a vertex where particles $A+B \to C$ we get

$$\mathcal{P}_a = p^C_a(0) - p^A_a(1) - p^B_a(1) = 0, \tag{2.7}$$

where the arguments (1) and (0) reflect respectively the end and beginning of the corresponding worldlines. Due to their enforcing a conservation law, $\mathcal{P}_a = 0$, the z_a at each interaction vertex live in the cotangent space at the origin of momentum space, $p_a = 0$.

Varying the free action gives two equations of motion,

$$\dot{p}^I_a = 0 \tag{2.8}$$

$$\dot{x}^a_I = 2\eta^{ab} p_b, \tag{2.9}$$

further to the mass-shell condition, Equation 2.5, and the conservation law for the vertex, Equation 2.7.

Now, the crucial point for our story of spacetime emergence is that at the ends of the worldlines the momenta $p_a(0)$ appear in both the free and interaction parts of the action such that we have

$$x^a_I(0) = z^a, \tag{2.10}$$

and hence *all the worldlines meet at a single point, a single event,* z_a, and this arises dynamically from the equations of motion in momentum space. To restate this, we begin with a variable that is conjugate to and dependent upon the momentum, $x^a(p_a)$, living as it does in the cotangent space to a point p_a in momentum space, and we recover dynamically, via the equations of motion, the coincidence of the variable x^a with an interaction in such a way that locality emerges and, we might say, spacetime functionally emerges, too.

Doubly special relativity, so special they relativised it twice

We must now modify the geometry of momentum space that we have assumed is flat thus far. Explicitly this assumption appeared in the mass-shell condition, Equation 2.5, via the (inverse) metric η^{ab}. Implicitly it appeared in the conservation law, Equation 2.7, where the momenta are composed linearly. Because this modification must be done in such a way as to preserve the relativity of inertial frames, it turns out we must still have a representation of the Lorentz group as this is the only group with the right structure. Hence, the flat geometry will be modified using a non-linear representation of the Lorentz group.

Changing the metric will change how the geodesic distance from each point, p_a, to the origin comes into the mass-shell constraint, replacing $\eta^{ab}p_a p_b = |p|^2$ with the more general $D^2(p)$. On the other hand, if the geometry of momentum space is not flat we no longer have a vector space and we need to introduce a connection in order to parallel transport momenta such that they can be compared, which means that the composition law will generally be non-linear. We may denote a non-linear combination rule by

$$(p,q) \to p'_a = (p \oplus q)_a, \tag{2.11}$$

with inverse $\ominus$ such that $(\ominus p) \oplus q = q \oplus (\ominus p) = 0$. Then Equation 2.7 may be reformulated as

$$\mathcal{P}_a = \big((p^C \oplus (\ominus p^A)) \oplus (\ominus p^B)\big)_a = 0. \tag{2.12}$$

While this is a mess of brackets, having not assumed associativity holds for the non-linear combination rule these are there for precision.

Then it may be shown that this combination rule gives a means of parallel transport in momentum space such that

$$p_a \oplus ddq_a = p_a + U(p)_a^b dq_b = p_a + dq_a + \Gamma_a^{bc} p_b \, dq_c + \dots, \tag{2.13}$$

where $U(p)_a^b$ indicates the parallel transport operator that gives the connection when expanded infinitessimally to first order. The connection is evaluated at the origin.

Finally, we must update the equations of motion and this will affect Equation 2.10 in particular which becomes

$$x_I^a(0) = z^b (\mathcal{W}_{x_I})_b^a, \quad \text{where} \quad (\mathcal{W}_{x_I})_b^a = \pm \frac{\delta \mathcal{P}_b}{\delta p_a^I}, \tag{2.14}$$

where the plus or minus indicates outgoing or ingoing particles respectively. This gives the *relative locality relations* (Freidel and Smolin 2011, p. 7). What do they mean?

Spacetime and locality emerge from interactions in momentum space, from the coincidence of worldline ends, x^a, and interaction events, z^a. This coincidence depends upon the way momenta are composed in the conservation equation, $\mathcal{P}_a$, which is varied with respect to momenta. In turn, this is because momenta must be parallel transported to be compared and the connection enabling this parallel transport arises from the momenta composition rule. In situations where the momenta are composed linearly the connection is trivial, x^a and z^a coincide, and $(\mathcal{W}_{x_I})^a_b = 1$. However, when the momenta are *not* composed linearly the connection is *non*-trivial and the variation of the conservation equation with respect to the momenta will give a linear transformation of z^a away from x^a.

Taking a momentary aside, given that in this model spacetime emerges from the cotangent spaces of different points in momentum space that may be compared using the technology of connections and parallel transport, the natural arena from which to describe this emergent spacetime is the cotangent bundle over momentum space. Fortunately the cotangent bundle over momentum space is just phase space. We note, however, that phase space is defined usually as the cotangent bundle over configuration space rather than momentum space, though it is mathematically consistent to take the bundle over momentum space instead because position and momentum are conjugate variables, in the usual sense that they are the Fourier transform of one another, giving rise to uncertainty relations and so on. Indeed, one of the implicit assumptions at the heart of finding spacetime within momentum space is that this mathematical consistency justifies interchanging the two conjugate variables despite their apparent physical differences. I question this assumption in section 3.2.

We recover the previous case, Equation 2.10, either when the momentum composition is linear and momentum space is flat – in which case $\mathcal{W}^a_b = \delta^a_b$ – or in those situations where the momenta are small – for which $\mathcal{W}^a_b \approx \delta^a_b$. Therefore, according to doubly special relativity, "the usual notion of locality is a consequence of the assumption that energy momentum conservation is linear," (ibid., p. 7).

As a consequence of this, it is predicted that an event that appears locally as the absorption of a photon by an atom will appear to a distant observer, instead, as the photon being absorbed while it is still some distance from the atom. And this distance, let's call it x, will depend upon the energy of the photon, let's call it E, proportional to the Planck energy, E_p, that is held fixed in this doubly special relativity. For an observer a distance d

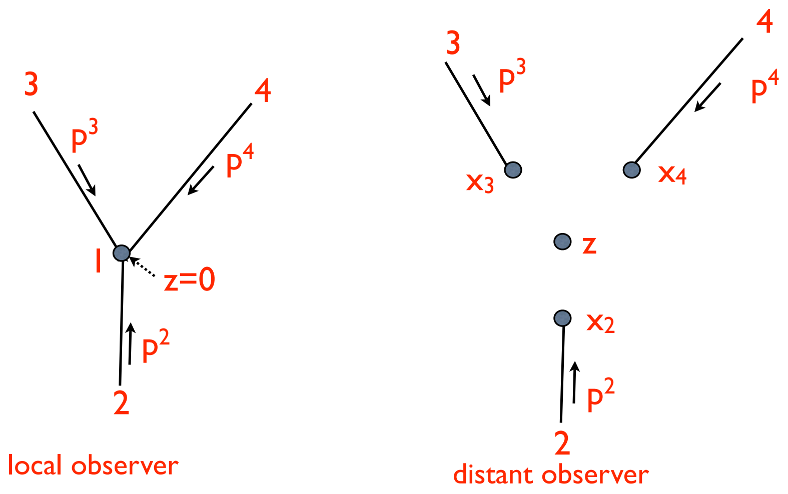

Figure 2.2: How an absorption event in emergent spacetime appears to a local observer and a distant observer. Reproduced from (Freidel and Smolin 2011).

from the absorption it will appear that the absorption happens when the photon is still a distance from the interaction vertex, as viewed locally, of approximately,

$$x = d\,\frac{E}{E_p}. \tag{2.15}$$

This is represented graphically in the case of a scattering event in Figure 2.2. It is predicted this will have observational consequences.

If two photons are emitted simultaneously, according to a local observer, in a gamma-ray burst at a distance d from Earth, then their arrival times will differ proportional to the difference in energy of the two photons. This is given by, reinstating c for a moment, (Smolin 2020, p. 165),

$$\Delta\, t = \frac{\Delta x}{c} = \frac{d}{c}\,\frac{\Delta E}{E_p}. \tag{2.16}$$

Therefore, it should be possible to detect a difference in arrival times.

So, relative locality arises when we set the Planck energy to be a fixed quantity as this causes deformation of momentum space away from the standard, linear representation of the Lorentz group and the effects of this deformation depend upon the distance of an observer's reference frame and the energy of the means by which that observer observes distant events. Because spacetime and locality emerge from momentum space, events that appear to be local in a nearby reference frame come apart at large distances, and this effect is stronger when the constituents of the event are higher. We note, however, it is possible that these effects may be observed at energies far below the Planck scale if the distance, d, is great enough.

As an aid to intuition we might view relative locality to be something like chromatic aberration, at the level of events. Chromatic aberration indicates a failure of a lens to focus all colours at the same point such that the focal point of light of different frequencies, hence energies, are displaced relative to one another. In the case of relative locality, the components of an interaction event are displaced relative to one another, indicating a failure of our attempt to construct a 4-dimensional spacetime from the underlying phase space.

Smolin argues that in relativising simultaneity, special relativity makes locality absolute: "if one observer sees two events to coincide at the same time and place, that is the way all observers see it," (Smolin 2020, p. 165). Special relativity forces us to give up an absolute, *velocity-independent* notion of space and replace it, instead, with *velocity-dependent* planes of simultaneity in 4-dimensional spacetime but in which locality is absolute. From special relativity, that is, we come to understand that space is a useful fiction by which we construct the world around us, but must be given up to understand the universe more fundamentally. In turn, doubly special relativity forces us to give up an absolute, *energy-independent* notion of spacetime and replace it, instead, with *energy-dependent* phase space in which relativity is local. In other words, we live in 3-dimensional space if we don't look *too* closely, 4-dimensional spacetime if we look *more* closely, but if we look *even closer still* we live in phase space from which spacetime is emergent (Freidel and Smolin 2011, p. 19).

So, I take Smolin to mean we should treat relativity of simultaneity as approximate at best. Planes of simultaneity only arise at an emergent level in which we must also understand that the locality of events is energy dependent. And any situation in which the temporal order of events is disputed will necessarily involve observers with large relative momenta to one another which will cause a coming-apart of locality according to doubly special relativity. That is to say, the fact that we think simultaneity is relative is, ultimately, *because we construct locality in an ineffective way* that generalises our experience at *low* energies to be true at all energies. Therefore, relativity of simultaneity is only approximately true. This is the best sense I can make of Smolin's argument here, because he is not explicit on this point in his papers.

So, in summary, if time, energy and momentum are fundamental but space and spacetime emergent, we may sensibly look for space and spacetime within momentum space. We have seen a sketch of how this is supposed to work. Then, we expect that there is some energy scale at which quantum gravitational phenomena arise and, if energy is fundamental, we should expect this energy scale to be independent of special relativistic effects such as length contraction. We may then fix an energy scale (the Planck energy for the sake of argument but ultimately an energy scale to be determined by experiment) by modifying the geometry of momentum space. Doing so forces us to give up absolute locality in favour of relative energy dependent locality and this suggests that the relativity of simultaneity that arises from a linear representation of the Lorentz group is true only approximately, at low energies or in frames local to interactions. The fact that we think simultaneity is relative is because we construct locality ineffectively.

Finally, we note that in making novel predictions and giving rise to observational consequences, doubly special relativity is theoretically testable. This should certainly be a mark in its favour.

However, the momentum space from which space, spacetime and locality emerge is continuous. Curved, deformed, but continuous. We finish the exposition of temporal relationalism by looking at the relationalist substrata from which everything else is supposed to arise: *similarity in the space of views.*

2.5 Points of view

According to Smolin's proposed similarity of views program, spatial position is dependent upon position in an underlying fundamental network of relations known as the space of views. We might say that position in space *supervenes* on this network of relationships, where supervenience is a relationship of dependence in which a set of properties A supervenes on a set of properties B just in the case where "no two things can differ with respect to A-properties without also differing with respect to their B-properties" (McLaughlin and Bennett 2021, §0). That is, any difference in position space entails a difference in the space of views but a difference in the space of views does not entail a difference in position space. This network of relationships resembles ontologically the network of sparse relative events and their perspectives as presented in section 1.5 regarding relational quantum mechanics but, again, the difference is one of temporality. On Smolin's view, "events do not exist, they happen" (Smolin 2022, p. 7).

This framework may be realised graphically by nodes, with those nodes involved in a relationship joined by an edge, and those edges labelling the properties of the relationship they represent. A metric on the graph, g_{IJ}, counts the minimum number of steps required to get from I to J, going node to node by moving along edges. Each node has a *view* of the system in which it is contained and this view "represents the knowledge it may have of the rest of the universe; all such knowledge is a function of the relationships that tie the object to the rest of the system," (Smolin 2020, p. 166).

We may describe such a view by a series of increasingly larger *neighbourhoods.* The first neighbourhood of a node J is the set of nodes surrounding J that are accessible by one step on the graph, along with the edges joining such nodes. This scales cumulatively such that the nth neighbourhood of J, $\mathcal{N}_J^n$, consists of all nodes K that are reachable by n steps from J or fewer. Expressed using the metric on the graph, this is $g_{JK} \leq n$. The neighbourhoods of J may be represented graphically by moving J to the origin of the graph. Finally, the view of an object is represented by the sets of neighbourhoods of a node and their embedding maps into each other (ibid., p. 166),

$$V_J = \{\mathcal{N}_J^0, \mathcal{N}_J^1, \ldots, \mathcal{N}_J^0, \ldots\}. \tag{2.17}$$

According to this programme, distance in space is emergent and imprecise while *similarity and difference of views is fundamental.* If two objects are described as local to each other we generally understand this to mean they are close together in space and we might say they have a propensity to interact, with greater frequency and strength the closer those objects are in space.[10] These interactions form the bonds of the fundamental network of relationships in the space of views. There would therefore appear to be some approximate relationship between proximity in the space of views and objects in space, or events in spacetime. In the latter context, the "view of an event is defined to be the information it receives from its causal past" (ibid., p. 169).

Smolin suggests that "distance in spacetime is only a proxy for difference of views," and "the locality that matters fundamentally is the distance in the space of views," (ibid., p. 167). At the level of events we may appeal to human experience, as Smolin does, to make this point more clearly. My view of the stars on a clear night will be very similar to those of a friend standing beside me, but markedly different than those of a friend on the other side of the world – who will see no stars, the Sun excepted – or a friend in the same spot a couple of hours later. As the friend beside me and I are interacting with almost exactly the same sphere of incident radiation,

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[10] I'm varying slightly from Smolin's presentation, here, which is that "the usual idea of locality is that two objects will interact more often, or more strongly, the closer they are in space" (Smolin 2020, p. 166). Arguably considerations of locality arise as a proxy for action not-at-a-distance, from a wish that interactions are mediated locally, not that locality *implies* interaction. One could make such an argument, but it's hardly the *usual* idea of locality.

receiving almost the same snapshot of the history of the universe moment by moment, the views corresponding to these events are going to be very close together in the space of views. We might write this as

$$d(e,f) \approx g(V_e, V_f), \tag{2.18}$$

where $d(e,f) = \sqrt{|e-f|^2}$ signifies spatiotemporal distance and $g(V_e, V_f)$ is a metric on the space of views (ibid., p. 166). This is one sense in which two events can have similar views: "they are events in the history of two macroscopic bodies and are close to each other in spacetime" (ibid., p. 167). I denote this sense $views_1$.

The second sense is that two events have similar views if they "arise in the histories of two atoms or molecules" (ibid., p. 167). I'll call this $views_2$. At this point in (Smolin 2020), Smolin starts talking about degrees of freedom in a way that seems unmotivated and unexplained. However, in *Views, variety and Celestial Spheres* (2022, p. 5) Smolin writes "by a view, I mean the information about the causal past of an event, which is coded in degrees of freedom at the event." And he tries to make this more precise, advocating the expansion from featureless points to two-spheres (ibid., p. 5), such that information can be received in a manner akin to the flux across the surface of that two-sphere. Therefore, by $views_2$ this is what I think he means. Atoms and molecules have few degrees of freedom. Given the view of an event relates to information it receives from its causal past, having few degrees of freedom means atoms and molecules have few ways for this information to be stored (essentially vibrational, rotational and translational modes). Having few ways to store information from its causal past means there are few ways for atoms and molecules to interact and hence their space of views will be small. On the other hand there are inordinate numbers of such atoms and molecules in the universe which have those same degrees of freedom. Therefore similar atoms and molecules will have similar views so may have very many neighbour in the space of views such that their space of views will be very large! Smolin calls these neighbours and neighbourhoods "ensembles of microscopic systems."

Furthermore, though these atoms and molecules may be very close in the space of views, and as such are more likely to interact, they may be separated by great distances in the emergent spatiotemporal aspect of the universe. This provides a mechanism by which interactions non-local in spacetime that are as a result of 'local' interactions in the space of views and, hence, offers a means to account for the nonlocality of quantum mechanics. In that case, Smolin writes, "the peculiarities of quantum mechanics arises from the fact that [the quantum state] is a course-grained description of" ensembles of particles in the space of views (Smolin 2020, p. 167). This is Smolin's *real ensemble formulation of quantum mechanics*, set out in (Smolin 2018) and other papers. This is the relational hidden-variables completion of quantum mechanics promised in section 2.2.

A measure for similarity of pairs of views is given by *distinctiveness*. The simplest way to define distinctiveness of a pair of two nodes, J and K, is as inversely proportional to the number of steps needed to describe a neighbourhood for each node, $\mathcal{N}_J^n$ and $\mathcal{N}_K^n$, such that those neighbourhoods are not isomorphic under all maps that preserve the origin,

$$\mathcal{D}_{JK} = \frac{1}{n_{JK}^p}, \tag{2.19}$$

where p is some fixed power. In this way it will require a greater number of steps to reach neighbourhoods that are not isomorphic if the two views are very similar, or indistinct.

This can then be scaled to measure the *variety* of sets of relations as a sum of the pair-wise disctinctiveness of the set,

$$\mathcal{V} = \frac{1}{N^2} \sum_{J \neq K} \mathcal{D}_{JK}. \tag{2.20}$$

The dynamics of the system seeks to maximise the variety of the system in question. This, Smolin writes, then yields exactly Bohm's quantum potential (Smolin 2016), and "how Schrödinger quantum mechanics emerges from a dynamics that involves comparisons among similar systems" (Smolin 2020, p. 167). Therefore, it would seem as though the success or failure of temporal relationalism solving the measurement problem ultimately rests upon Bohmian mechanics ability to do so.

Linking back to the discussion in section 2.1, we note here that Smolin takes the complete and unique characterisation of events by their view to be an instantiation of Leibniz's principle of the identity of the indiscernible. The principle of the identity of the indiscernible "is implemented dynamically via an interaction that drives all pairs of views to differ," (Smolin 2018, p. 4).

Finally, Smolin then proceeds to demonstrate how this abstract framework can be realised as an energetic causal set model and, in other papers (Smolin 2018; Smolin 2022) he outlines how a *relativistic causal theory of views* can function as a discretised version of the relative locality construction in momentum space or products of momentum spaces from which space and spacetime may emerge dynamically, as set out above, as a coarse-graining of the fundamental causal view structure.

2.6 State of play

We finish this chapter by recounting where we've got to before coming on to some criticisms of the project in the chapter 3. We start at the beginning, with the principles upon which the project is based.

Principles

- There are no facts about the world about which no explanation can be given. Progress in physics should be a process of removing arbitrary elements and making explicable what was previously inexplicable, unexplained, and considered to be necessary. (*Increasingly sufficient reason.*)
- All contingent variables are relational in nature. These include time, space, energy and momentum. (*Relationality of space and time.*)
- Physical theories should be increasingly background independent by unfreezing background elements, and bringing into the theory all elements that it must be supposed are external for the theory to work. (*Increased background independence.*)
  - General relativity makes background spacetime dynamical and by doing so exemplifies the making independent of background structure.
- Theories must be causally complete in the sense that all events are traced back to previous events that are within the same universe. (*Causal completeness.*)
- All objects act reciprocally. (*Reciprocity.*)
- Indiscernible objects are identical. (*Identity of the indiscernible.*)

Fundamentals

Then a number of choices are made as to what is fundamental and what emergent:

- Time is fundamental and irreducible in its role as the generator of novel events from those in the thick present.
- The present moment exists objectively and universally. It is a "thick" present in which events may be causally connected.

- The past was real but is no longer real. The future has yet to become real.
- Energy and momentum are irreducible, as are their conservation.
- Space and spacetime are emergent.

Realisation

Finally, these principles and choices are realised in various models. Working backwards from the end:

- At the fundamental level is a set of causal of events on momentum space that are linked by shared events in their causal pasts. The information received from the causal past of each event constitutes the *view* of that event.
- Views are the information an event receives from its causal past.
- Space, spacetime and locality emerge dynamically from this network of causal views in interactions.
- If we add to special relativity a fundamental maximum energy scale to complement the maximum velocity this causes a deformation of momentum space via a non-linear representation of the Lorentz group in such a way that locality becomes relativised.
- If we look closer at the apparently 3-dimensional spatial world of experience we realise it is actually 4-dimensional spacetime and simultaneity becomes relativised in giving up this absolute space. If we look closer still 4-dimensional spacetime is actually emergent as the cotangent bundle over momentum space and locality becomes relativised in giving up this absolute spacetime.
- Locality in spacetime supervenes upon similarity of view in the fundamental network of causal views.
- Events with similar views, hence proximate in the fundamental causal network, may interact in a way that appears non-local in emergent spacetime.
- At a certain level of coarse-graining of the ensembles of particles in the space of views we recover quantum mechanics, emergently. This is a particular realisation of the relational hidden-variables theory described in section 2.2.

Finally, we note that ultimately solves the measurement problem ultimately via Bohmian mechanics.

Chapter 3

Discussion

Temporal relationalism is a manifesto of sorts, a summary of an almost 20 year research programme that is overtly principled, with those principles arising as subsidiaries of Leibniz's principle of sufficient reason which Smolin claims is a methodological guide rather than metaphysical constraint. Nothing about the world should be taken as a given; if nothing should be taken as a given, all contingent variables should be defined by their relation to one another; if all contingent variables should be defined by their relation to one another, we better not have any fixed, nondynamical background structure that is external to the system; therefore, we should remove fixed, external background structure in order to make progress in physics. In a sense, all principles lead to the principle of increased background independence. I take this to be the central principle underlying Smolin's project.

The principle of increased background independence has several problems, though, that make it unsuitable as a methodological principle but also unsuitable as a principle from which to build the temporal relationalism project in particular. It is unsuitable to use a methodological principle because there is no theory independent formulation of what background independence means. And it is unsuitable as a principle from which to build the project of temporal relationalism because, as I will argue, a theory in which time was not fundamental would be more background independent than temporal relationalism.

Next, I will question the extent to which momentum can be truly considered non spatial which would seem necessary for the picture of spacetime emergence Smolin presents, although I will argue that understanding spacetime functionally, to be whatever "serves to define the structure of inertial frames" (Knox 2019, p. 122), makes sense of Smolin's account of spacetime emergence. Then, I will argue that in the causal theory of views Smolin is using "similarity of views" to refer to different things without explaining how those things are the same. I suggest these things are in fact not the same and argue that Smolin is using analogously the word "view," to equate human sight with the degrees of freedom of elementary particles in a way that is inadmissible.

Finally, I will suggest Smolin concludes that time must be fundamental on the basis of subjective experience and give reasons for and against the validity of this approach.

3.1 Background independence?

The theory dependence of background independence

Intuitively, we can understand the metric that describes the spacetime involved in a theory to be the background of that theory. On this reading, general relativity exhibits background independence as the metric is a dynamical variable that one solves for and hence there is no fixed, frozen spacetime upon which the theory plays out as is the case with the Minkowski metric in special relativity. This is the notion Smolin has in mind when he writes "nondynamical, fixed structures define a frozen background against which the system we are interested in evolves" (Smolin 2020, p. 148). But if we try to move beyond this intuitive notion, to a definition that is concrete we face problems. Ineed, if we think back to the historical examples of the unpeeling of background dependence in section 2.2 one might argue all of them served as steps on the way to fully dynamical spacetime in general relativity. But then how do they help us move beyond the background independence of general relativity? They would seem to fail to support the usefulness of background independence as something for which to strive in fundamental physical theories.

Furthermore, it does not seem as though a theory-independent definition of background-independence exists. That is: background independence as Smolin describes will be unacceptable to many from differing approaches to quantum gravity, and perhaps some who are sympathetic to the parameters of this project. Indeed, various arguments exist that claim string theory is background independent on their terms, though Smolin disagrees.[1]

For example, in string field theory classical spacetime is emergent from the two-dimensional conformal theory on the strings worldsheet and this arguably, intuitively, may be regarded as exhibiting background independence, albeit there are then questions regarding how the metric on the worldsheet is induced by the metric in the ambient target spacetime. Or, if

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[1] I partially follow here the argument presented in (Weinstein and Rickles 2021, §5.5).

by background independent we are demanding structures to be dynamical and requiring the solution of an equation of motion, then we might point to the dimensionality of spacetime in string theory which would conform to this definition. Indeed, this might imply *greater* background independence than in general relativity where dimensionality is fixed, albeit this dimensionality is the same in all string theoretic models, once it's decided whether supersymmetry is to be imposed or not, and hence does not vary across different models in the way we might expect.

The point here is not that these examples help pin down an independent notion of background independence but, rather, that if different theories mean different things when they refer to background independence then a general edict to increase it lacks clear meaning. Unless there can be defined some theory independent notion of what background independence actually is then it does not appear to be so virtuous a feature of one's theory; proponents of different approaches run the risk of talking past each other, of incommensurability.

Is time a background structure?

As we have seen, Smolin argues that causitive time, as the generator of novel events from present ones, is fundamental and irreducible, and there is an objective, universal thick present moment. But Smolin also defines background structure as something that is nondynamical and fixed. Do time and the thick present then not count as background structure?

It is obviously the case that according to this view time is relational. Certainly there is no absolute time by which others are defined. And one might argue that the *rate* at which time passes may change dynamically, if it is even possible to talk clearly about rates when the variable is time. Nonetheless, is there not a sense in which if time was an emergent structure we would have a more background independent theory? That is, if space and spacetime are emergent then could we not find time, too, at the emergent level, removing "background structure" from the theory in some sense?

The temporal relationalist at this point may argue that two separate issues are being conflated here: background independence is a way of thinking about whether time is relational or absolute, not about whether time is emergent or fundamental. Indeed, Smolin writes elsewhere that "we often take background independent and relational as synonymous" (Smolin 2006, p. 10). But the notion of background independence, and perhaps of relationalism itself, somewhat blurs the two issues. For a timeless relationalism, in Smolin's terms, would posit less "background structure" than one, such as temporal relationalism, in which time is fundamental and the present moment is universal. In a sense, one might argue that the theory becomes less background independent at the moment when we reduce from the full Diff($\mathcal{M}$) group of the manifold to Diff(Σ) as, at that point, we move time into the background. In fact this is exactly what we saw in section 1.5: the advocate of relational quantum mechanics will argue against a universal, objective present because it would violate relationalism; perhaps relationalism in its fullness implies emergence.

The temporal relationalist may respond, further, that I'm misunderstanding what "structure" actually refers to. That may well be the case. If we define narrowly "structure" to mean "spacetime" this is both then of little methodological use in furthering physics and clearly too restrictive a notion to afford any cross-approach agreement and we fall back upon the previous concern about the theory dependence of background independence.

On the other hand, Smolin defines background structure as something against which *a system is evolved in time*. Elsewhere this is rendered "the background consists of presumed entities that *do not change in time*, but which are necessary for the definition of the kinematical quantities and dynamical laws" (Smolin 2006, p.9, emphasis added). So background structure is defined with direct reference to time and evolution. Yet, if background structure is defined as to exclude time, perhaps this could be seen to support the case that temporal relationalism is background independent but, on the other hand, feels somewhat to be cooking the dictionary, to stretch a bookkeeping metaphor.

For these reasons, background independence does not seem so virtuous a feature of temporal relationalism and nor can it be a useful methodological tool in the development of further theories unless its definition is tightened up conceptually. And the point is not to advocate either for alternative string theoretic notions of background independence, or for timeless over temporal relationalism but, rather, to highlight the difficulties faced by any account that tries to underpin such an account with hard principles in the way Smolin attempts to do.

3.2 Momentum spacetime?

Momenta have historically been understood to be something that depend or supervene on position, derivative to position in both the mathematical and non-mathematical senses of that word. Momenta, that is, have been understood to be derivative to spacetime. And this would seem to be the case regardless of whether we're talking about the Lagrangian formalism, as above, or relativistic 4-momentum, or non-relativistic 3-momentum: each relates to the rate of change of position that is velocity $\frac{dx}{dt}$. (Of course, the momentum of a massless particle is slightly more complicated and isn't so directly related to a velocity, but we're still describing the propagation of a wave and, via Planck's constant, end up with something that has the dimensions of position per unit time.) So on the one hand, momentum depends on position in spacetime.

On the other hand, the conjugacy of position and momentum expressed via the Fourier transform, Poisson bracket and Heisenberg algebra mean there is some equivalence between the two. It was perfectly mathematically consistent to construct a Lagrangian in section 2.3 from momentum rather than position, with position entering only as the "momentum to the momentum." And to recover phase space as the cotangent bundle over momentum space rather than configuration space. And all of this is mathematically consistent but, at root, are we really free to choose between position and momentum as if they're on an equal footing? In fact, when we talk about position one might argue we are implicitly referring to spacetime. So, even if we accept that conjugacy draws an equivalence between the two, surely the equivalence is between position *in spacetime* and momentum *in spacetime*?

In fact, momentum space began its life as a *state space* in analytical mechanics, as a space in which the momenta of all components of the system are expressed as a point rather than as many points in a low (usually three) dimensional space as in elementary Newtonian mechanics. And one could presumably run an argument parallel to Smolin's, in which a particle is in configuration space and from that configuration space momentum space emerges and we recover phase space as the cotangent bundle over configuration space but the question would presumably be: what's the point? For in a sense the issue is not whether position or momentum, it's whether spacetime or state space. Smolin's account tells us that spacetime is constructed locally and in an interactive energy-dependent way, so there's a sense in which momentum space is being used quite differently to its original use in analytical mechanics as a state space dependent upon spacetime. Nonetheless, privileging momentum over position and therefore recovering phase space is all well and good, but is spacetime really what we recover according to this construction? In fact, what criteria do we have for identifying whether something is spacetime, or not?

One answer to this question is functionalism about spacetime: spacetime is the the thing that plays the role of spacetime, or, as a slogan "spacetime is as spacetime does" (Lam and Wüthrich 2018, p. 1). But, then, what does spacetime do? Which role or roles are necessary to pick out something functionally as spacetime? The answer proposed by Eleanor Knox in her *spacetime functionalism* account is that "the spacetime role is played by whatever defines a structure of local inertial frames" (Knox 2019, p. 122). On that basis it would seem as though Smolin's account of spacetime emerging from momentum space fits the bill, for maintaining the relativity of inertial frames was an explicit consideration in modifying the geometry of momentum space by using a non-linear representation of the Lorentz group. Of course, in this situation "local" has a non-standard meaning in that locality becomes relative in Smolin's account, as we have seen. But, nonetheless, it would seem true to say that the emergent, interaction dependent inertial frames picked out by temporal relationalism do play the role necessary for it to be considered spacetime, regardless of concerns regarding the previously spatiotemporal character of momentum.

Smolin does not appeal directly to functionalism in making his argument about spacetime emergence, but perhaps that's unsurprising if we follow Daniel Dennett and believe that functionalism is "the idea that handsome is as handsome does, that matter only matters because of what matter can do. Functionalism in this broadest sense is so ubiquitous in science that it is tantamount to a reigning presumption of all of science," (Dennett 2005, p. 17).[2] Nonetheless, some would argue that functionalism provides an alternative reading of general relativity (Knox 2019, p. 119), so perhaps there is further work to be done in assessing the extent to which Smolin's relationalism is in agreement or conflict with the functionalism I have argued is necessary in his account of spacetime emergence.

3.3 When is a view not a view?

In section 2.5 I described two ways in which views can be similar in Smolin's theory of causal views. For reference, these were that two events can have similar views if

$views_1$ they are both proximate in spacetime and are events in the history of two macroscopic bodies; or

$views_2$ they arise in the histories of two atoms or molecules.

In the case of $views_2$, the space of views is a reflection of the possible degrees of freedom of the atoms and molecules and the atoms and molecules will have similar views to the extent that they have similar degrees of freedom. So how are $view_1$ and $view_2$ related? What's the link between the degrees of freedom of atoms and molecules on the one hand and the causal history of events on the other?

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[2] As quoted in (Wallace 2012, p. 46).

There's a clear and profound sense in which if I look up at the stars on a clear night "celestial spheres" of light are washing over me from the cosmos and I'm seeing snapshots of the history of the universe through shells of incident radiation; when I look at the stars truly what I'm looking at it the causal history of the universe. But it's unclear how this relates to the same thing as the degrees of freedom of an atom or molecule apart from if we are talking analogously such that we understand atoms and molecules to have a "view" on a purely metaphorical level. Is it really permissible to appeal to notions of our looking at the stars when talking about the the discrete causal structure of momentum space that Smolin says is fundamental?

Furthermore, it seems reasonable to expect that $views_1$ arises out of $views_2$ and this makes no sense if $view_2$ is an analogy for $view_1$. That is, we should expect that the similarity of views in the case of macroscopic bodies ($views_1$) supervenes on the case of atoms and molecules ($views_2$). And it just seems unclear how this works. Yes, we could and should argue that my perception at the emergent macroscopic level supervenes upon the fundamental microscopic level, that my "view" of the stars as a macroscopic being is the result of absorption of photons in my retina and phototransduction and so on which is ultimately a series of microscopic processes. But I think that gap between the two senses of the similarity of views as outlined is quite profound and more work needs to be done to make more of a progression than a leap.

In short, I think the word "views" is itself doing a lot of heavy lifting to make the theory sensical and ultimately the ontological foundations of the causal theory of views depends upon an analogy in a way that, really, it should not. The theory doth anthropomorphise too much, methinks.

3.4 It's about damn time

Though the temporal realist project is built upon many principles as we've seen, there is an assumption at its heart: time is fundamental and irreducible. If we agree this should be the case we can then run through the construction of the various different models that come together to make the causal theory of views and we may find compelling or not the criticisms I have laid out above. But, if we disagree with the fact that time should be fundamental and irreducible then the project never really gets off the ground. Therefore, I ask, on what grounds should we assume time is fundamental and irreducible and the present is global and objective?

Ultimately, I believe the answer is intuition guided by human experience. I don't say this to be glib or reductive, and I'm certainly not saying human experience is the only basis upon which Smolin argues for presentism and the fundamentality of time. In the paper *Temporal Naturalism* (2015), and the two books *Time Reborn* (2013) and *The Singular Universe and the Reality of Time* (Unger and Smolin 2015) among other texts, Smolin has set out at great length why we should consider time to be fundamental and the fact that most of physics is considered time-reversal invariant is a mistake. But it seems undeniable that this work is motivated by the fact that our experience is temporal. "The reason our experience is structured as a flow of moments is because that is how the world is structured," Smolin writes (2020, p. 157).

Given the abstraction of modern physics, though, why should we base anything off our experience? One hundred trillion neutrinos flow through my body every second as I write, and yours as you read. My wrists rest on the table as my fingers stroke the keys, but the stable, solid surface I experience is due to the electromagnetic repulsion of skin, bones and hair by a few iota of matter strewn through almost entirely empty space. All that is solid melts into air. Smolin draws conclusions at multiple points about the tendencies of science in general and physics in particular (increasing background independence, and so on). Surely the overwhelming conclusion that must be drawn from modern physics is that the classical, solid, mereological world of experience is not an accurate reflection of the fundamental physical nature of reality. Why, then, should we conclude from the basis of our experience of time that it must appear irreducibly at the most fundamental level?

One might argue that all of physics is based upon our experience, that theory must take as its starting point phenomenology. Novel predictions may well be made that would seem to conflict with that experience but in order even to get to those novel predictions phenomenology, or at a higher order experiment, must have given reason to theorise as such in the first place. Yet if presentism is indeed incompatible with the relativity of simultaneity as I have argued, maintaining presentism and the fundamentality of time requires that we "give up detectability with known physics," as Rovelli writes. Yet "our experience *is* accounted for by the physics we know. What is the point of trying to salvage an extrapolation of our intuition, if we loose the connection with the reality that generated the intuition" (Rovelli 2019, p. 2).

It would seem as though we must rely upon intuition if we are to accept that our sense of the passage of time, of *Becoming* to use a philosophical term. Perhaps that's okay, though. I finish with a quotation from someone who supports the foregrounding of the Becoming in fundamental physics, Fay Dowker.

> Thus, if one accepts one's perception of time passing as empirical data, then a model with an asynchronous becoming process is empirically favored over a block Universe model. The form of these data are peculiar, subjective and nonquantitative. It seems therefore to be a matter of personal choice for a scientist whether to accept or reject the call of his or her own perception of time passing to be coordinated with some element of physical theory. However, one's perceptions change when one understands the world better. It is possible that to view the world through a theory with Becoming is necessary to be able to interrogate and describe one's perceptions systematically. (Dowker 2020, p. 137)

Chapter 4

Conclusion

So, temporal relationalism is a wide ranging exploration of the consequences of choosing as fundamental time, energy and momentum, and a project that demonstrates effectively that such a view can be instantiated in physical models. Curiously, it does so on the basis of Leibnizian metaphysics, though it describes the consequent principles as methodological tools rather than metaphysical constraints.

Most important among these principles are relationalism and increasing background independence. I have tried to show that relationalism in some form is an idea supported by much of modern, and perhaps premodern, physics and therefore able to stand on its own feet, with or without the backing of Leibniz's philosophy. Background independence, on the other hand, is a term whose usage is context specific, dependent upon which approach to quantum gravity the user favours, and even in Smolin's terms struggles to be defined without reference to time which is a problem in a project like temporal relationalism. Therefore, while relationalism seems like a reasonable principle by which to adhere, I have argued that increasing background independence is not a useful methodological tool, as it stands.

With only time, energy and momentum at the fundamental level, the burden of proof lay with temporal relationalism to account for the emergence of space and spacetime. The argument went that, if energy and momentum exist at the fundamental level, momentum space is a sensible place to start and through doubly special relativity spacetime emerges via the coincident position (used here as the variable conjugate to momentum) of multiple particles arising through interaction in a way that is purported to describe the emergence of spacetime. And, despite concerns that momentum has traditionally be understood to be of spatiotemporal character, I argued that temporal relationalism picked out spacetime functionally via its role of defining the structure of inertial frames, albeit ones that exhibit relative locality. Nonetheless, it remains to be examined whether Smolin's radical relationalism is compatible with this form of functionalism or not. Furthermore, by doing so, temporal relationalism manages to avoid the charge that presentism is incompatible with special relativity and in particular the relativity of simultaneity, for it manages to achieve presentism without picking out a preferred reference frame.

Then, Smolin argues that the discrete substrata at the fundamental level are sets of causal events whose *views* are the information an event receives from its causal past. Locality in spacetime supervenes upon similarity in this fundamental space of views. Furthermore, the *views* of atoms and molecules pertain to the degrees of freedom of those atoms on molecules in this account and, as a result, interactions that may appear nonlocal in spacetime may be explained from local or proximate interaction in the fundamental space of views. Therefore ensembles of particles in the space of views, at a certain level of coarse-graining, account for the nonlocal interaction in quantum mechanics. However, I have argued that the word "views" is being used to do too many different things and in relating the degrees of freedom of atoms and molecules to human sight, the usual understanding of "view", Smolin is relying too heavily upon analogy in an unacknowledged way.

Finally, I questioned whether human experience, that I take is at the heart of choosing time to be fundamental, is a good basis from which to build physics. On the one hand modern physics seems increasingly abstract and removed from the naïve world of experience while, on the other hand, phenomenological experience is still at the heart of how we ended up with these hugely abstracted descriptions of the world in the first place. It remains an open question to me whether we should take time to be fundamental or not.

Nonetheless, *if* we assume that time, energy and momentum are fundamental, but space and spacetime are emergent; and *if* we accept the radical relationalism Smolin proposes, then temporal relationalism describes a program to realise the things it set out to, my criticisms and concerns notwithstanding: provide a unified metaphysical basis both with which to interpret quantum mechanics and general relativity, and from which these theories can arise from a more fundamental quantum theory of gravity. But in order to do so, it forces on us quite a radical metaphysics. Maybe that will prove necessary to make sense of the world.

Nonetheless, there's an aphorism that comes to mind here, originally pertaining to the interpretations of quantum mechanics: in trying to solve the measurement problem the physicists advocate changing the philosophy while the philosophers advocate changing the physics. The best counterexample to this, to my mind, is the development of the modern version of the Everett interpretation: it necessitates quite a radical metaphysical philosophy but this is made sense of by taking seriously actually existing physics in the form of decoherence. One could think of it as a third way of some kind.

Perhaps the radical metaphysics proposed by temporal relationalism will prove necessary to make sense of the world, the inference to the best explanation. Or perhaps there is some way for this to be softened in a way that serves to strengthen the account overall. In particular, could the fundamentalist relationalism in Smolin's account could be softened by some form of functionalism? A topic for further investigation.

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