Philosophy of Spacetime Physics

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1 Introduction

The study of space and time is a natural meeting point for philosophy and physics. Although one could start the story earlier (space, time and motion were a major consideration in, for example, Aristotelian physics), this article starts with Newton and the birth of modern physics, and works its way through to the nature of space and time in our hitherto unestablished theory of quantum gravity. Although the theories themselves differ considerably, the considerations on which our understanding of spacetime is based will remain remarkably connected. Unifying themes emerge: the symmetry group of the dynamics is crucial to our understanding of spacetime structure (although understanding that symmetry group is not always straightforward). Understanding this requires thought about the role of reference frames and coordinate systems. Perhaps more surprisingly, understanding inter-theoretic relations is also crucial to understanding spacetime structure.

2 Spacetime in Newtonian theories

2.1 From Newtonian Space to Galilean Spacetime

Newton famously set his mechanics against a background of absolute space and time. Absolute space can be thought of as a container relative to which rest and motion may be defined; absolute space has parts, and these parts persist through time. An object at rest remains in the same part of space, and an object in motion moves relative to absolute space. (Absolute time defines a universal moment, or simultaneity standard, throughout absolute space.) Newton's reasons for postulating absolute space in the *Principia* are clear: he is well aware that his system presupposes absolute, rather than merely relative, differences between states of motion.

A scholium to Book I of the *Principia* posits a thought experiment in which a bucket is suspended by twisted ropes that cause it to rotate. As Newton notes, the concave shape of the water's surface in a rotating vessel cannot be explained either by motion relative to the bucket itself (which is greatest before the water's shape is much affected), or by motion relative to the environment: spinning the bucket's surroundings does not have the same effect. Insofar as his observation is empirical, one might question this last claim - after all, an experiment in which *all* the bucket's surrounding are rotated is impossible. But the crucial point to note here (especially in a context in which Newtonian mechanics is not the last word!) is that Newton's result follows from his mechanics - if a rotating bucket can be accurately described by Newton's physics, then the rotation of the bucket, but not its surroundings, leads to observable effects. This is a simple consequence of a fact that every physics student who has modelled classical systems in rotating reference frames knows: Newton's mechanics is *not* invariant under rotations. Newton postulated absolute space in order to explain the existence of absolute rotational motion, which was a consequence of his mechanics. Newton then defines absolute motion (rotational or otherwise) as motion relative to absolute space.

Newton's logic is clear, but his postulation of absolute space has other consequences. If motion is defined relative to absolute space, then it follows that there are facts about whether a body is at rest or in motion relative to absolute space, and about what its precise velocity is. But, as Galileo famously observed, absolute velocities are unobservable:

> Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need to throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though doubtless when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least

> change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. [Galileo:1967]

Galileo is here describing an *empirical symmetry*: without reference to the outside world, there is no way to tell whether the ship is stationary or moving with constant velocity. This robust empirical observation is enshrined in Galileo's Principle of Relativity, which holds both empirically and in all contemporary theories. It is also enshrined as a theoretical symmetry in Newton's mechanics, which is invariant under the group of Galilean transformations:

$$t' = t + \tau, x'^i(t') = R^i_j x^j(t) + v^i t + a^i \tag{1}$$

where R^i_j is a constant orthogonal matrix and a^i is a constant.

This means that Newtonian mechanics is invariant under velocity boosts: the symmetries of Newtonian mechanics rule out the possibility of observing any internal difference between Newtonian systems moving with different constant velocity. Newtonian mechanics thus enshrines the Galilean Principle of Relativity as a symmetry.

But, as Leibniz famously pointed out in his correspondence with Clarke (a devotee of Newton), all of this poses a problem for Newton. If absolute space exists, then the world is filled with facts about absolute velocity - facts about the velocity of my office chair, of the earth itself, and of the other planets and stars. And yet no experiment has ever detected these, and Newtonian mechanics itself tells us that they are in principle unmeasurable. If one boosted all the contents of the universe by some constant velocity, absolutely nothing measurable would change. This places Newton in a tricky position: on the one hand, he needs absolute space to underpin the observability of absolute rotational acceleration, on the other hand, absolute space has too much structure. Because absolute space fails to reflect the symmetries of Newtonian mechanics, it introduces structure (in the form of absolute velocities) that can never be observed.

Leibniz saw the problem with universal velocity boosts as an argument for *relationism* - the view that space is not a substance, but reduces to relations between bodies, as opposed to Newton's *substantivalism* - the view that space is a substance. However, neither view seems to quite fit the features of Newtonian mechanics - relationist views fail to explain why rotation is absolute in Newtonian mechanics, and substantivalism fails to explain why velocities seem to be relative. Newton himself had no way out of this dilemma, and the modern literature tends to conclude that he was right to postulate absolute space given the tools that he had. However, it would be better to have a formulation of the theory in which the spacetime structure supported absolute rotational acceleration without introducing unobservable absolute velocities. Contemporary mathematical resources allow us to do just that. In 1967 Howard Stein[1]

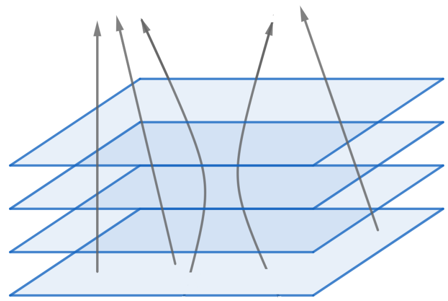

Figure 1: Galilean Spacetime: Each 'leaf' here represents a three dimensional space at a time, and the trajectories the worldlines of point particles. This geometrical structure can be represented by a tuple $(M, t_{ab}, h^{ab}, \nabla)$ where M is a four dimensional manifold, t_{ab} is a temporal metric, h^{ab} is a spatial metric, and ∇ is derivative operator that imposes a flat affine connection. Note that straight lines in spacetime are picked out by the connection, not by extremal distance in a spacetime metric - Newtonian spacetimes have separate spatial and temporal metrics and no spacetime metric.

proposed that the structure of a four dimensional classical spacetime could underpin Newtonian mechanics in a way that allowed for absolute acceleration without absolute velocity. He dubbed this structure *Galilean Spacetime*.

Galilean Spacetime, also sometimes called Neo-Newtonian Spacetime, is a four-dimensional spacetime with a preferred foliation into same-time slices - that is, it preserves the absolute simultaneity structure of Newtonian mechanics. However, instead of identifying points across time, the spacetime is equipped with affine structure (represented geometrically via a connection) that distinguishes straight timelike trajectories in the spacetime from curved ones (timelike trajectories are those that intersect different time slices). Straight trajectories represent the possible motions of force-free point particles - the inertial trajectories - while curved trajectories represent accelerated motion. The reference frames associated with these inertial trajectories are inertial frames: those in which force-free bodies move in straight lines, and in which Newton's laws take their standard form. This provides the structure needed to define absolute accelerations without absolute velocities.[2]

The move to Galilean spacetime can be seen as motivated by what is sometimes known as Earman's principle (Earman, 1989, p.46): the symmetries of our spacetime should match the symmetries of our dynamical theories.

2.2 Alternative Newtonian Spacetimes

Although there is some consensus that Neo-Newtonian spacetime captures the spacetime structure needed for Newtonian mechanics better than Newton's absolute space, it fails to fully account for the symmetries of Newtonian mechanics. Newton notes a further symmetry in Corollary VI of his *Principia*:

> If bodies, any how moved among themselves, are urged in the direction of parallel lines by equal accelerative forces; they will all continue to move among themselves, after the same manner as if they had been urged by no such forces. (Newton, 2003, p.31)

Although Leibniz did not mention it, Newton's mechanics has another empirical symmetry: all relative motions are invariant under uniform, arbitrary, linear accelerations. That is, it looks as if the symmetry group of the theory should be wider than the Galilean group, and one should seek a theory that is invariant under the wider Maxwell group of transformations:

$$t' = t + \tau, x'^i(t') = R^i_j x^j(t) + a^i(t) \tag{2}$$

where $a^i(t)$ generated arbitrary time-dependent translations.

But Newton's equations as standardly presented are not invariant under the full class of transformations above - if all bodies are subjected to forces causing equal accelerations, then, in Newtonian terms, the absolute forces differ. The question of invariance is a slightly tricky matter here - one might have argued that Newton's original mechanics is not invariant under the Galilean transformations precisely because it postulates absolute velocities, and these are not invariant under boosts! But excising absolute forces from the standard presentation of Newtonian mechanics is a trickier matter than excising absolute velocities. The apparent symmetry under linear accelerations seems to require some reformulation of the dynamics of the theory, and a move to a spacetime setting that reflects these dynamical symmetries.

There are now (at least) two options. One, advocated by Simon Saunders (2013), is to move to Maxwellian Spacetime[3] and articulate a theory that is explicitly invariant under the Maxwell group. Saunders thus offers us a version of Newtonian mechanics (which Wallace (2020) calls *vector relationism*) that gives a well-defined dynamics for the vector displacements of particles. This theory has some interesting features. It has much less structure than Galilean spacetime: it does *not* appear to posit a structure of inertial frames, a standard part of defining a spacetime structure. On the other hand, it is not a fully relational theory, nor should it be. Although uniform *linear* accelerations are unobservable in Newtonian systems, rotational accelerations *are* observable, as demonstrated by Newton's rotating bucket. So the theory requires at least enough background structure to distinguish absolute acceleration from relative acceleration. If one chooses to express the spacetime structure in the language of differential geometry (an awkward fit for Maxwellian spacetime), the spacetime structure is represented by a tuple $, t_a, h^{ab}, [\nabla]\rangle$, where the manifold and metrics are the same as in the Galilean case, but such affine structure as there is is now represented by a class of derivative operators that pick out a standard of non-rotation. Given that inertial trajectories are usually picked out by the derivative operator, this makes explicit the sense in which there is no class of inertial trajectories defined by the structure of Maxwellian spacetime.

Another option is to note that Newton's Corollary VI expresses a symmetry very like that expressed by general relativity's *equivalence principle* (further discussed in 4.1). Given the equivalence of gravitational and inertial mass, gravity provides just the universal force needed to induce equal accelerative forces. Bodies moving in a homogeneous gravitational field will experience the same relative motions as unaccelerated bodies. This is the insight that led Einstein to postulate a curved spacetime structure in general relativity in which force-free bodies follow geodesics of the curved metric. Elie Cartan (1925) was the first to realise that the reasoning that leads to curved spacetime in a relativistic context could also lead to curved spacetime in a Newtonian context: the result is Newton-Cartan theory, also known as Geometrized Newtonian Gravitation. This theory maintains the absolute time structure of Galilean spacetime, but replaces the flat affine connection with a dynamical connection that curves in response to matter. Bodies that Newtonian gravitation considered to be moving under gravitational forces are now considered to be freely falling bodies following the inertial paths picked out by this new, non-flat connection. Malament (1995) offers a formal account that connects Newton-Cartan theory to the kind of symmetry considerations mentioned above. Knox (2014) argues that, in light of Corollary VI, Galilean spacetime is an unstable stopping place: once one is committed to finding a spacetime structure that respects the empirical and dynamical symmetries of Newtonian systems, those commitments lead inexorably to Newton-Cartan theory.

This suggests a puzzle: how do the same kinds of symmetry considerations seems to lead both to Maxwellian spacetime and to Newton-Cartan spacetime? Further work has explored the degree to which Saunders' vector relationism in Maxwellian spacetime with gravitation is equivalent to Newton-Cartan theory. Weatherall (2016) demonstrates that there is a natural two-way mapping between Newton-Cartan and Maxwellian spacetimes with gravitation. Wallace (2020) gives a more philosophical account of the link between the two accounts: Wallace points out that although Maxwellian spacetime does not 'come' equipped with inertial structure, once gravitating systems are introduced, an effective or emergent inertial structure can be defined. This inertial structure is that of Newton-Cartan theory. One moral of Wallace's paper is that spacetime plays two different roles in our theorizing; in this case they come apart. When one asks what the 'right' spacetime is given some symmetry, one might be asking for the minimal background structure needed to write down a theory with the relevant symmetry. Maxwellian spacetime provides this structure. Alternatively one might be asking for the inertial structure of the theory, in order to understand force-free motion and preferred reference frames. This latter kind of spacetime structure can, according to Wallace, be scale-relative and emergent.

3 Spacetime in special relativity

3.1 From Einstein to Minkowski

Spacetime considerations are more familiar in the relativistic context. In 1905, Einstein pointed out that, once combined with the newly established fact that the two way speed of light was the same in all reference frames, the relativity principle could be used to derive the Lorentz transformations:

$$x' = \gamma(x - vt) \tag{3}$$

$$t' = \gamma\left(t - \frac{xv}{c^2}\right) \tag{4}$$

where $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$. This transformation, of course, is for a velocity boost of v along the x axis, and other spatial coordinates transform trivially. A more general, but possibly less informative, form of the transformations relevant for relativity is given by.

$$x'^{\mu} = \Lambda^{m}u_{n}ux^{\nu} + a^{\mu} \tag{5}$$

where $\Lambda^{m}u_{n}u$ is the Lorentz transformation matrix (defined by the need to preserve the spacetime interval) and a^{μ} generates spatiotemporal translations. Equation 5 includes translations, and therefore represents a slightly wider group: the Poincaré transformations.

The Poincaré group is the symmetry group of electromagnetism (as well as all other relativistic theories). Following Earman's Principle (see section 2.1), it is natural to seek a spacetime whose symmetries match these dynamical symmetries. Einstein, however, did not originally think of his special theory of relativity in these terms, and indeed, was somewhat relectant to adopt them.[4] In Einstein (1905), he was focused on operational matters - the lengths and times reflected by rods and clocks in motion, which in turn depended on the equations governing these moving bodies. It was only in Minkowski's 1908 presentation of the theory that its now-standard setting in Minkowski Spacetime was developed. From this perspective, the Lorentz transformations relate inertial coordinate systems in which a flat pseudo-Riemannian Minkowski metric takes the form $\eta_{\mu\nu}$:=diag$(-1, 1, 1, 1)$.

3.2 Time in special relativity

One crucial way in which Minkowski spacetime overturns our Newtonian intuitions in in the relativization of simultaneity. Whereas Newtonian spacetimes

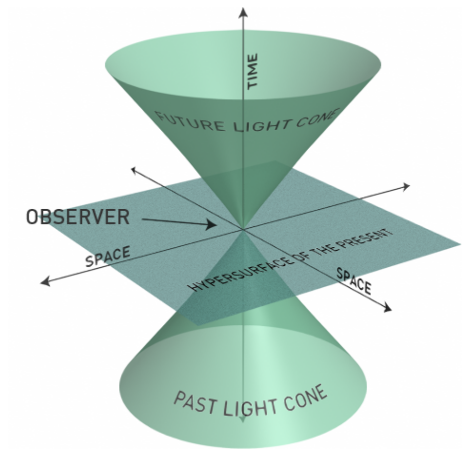

Figure 2: Minkowski Spacetime: The Minkowski metric defines a spacetime interval between any two spacetime points. This in turn distinguishes spacelike and timelike trajectories and the light-cone structure. Inertial frames are those in which force-free bodies move in straight lines and the Minkowski metric and the relativistic laws take a particular form. The simultaneity plane in this diagram no longer reflects invariant structure, but depends on the reference frame adopted. Image created by Stib available at `https://en.wikipedia.org/wiki/Minkowski_space`.

come equipped with a preferred foliation into simultaneity slices, in special relativity, simultaneity is only defined relative to a reference frame. Observers in different states of motion judge different sets of events to be simultaneous.

The relativity of simultaneity has far-reaching consequences for the philosophy of time.[5] In particular, it appears to rule out both *presentism* and the *growing block* accounts of the metaphysics of time. According to the presentist, reality is fundamentally three-dimensional and changes continuously - the presentist holds that all and only the present is real. The growing block advocate sees reality as four-dimensional sand continuously growing as a new moment becomes present. It is relatively easy to see how this is at odds with the relativity of simultaneity: both views assume that there is a unique present moment, but Minkowski spacetime does not admit of a preferred foliation into same-time spaces.

This incompatibility between special relativity and presentism was developed in detail by Hilary Putnam (1967) (although Wim Rietdijk articulated a similar argument at roughly the same time (1966) and the argument has also been put forward by Saunders (2002) and others.) Putnam takes presentism and special relativity to be incompatible with the following three claims:

1. I-now am real.
2. At least one other observer is real. It is possible for this observer to be in motion relative to me.

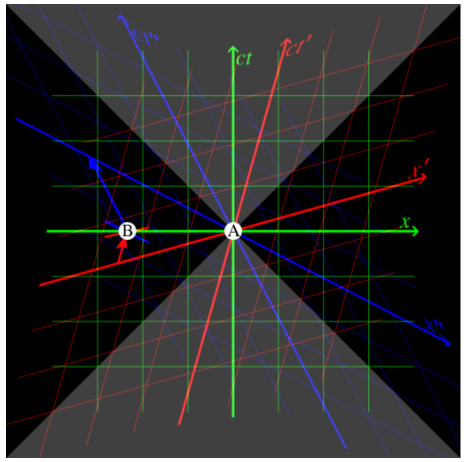

Figure 3: The relativity of simultaneity: Event B is simultaneous with event A in the green reference frame. B occurs before A in the blue frame, and after A in the red frame. Image created by Wikipedia user Army1987, available at `https://en.wikipedia.org/wiki/Relativity_of_simultaneity`.

3. If B is real for A and C is real for B, then C is real for A. (The 'real for' relation is transitive.)

The conjunction of these three claims (which amount to the claim that 'A is real for B' must pick out an equivalence relation) with the relativity of simultaneity implies that all observers at all times should be real for one another: if observer B (in motion relative to A) is on A's simultaneity slice and hence present and real for A, then all those on B's simultaneity slice (which differs to A's) must be real for A as well. Thus, for Putnam, relativity of simultaneity implies not just the negation of presentism but *eternalism*: the view that all events at all times are equally real. This view is sometimes also called the block universe view.

Many, both in physics and philosophy, embrace the block universe, but some resist. If one wishes to rehabilitate presentism in the face of special relativity the options fall into two broad categories. The first is to redefine what one means by the present, decoupling it from the concept of a simultaneity surface. This may involve denying one of Putnam's three claims. The second is to deny that special relativity should be the last word on our metaphysics of time, either by arguing that metaphysics gives us reason to believe in a privileged reference frame, or by arguing that physics itself might introduce such a frame.

How might one change the notion of the present to better fit relativistic physics? Howard Stein (1991) pointed out that the move to spacetime means that, in some sense, the analog of temporal moment in relativity is a spacetime point. This suggests that the relativistic analog of classical presentism is so-called "point presentism"; only a single spacetime point is real. This option, which involves denying Putnam's second premise, has never actually been defended; Stein is interested in defending a notion of 'becoming', rather than presentism itself. Not only is it *lonely* (see (Hinchliff, 2000, p.597), but it means that many past events (in the past lightcone) were never present. An alternative, advocated by William Godfrey-Smith (1979), is "cone presentism", in which the present for a given point is identified with its past lightcone. This does a good job of capturing our everyday notion of the present at ordinary scales - after all, the things considered to be present are usually the things one can see - but is quite counter-intuitive at larger scales: given that cosmic microwave background (CMB) radiation is currently reaching us, the big bang itself is on our past light cone and hence counts as present. Cone presentists must also give up the transitivity of the present - there will be events present to those on my past light cone but not to me. (Note that cone growing block views avoid this.)

If radical re-conceptualizations of the present make "red-blooded presentists squirm" (Savitt, 2000, p.566), then a better option may be to insist that, despite the empirical success of special relativity, there is a preferred foliation of spacetime and the present may be identified with a three-dimensional spatial slice. Proponents of this view will note that nothing in special relativity actually forbids the idea of a preferred reference frame and hence preferred foliation - it is just that, insofar as special relativity is correct, such a reference frame would be undetectable, in principle and in practice. The motivation for postulating such a frame must come from outside of special relativity. The motivation is usually metaphysical - presentists claim that coherent metaphysics requires a notion of the present not postulated by special relativity. However, some presentists also appeal to empirical or theoretical motivations. For example, Lee Smolin (2013, Ch.14) argues that the CMB picks out a preferred reference frame, that hidden-variable theories require it, and General Relativity can be reformulated as shape dynamics, which is more hospitable to presentism. Many presentists (Smolin included) appear to believe that our conscious experience is evidence for the existence of this reference frame, although it is unclear how the physics of the brain might work so as to probe non-Lorentz covariant physics.

3.3 Clock synchrony and the conventionality of simultaneity

It has also been claimed (Reichenbach, 1958; Grünbaum, 1973) that simultaneity in special relativity is not only relative but also *conventional*: one can adopt any value for the one-way speed of light one chooses, as long as one maintains the empirically established two-way speed of light. Einstein (1905) explicitly introduces his clock-synchrony procedure as a convention: To synchronise two clocks, send a light pulse from clock A at time t_0, and reflect it back from clock

B to clock B. If the light is received back by A at time t_2 as measured by clock A, then the time assigned to clock B at the moment of reflection should be $t_1 = t_0 + \frac{1}{2}(t_2 - t_0)$. Because any one-way velocity measurements already assume that we have clocks synchronised at different points, we cannot establish the one-way speed of light independent of clock synchrony, and both the one-way speed of light, and our standard of clock synchrony and hence of simultaneity must be considered conventional.

This leaves open the idea that we might adopt some alternative synchrony convention $t_1 = t_0 + \epsilon(t_2 - t_0)$ where $\epsilon \neq \frac{1}{2}$. Doing so has far-reaching consequences for what are usually thought of as standard results in special relativity. With a non-standard synchrony convention, the Lorentz transformations look different, and length contraction and time dilation are no longer governed by the usual equations. The speed of light now depends on the direction in which it travels, as do other velocities; length contraction and time dilation likewise vary with direction of travel. If ϵ can take values smaller than 0 or larger than 1, then causality is not respected in the clock coordinates; it is possible for signals to arrive at B before they left A.(See Winnie (1970a,b) for more details.)

These odd consequences of a non-standard synchrony convention have led various authors to argue that clock synchrony is not, after all, conventional, and that there are non-pragmatic reasons to adopt the Einstein synchrony convention. These arguments try to establish that some phenomenon requires standard synchrony - a notable example is the argument from slow clock transport, originally proposed by Eddington (1923). This argues that one can establish a synchrony convention by slowly transporting a clock from A to B, and then synchronising the two clocks present at B. If one considers the limit of a sequence of such processes as the velocity of the transported clock tends to zero, one gets a standard of synchrony that coincides with the Einstein synchrony convention. The trouble here, of course, is that the very concept of 'slow' transport depends on a standard of one-way velocity, and thus assumes a synchrony convention. Various attempts have been made (Bridgeman, 1962; Ellis and Bowman, 1967) to establish a standard of slow clock transport that does not depend on synchrony, but it is generally agreed that all of these implicitly assume some kind of synchrony standard.

A more widely accepted argument for non-conventionality was proposed by David Malament in 1977. Malament argues that, relative to some inertial observer with worldline O, there is only one simultaneity relation that can be defined if we demand that that relation is an equivalence relation, is defined in terms of O and the structure of causal connectability, and relates points on O to points off the worldline. This relation is the one picked out by the standard synchrony convention. Technically, the result is valid, and some authors (e.g.Torretti (1983) and Norton (1992)) accept that this closes the issue of the conventionality of simultaneity. Others (e.g. Grünbaum (2010)) disagree with the restrictions Malament places on the simultaneity relation, and hence argue that his result does not establish non-conventionality.

With hindsight, one can adopt a perspective from which both positions are understandable. Establishing a standard of simultaneity effectively involves picking a coordinatization of time, and then insisting that velocities and simultaneity are defined via the relevant coordinates. From this perspective, we are free to choose our coordinates however we like - our choice of coordinates is conventional. At the same time, some coordinates are better adapted to the geometrical structures of Minkowski spacetime than others. In these coordinates, special relativistic laws will take familiar forms. Malament's result shows that the standard inertial coordinates associated with an inertial worldline bear a particular relation to the causal structure of spacetime, and are thus privileged. This result is compatible with our freedom to choose mal-adapted coordinates. The conventionality of simultaneity debate thus highlights a theme that appears elsewhere in the philosophy of spacetime: the relationship between coordinate descriptions of spacetime theories and geometrical descriptions that aim to describe spacetime structure in a coordinate independent way.

3.4 Dynamical and geometrical relativity

Questions about the relationship between dynamics, coordinates, and geometry sit beneath many debates in the philosophy of spacetime. They reach their most explicit form in the literature on special relativity. An orthodox position in the literature (expressed in e.g. Friedman (1983) and Maudlin (2012)) holds that the content of special relativity is best captured by expressing the structure of Minkowski spacetime in coordinate invariant form. That is, the theory is well-described by a tuple of geometrical structures $\langle M, \eta, \phi \rangle$, where M is a four-dimensional manifold, η is the Minkowski metric, and ϕ are matter fields whose dynamics are adapted to the Minkowski metric. Implicit in this kind of approach is the idea that this description captures the structure of spacetime itself, and that Minkowski's reformulation of Einstein's theory was a substantial step forwards in understanding the nature of space and time.

In his book *Physical Relativity*, Harvey Brown questions this orthodoxy. He points out that the Minkowski metric is empirically relevant because it has operational significance; it governs the behaviour of the "rods and clocks" used to survey physical geometry. This leaves open a question of *why* physical systems like rods and clocks reflect the relevant geometry. Brown takes the orthodox position to assume that the behaviour of material bodies is constrained by the structure of spacetime (as in Nerlich (1979)), but argues that Einstein thought that such behaviour requires a "constructive" explanation in terms of the constituents of matter. While a full such picture is unavailable, Brown argues that we have a shortcut if we assume that the laws governing matter dynamics are Lorentz covariant. It is, he claims, this fact about the symmetry of the laws, and not the structure of spacetime, that explains why moving clocks dilate and moving rods contract. In Brown and Pooley (2001), this argument is explicitly used in favour of a kind of relationism: Minkowski spacetime is held to be "a glorious non-entity".

Brown's work points to the need for analysis of the relationship between the structure of spacetime and the symmetries of the dynamical laws. At least three options present themselves in the literature. One possible position is that spacetime is a substantival entity whose geometry serves to constrain its contents. Another is the relationist position: spacetime is reducible to the symmetry properties of the laws. A third, offered by Myrvold (2019), interprets Brown not as reducing spacetime geometry to dynamical symmetry, but as pointing out that the two are conceptually intertwined. Knox (2019) interprets this view as a form of *spacetime functionalism*, the view that spacetime is whatever plays the functional role of spacetime, part of which is to define the dynamical symmetries.

4 Spacetime in general relativity

The philosophy of general relativity (GR) shares some themes with the philosophy of special relativity and Newtonian spacetime theories, but several debates are fundamentally changed by key features of the theory. For one thing, the metric field in GR is now governed by dynamical equations - the GR field equations. As a result, the issue discussed in 3.4 has no exact parallel; there is little question that the metric is one of the entities postulated by the theory. For another, the theory does not, in general, admit of any global coordinatization, let alone a choice of privileged coordinates. The combination of these two (related) facts means that questions about symmetries, coordinate transformations, and the reality of spacetime take on a different character in GR.

4.1 The equivalence principle

In 1919, Einstein offered a retrospective origin story for general relativity: in 1907, while writing an essay on special relativity, Einstein had "the happiest thought of my life":

> the gravitational field ... has only a relative existence. Thus, for an observer in free fall from the roof of a house there exists, during his fall, no gravitational fieldâat least not in his immediate vicinity. If the observer releases any objects, they will remain, relative to him, in a state of rest, or in a state of uniform motion, independent of their particular chemical and physical nature.(Einstein, 1919)

What is now usually called the *Einstein Equivalence Principle* was central to the development of general relativity. Its core thought is that there is an intimate relationship between gravitation and inertia: homogeneous gravitational fields can be simulated by accelerations, and they can be cancelled by the acceleration of freefall. The most perspicuous formulation of this principle, and its relation to the "Weak Equivalence Principle", which asserts the equivalence of gravitational and inertial mass, is a matter of some debate - see Lehmkuhl (2021) for a comprehensive overview. There are also interesting questions about exactly how the principle played a role in Einstein's thinking - see Norton (1986) or Norton (1984). But even without the historical details, the principle itself is puzzling in the context of general relativity. Once we move to GR, it is doubtful that anything can be identified with the gravitational field, and those things that might be are usually tensorial and cannot be transformed away. There is certainly no counterpart for a homogeneous gravitational field. It therefore seems that the Einstein Equivalence Principle is not applicable to GR itself - it, as Synge (1960) famously commented, merely "performed the office of midwife at the birth of general relativity" and should now be "buried with appropriate honours".

Even if the Einstein Equivalence Principle should not be buried, there is another equivalence principle that has more claim to be contentful in GR, although this too is contested. The *Strong Equivalence Principle* (SEP) says something about the local validity of special relativity in GR. While Einstein discussed something like this principle at various points (Lehmkuhl, 2021, p.134), its first clear formulation is due to Wolfgang Pauli:

> For every infinitely small region of the world (i.e. a region so small that the spatial and temporal variation of gravity can be neglected therein), there always exists a coordinate system $K_0(X_1, X_2, X_3, X_4)$ such that there is no influence of gravity either on the motion of mass points or on any other physical processes. (Pauli, 1921)

The idea here is that there exist freely falling coordinates in which any gravitational effects may be neglected, and the laws may be formulated as they would in inertial coordinates of flat Minkowski spacetime. The best formulation of the principle is a matter of some debate. The SEP is only valid in some neighbourhood to the extent that tidal effects due to curvature may be neglected. This has lead some (e.g. Ohanian (1977)) to try to constrain the principle to a point. Others (e.g. Brown (2005) or Knox (2013)) think that it holds approximately for some small region picked out by the accuracy of the measurement systems involved. Harvey Brown sees the SEP as crucial to the 'geometricity' of general relativity. That is, the SEP is taken to pick out that feature of the matter fields that ensures that the metric has operational significance. Further work by Brown, Read and Lehmkuhl (Read et al., 2017; Brown and Read, 2021) explores the requirements and limitations of this connection to the matter fields. Disagreements in this literature center around the tension between two thoughts. The first is the compelling idea that the SEP says something non-trivial about the behaviour of matter in GR, and that what it says is intimately related to the validity of the Einstein Equivalence Principle in pre-GR theories. The second is the undeniable fact that, in a curved spacetime, the inertial frames picked out by the theory only hold locally and approximately.

Some prefer to cast their expression of the local validity of special relativity in a more geometrical form. The GR metric, it is claimed, is 'locally flat' - that is, it approximates the Minkwoski metric at small scales. This requires some non-trivial sense in which one metric approximates another. Fletcher and Weatherall (2023a) explore various ways to cash this out, and conclude that none are contentful - insofar as one can find true readings of the statement that one metric locally approximates another, every metric approximates every other with the same signature. One might hope (returning to something more like the full SEP above) that one could give the claim more content if one said something not only about the metric, but about the form of the laws that are adapted to it. This too, proves tricky to make precise (Fletcher and Weatherall, 2023b). Many formulations appeal to 'minimal coupling', often stated as the holding that one should replace ordinary derivatives in pre-GR laws with the covariant derivative in GR. While there is *something* right about this - the behaviour of matter in the SEP does depend on a general absence of curvature coupling - more work is needed to make this precise.[6]

4.2 The hole argument

Einstein saw the lack of global inertial structure in his theory as a positive move away from absolute structures. One of his motivations for the original Einstein Equivalence Principle was the desire to implement a General Principle of Relativity - to create a theory with no privileged reference frames whatsoever, not even inertial frames. In order to do this, he sought a theory that could be written in any coordinates whatsoever - that is, a generally covariant theory.

But general covariance is conceptually tricky. In 1913, Einstein was very close to arriving at the GR field equations, but it would take him two more years before arriving at their final form (Norton, 1984, 1995). This is because concerns about general covariance led him to temporarily abandon the original form of the theory. Einstein became convinced that general covariance led inevitably to an indeterministic theory. The problem is this: generally covariant equations remain true under arbitrary coordinate transformations - that is, if the variables of the theory (like the metric) are transformed: $g(x) \rightarrow g'(x')$. This passive transformation seems unproblematic. But, formally, if $g'(x')$ satisfies the equations, so will $g'(x)$. The transformation $g(x) \rightarrow g'(x)$, a diffeomorphism, appears to be an active transformation - that is, it *appears* to involve assigning different variable values to one and the same spacetime point, because we have held the original coordinate assignments fixed. (This formulation of the problem follows Pooley (2021), which gives an up to date overview of the hole argument).[7] Einstein reasoned as follows: imagine an active diffeomorphism that leaves variables unchanged everywhere except some bounded spacetime region in our causal future - a 'hole' diffeomorphism. No amount of information about the physics outside of the hole determines the values of the variables at points inside the hole (determines whether, at some point a inside the hole, we have $g(a)$ or $g'(a)$). Thus the theory is indeterministic.

In 1987, John Earman and John Norton recast this as an argument against *spacetime substantivalism* - the view that spacetime is a substance. In their view, the active interpretation of the diffeomorphism arises because we reify the points of GR's four-dimensional manifold. That is, the problematic interpretation of the diffeomorphism comes from attributing a certain meaning to the transformation $\langle M, g, T\rangle \to \langle M, g', T'\rangle$, where now g represents the metric and T the matter fields. The active reading of the diffeomorphism is only possible because we see the above as assigning new metric and matter-field values to one and the same manifold points, and hence see our transformed tuple as representing a new physical situation. Earman and Norton claim that the substantivalist is required to interpret the transformation in this way: taking these *Leibniz Shifts* to represent new physical situations is an "acid test of substantivalism"Earman and Norton (1987)[p.521]. In order to avoid indeterminism, one should take the diffeomorphically related solutions to represent one and the same physical situation. Earman and Norton take this to involve the denial of substantivalism.

Those who accept Earman and Norton's argument must either deny substantivalism (Earman and Norton's preference), or accept indeterminism (see, e.g. Brighouse (1997)). Others resist Earman and Norton's central dilemma. A number of strategies have been put forward for reconciling substantivalism with the hole argument. Tim Maudlin's *metrical essentialism* (1988; 1990) argues that spacetime points hold their metrical properties essentially, so that, relative to one choice of representation, diffeormorphically related solutions represent metaphysically impossible worlds. Sophisticated substantivalists, such as Hoefer 1996 or Pooley 2006 deny that the reality of Leibniz shifts should be a hallmark of substantivalism. They note that viewing $\langle M, g, T\rangle$ and $\langle M, g', T'\rangle$ as representing different possible worlds depends on *haecceitism*, which holds that worlds could differ solely in terms of which objects (in this case spacetime points) are assigned which properties (in this case the values of metric and matter fields). Metaphysical commitment to the reality of an object need not commit us to the reality of purely haecceitistic differences, so substantivalism need not commit us to interpreting diffeomorphically-related solutions as distinct physical possibilities. A wide range of authors (e.g. Butterfield (1989); Stachel (1993, 2014); Rynasiewicz (1994); Saunders (2003)) ultimately endorse anti-haecceitism as a solution to the hole argument, although they may not always call themselves sophisticated substantivalists.

More recently, Weatherall (2018) and Fletcher (2020) have suggested that the hole argument rests on a mistaken understanding of the representational capacities of general relativity's mathematical structure. A correct understanding of the notion of a Lorentzian manifold should commit one to regarding diffeomorphically related solutions as representationally equivalent. Other authors question whether mathematics alone can determine one's interpretation of GR models - see Pooley and Read (2021) or Roberts (2020).

4.3 Background independence and general covariance

Although their metaphysics may differ, the vast majority of authors in the hole argument literature ultimately reach the same conclusion that Einstein reached: models related by diffeomorphisms can be thought of as representing one and the same physical situation. General covariance is thus secured as an unproblematic feature of general relativity. But what of Einstein's original motivation: to implement a general principle of relativity? Einstein's interest in such a principle was inspired, in part, by his hope that his theory would implement Machian relationism, and that all spacetime features would depend on the distribution of matter. This did not come to pass in the final theory: in the end, the metric has its own degrees of freedom independent of matter, so the geometry of spacetime is not fully specified by the matter fields. Nonetheless, general covariance does seem to implement some kind of generalised principle of relativity: except in specific solutions, GR has no globally preferred reference frames, and is written in the explicitly coordinate independent language of differential geometry.

To many this has seemed to be a crucial feature of GR and perhaps *the* feature that should be carried through into a theory of quantum gravity. However, putting one's finger on an account of substantive general covariance proves tricky. The problem stems from the 'Kretschmann objection' (Kretschmann, 1917): all our familiar pre-GR theories of spacetime can be rewritten in the language of differential geometry, with their geometrical structure made explicit. Once written in such a form, they too have equations that hold true in any coordinates whatsoever. Why, then, think of this as a special feature of general relativity? General covariance seems to be trivial.[8]

To get a handle on what an account of *substantive* general covariance might involve, start by noting that, while Kretschmann is correct that special relativity and other pre-GR theories can be given a generally covariant form, general relativity appears novel insofar as it *must* be written in such a form - there is no non-generally covariant formulation of GR. This feature of GR stems from the absence of preferred reference frames in the theory, and that, in turn, stems from the dynamical nature of the GR metric. Contrast this with the Minkowski metric in SR, which underpins the existence of a preferred class of frames in which the theory can be written in its non-generally-covariant form. The

Minkowski metric, unlike the GR metric, remains the 'same' across dynamical solutions of the theory. Let us (following Anderson (1967)) define:

Absolute Object. *A geometrical object that is the same (up to isomorphism) in all dynamically possible models of the theory.*

and

Background Independence, absolute objects version. *A theory is background independent if it has no absolute objects in its formulation.*

This captures a sense in which special relativity, even in its generally covariant formulation, differs from GR. The Minkowski metric is present in every model of the theory, qualifies as an absolute object, and thus provides a fixed and non-dynamical background on which the theory plays out. However, this definition of background independence is insufficient to distinguish GR from SR: for one thing, as Brian Pitts (2006) points out, GR has an absolute object in Anderson's sense, namely $\sqrt{-g}$. This prompts a search for a better definition of Background Independence. One might, for example, replace the notion of absolute object above with the concept of a *fixed field* - a field fixed by the kinematics of a theory or an *absolute field* - a field specified by the kinematics and fixed in all the dynamical models of the theory. These successive definitions try to capture the sense in which the Minkowski field qualifies as a piece of background structure where, for example, $\sqrt{-g}$ does not.

In the end, no particular tweak to the notion of absolute object succeeds in carving the space of theories in a way that all commentators agree on. Other definitions, for example in terms of variational principles, are available: In his comprehensive book on the subject (2023) James Read surveys 5 main kinds of classical definition alongside a number of precisifications and alterations for the quantum context. Inevitably, no definition proves apt for all applications. Gordon Belot (2011) argues that Background independence is a matter of degree. Read espouses explicit pluralism about background independence - rather than rendering background independence otiose, our array of definitions afford us a range of guiding principles depending on the context.

Read's optimism seems well-founded: despite the ambiguity of the term, background independence has been a major motivation behind a number of approaches to quantum gravity. Carlo Rovelli, in particular, saw background independence as a guiding principle for the original foundations of loop quantum gravity (Rovelli, 2004a). Various authors (e.g. Huggett and Vistarini (2015) and De Haro (2017)) have since argued that other approaches to quantum gravity - such as string theory and holography - can also offer background independent theories. The pluralism above suggests that we take such general claims with a pinch of salt, but nonetheless learn something from understanding the various senses in which these theories are or are not background independent.

5 Spacetime in quantum gravity

Discussions of spacetime in quantum gravity inevitably have a different flavour to those in the preceding sections: after all, we don't have an agreed theory of quantum gravity, or even a candidate theory that makes empirical predictions. Comments on individual theories are therefore speculative, and this article won't go into specific questions about loop quantum gravity, string theory or causal set theory (to name a few). But some broader philosophical questions about spacetime (or space and time) cut across different theories. One of these, the question of whether the general covariance of GR provides a guide to quantum gravity, has already been discussed in 4.3. Another concerns the possible disappearance of spacetime itself in quantum gravity. And a third concerns the 'problem of time', which arises quite generally for Hamiltonian theories of gravity.

5.1 The emergence of spacetime

Newtonian mechanics, quantum mechanics, and special relativity all proposed a fixed background spacetime on which our dynamics might be defined. General relativity changed this: spacetime itself, or at least the metric field that represents its geometry, is a dynamical player. But many theories of quantum gravity seem to need a more extreme shift - one in which nothing like a fixed or dynamical spacetime appears in the 'fundamental' quantum gravity theory. In such a context, the spacetime of General Relativity, and the space and time of our ordinary experience[9] are said to 'emerge' from the more fundamental theory.

The term 'emergent spacetime' originates in the theoretical physics community.[10] 'Emergence' here is thus intended in the sense of the physicist or philosopher of physics, where emergence is compatible with reduction. Butterfield (2011), for example, holds emergent behaviour to be behaviour that is novel and robust with respect to some lower-level theory. The emergent spacetime idea is therefore compatible with the project of deriving the GR field equations in some limit of a quantum gravity theory - presumably a desideratum for a theory of quantum gravity.

What then is required for a theory to posit emergent spacetime? In the usual case considered by philosophers, spacetime emerges from a theory with no candidate spatiotemporal variables. Spacetime is not present in the more fundamental quantum gravity theory, but is present in general relativity, the higher-level theory. But spacetime might also emerge from a theory that *does* have a candidate spacetime, if the relationship between that fundamental spacetime and the spacetime of GR is sufficiently distant that one cannot think of the GR metric as approximating the spacetime structure of the lower-level theory.

Exactly what level of distance is required for emergence is a matter of philosophical debate - see e.g. Butterfield (2011); Knox (2016); Franklin and Knox (2018); Franklin and Robertson (2021); Wallace (2022b); **?**); Palacios (2022).

Some have worried that the very notion of an emergent spacetime is incoherent. One source of these worries originates in debates about the status of configuration space in quantum mechanics: Maudlin (2007) suggests that a therory's empirical (and metaphysical!) coherence depends on the existence of what John Bell called 'local beables' (Bell, 1987, p.234) - fundamental objects located in space and time. Were that to be the case, the very notion of a non-spatiotemporal fundamental theory might seem problematic. Huggett and Wüthrich (2013) argue that emergent spacetimes are neither metaphysically nor empirically incoherent. While Maudlin believes that the physical salience of a higher-level structure must be secured by the nature of the lower-level entities that compose it, there is an (appealing) alternative: physical salience of lower-level structures is secured by their relation to empirically accessible higher-level theories. This implies that the structures of a non-spatiotemporal theory of quantum gravity gain their empirical significance and physical salience from the spatiotemporal entities and structures that emerge from them, rather than vice versa.

Traditional substantivalist views of spacetime might suggest that it cannot be a candidate for an emergent entity: if spacetime is the fundamental background or container in which all physical processes (including fundamental ones) play out, then it is not the kind of thing that can emerge from our fundamental theory. We therefore need an alternative way of thinking about spacetime if we are to entertain the possibility of emergent spacetime. One strand running through recent philosophical literature is *spacetime functionalism* (Lam and Wüthrich, 2018; Knox, 2013, 2019). On this view, spacetime is whatever fills some functional role - to use Lam and Wüthrich's slogan: *spacetime is as spacetime does*. Just as functionalism in the philosophy of mind is intended to help reconcile a physicalist neurological theory with the particular nature of mental phenomena, spacetime functionalism is intended to help us understand how a non-spatiotemporal fundamental reality can be reconciled with spatiotemporal phenomena. Opinions differ as to exactly how spacetime functionalism achieves this. For Knox (Knox, 2013, 2019; Knox and Wallace, 2023), spacetime functionalism is intended as an interpretative tool - it allows us to identify spacetime structure in a higher level theory. For Lam and Wüthrich, it aids in reduction. Butterfield and Gomes (2023) have recently argued that funcitonalism in physics should be seen as offering a reductive programme á la David Lewis (1972; 1970). However, such reductive programmes struggle to make sense of the *emergence* of spacetime: as Baron (2020) argues, functional reduction ultimately serves to identify spatiotemporal structure in the fundamental theory, and thus demonstrates that this theory contains spacetime after all. Another key debate in the spacetime functionalism literature concerns spacetime's functional role. Knox (2019) argues that many key aspects of spacetime involve picking out a structure of inertial frames, but critics (Read and Menon, 2021; Baker, 2021) argue that this fails to capture important features of spacetime. Lam and Wüthrich explore a wider range of roles, while Chalmers (2020, 2021) examines the role of spacetime in our phenomenal experience.

Beyond these broad debates, questions about the emergence of spacetime depend on the details of particular theories. Group Field Theories (a class of background independent approaches to quantum gravity) can give rise to 'geometrogenesis', a putative emergence of geometry (Oriti, 2014; Huggett, 2021). Loop Quantum Gravity's discrete spin network states are far-removed from the continuous spacetimes of general relativity and suffer from the 'problem of time' (see 5.2 for the problem of time, and Wüthrich (2021) for discussion of loop quantum gravity). Some physicists (e.g. Seiberg (2006a) or Horowitz and Polchinski (2009)) see string theory's AdS/CFT duality not as an exact duality but rather as an instance of the emergence of spacetime. Understanding particular theoretical instances of spacetime emergence depends on the particular details of the relation between these theories and GR (or some other spacetime theory), and thus need considerable speculative theoretical work.

5.2 The problem of time

In the roughest of terms, the problem of time in quantum gravity refers to the 'disappearance' of a time parameter when we attempt to quantize a reparameterization invariant theory like quantum gravity. It is sometime said to result from the clash between the absolute nature of time in quantum theories and its dynamical nature in General Relativity: this is at best a gross oversimplification. A lesser oversimplification points out that our quantization techniques usually require a theory to be cast in Hamiltonian form, and that for General Relativity, the Hamiltonian is zero, which implies no temporal change to observables of the theory. This section will attempt a to give a slightly more nuanced gloss on this latter claim, but will inevitably omit important technical and philosophical details. For a better, slightly less brief, overview, see Thébault (2021).[11]

Start with the Lagrangian formulation of a mechanical system - that is, the formulation that specifies the dynamics of the system in terms of the positions and velocities of its particles. Time in this kind of system plays one role as a parameter - it serves to label the succession of positions and velocities of the particles. But it also plays a second role in defining the velocities. Classical mechanics as standardly presented in the Lagrangian formulation is therefore *not* invariant under reparameterizations of time that preserve temporal ordering - if we change the time parameter in such a way that we change the time elapsed between two states of the world changes, we alter not only the labelling of successive states but also the velocities assigned to the particles.

However, some theories (including classical non-gravitational theories with the right characteristics - see Gryb and Thébault (2023)) can be cast in a reparameterization invariant form. That is, they are invariant under any change to the time parameter that leaves the temporal ordering of events the same. As Gryb and Thebault point out, one might have philosophical grounds for preferring such a theory - Leibnizian relationism about time implies that time should be reducible to temporal ordering of events. And General Relativity is one such theory: its diffeomorphism invariance implies that all smooth changes to the time coordinate preserve solutions of the theory, and the nature of its dynamical metric means that a preferred time coordinate cannot be reintroduced. But, as it turns out, reparameterization invariance implies a zero Hamiltonian.

Arguably, this zero Hamiltonian creates a 'problem of time' even in non-quantized theories, especially if relationism about time makes one resistant to a move back to a non-reparameterization invariant form of the theory. But this problem becomes particularly obvious and acute when we attempt canonical quantization of the theory. Following Dirac's method for quantizing constrained Hamiltonian theories (a zero Hamiltonian acts as a constraint), the observables of our quantized theory should commute with the constraint:

$$\{g, H\} = 0 \tag{6}$$

But observables that commute with the Hamiltonian are those that do not change over time - what Kuchař calls *perennials*. Straightforward quantization of any reparameterization invariant theory thus results in a theory whose physically measurable quantities are unchanging: hence the claim that time vanishes from the theory. Related lines of reasoning lead to the Wheeler-DeWitt equation, which suggests a frozen universal wavefunction:

$$\hat{H} |\Phi\rangle = 0 \tag{7}$$

As stated, the problem affects quite a large class of theories, but it is usually associated with 'canonical' quantum gravity theories like Loop Quantum Gravity. One solution, advocated by Carlo Rovelli (1991; 2002; 2004b; 1990), is to supplement the usual quantum notion of an observable with 'partial observables' that can serve as internal clocks. Rovelli claims that these partial observables, which do not commute with the Hamiltonian, are sufficient to develop a physically measurable notion of relative time - relative to some system of partial observables, we can measure change with respect to some other system of partial observables. The debate here turns on whether these partial observables are truly mneasurable - Thiemann (2008) claims that they are not. This is inevitably a theoretical and conceptual debate given the non-empirical status of quantum gravity: see Rickles (2008) for an account of how this connects to earlier philosophical debates.

One alternative approach to the problem of time comes from Gryb and Theébaulr (2012; 2014; 2016a; 2016b) who advocate what they call *relational* *quantization*. This approach seeks to reinstate a global time parameterization, although only up to rescalings, so there is no preferred temporal metric. Such an approach effectively requires a preferred foliation, something that general relativity does not admit of. However, alternative approaches offer some hope for such a foliation - for example *shape dynamics*, originally proposed by Julian Barbour and collaborators (Barbour, 2003; Anderson et al., 2003, 2005) and since developed by Gomes et al. (2011).

6 Conclusion: unifying themes

What, of anything, connects our various debates about the philosophy of spacetime physics? Several themes emerge from the debates discussed here. One obvious issue is the importance of symmetry, and the link between spacetime structure and the symmetries of the dynamics. In Newtonian mechanics and special relativity alike, the recognition of dynamical symmetries leads to the rejection of metaphysical claims about absolute space and time. And yet, despite the apparent simplicity of Earman's directive that we should match our dynamical symmetries to our spacetime symmetries (see 2.1), determining the relevant dynamical symmetries is a non-trivial issue.[12]

A second thread that weaves across different theories is the status of reference frames and coordinate systems. We saw this in the discussion of clock synchrony (3.3), the equivalence principle (4.1), the hole argument (4.2) and general covariance (4.3). In many of these cases there exists tension between the crucial representative capacities of reference frames and their associated coordinates, and our freedom to transform between coordinates. An orthodox, geometry-first view (as discussed in 3.4) holds that these coordinates only contain physics insofar as they reflect the symmetries of an invariant geometrical description. However, such views risk ignoring the centrality of coordinate based approaches to both applications and theory. Not only do virtually all applications of spacetime theories rely on coordinate descriptions, but not all spacetimes are well-suited to a coordinate-free characterisation in terms of differential geometry. Wallace (2019) argues that coordinate-based descriptions contain more physics than orthodox views give them credit for.

A final theme may be more surprising: questions about the philosophy of spacetime physics are shot through with questions about inter-theoretic relations. Some of these are obvious, as in the case of emergent spacetime (5.1). But others are less obvious - questions about Newtonian theories, for example, depend on questions of theory identity and equivalence, and perhaps also on our ideas about emergence.[13] Furthermore, the sequence of theories discussed here provide an example of how theories can remain in use in physics despite being apparently superseded by a more 'fundamental' theory. Understanding how Newtonian theories remain just as, if not more, relevant to astrophysics as general relativity requires a nuanced view of inter-theoretic relations.

Notes

[1]Stein wasn't the first to suggest that the geometrical tools used by relativity could be repurposed for classical mechanics. Hermann Weyl 1952, Élie Cartan 1923; 1924 and Kurt Friedrichs 1927 all proposed four-dimensional settings for classical theories, but Stein was the first to explicitly propose this as a solution to the Leibniz-Clarke debate.

[2]For an more thorough overview of classical spacetime structure, see Weatherall (2021)

[3]Saunders calls this Newton-Huygens spacetime, choosing to differentiate his presentation of the spacetime from one presented in terms of differential geometry.

[4]Einstein reportedly called Minkowski's presentation 'superfluous learnedness' (Pais, 1982, p.152).

[5]Other physics has further consequences for the philosophy of time that lie outside the scope of this article. For example, debates about the arrow of time are intertwined with the philosophy of thermodynamics and statistical mechanics. See **?** in this encyclopedia for more details.

[6]Read et al. (2017) explore the limitations of our minimal coupling prescriptions in some detail.

[7]Note that in the presence of fixed fields like the Minkowski metric, the relationship between general covariance and diffeomorphism invariance becomes more complex, and general covariance does not in general imply diffeomorphism invariance. See Read (2023) for details.

[8]For a comprehensive review of the general covariance debate up until the mid-nineties, see Norton (1993). For a sweeping look at the issues in the contemporary Background Independence debate, see Read (2023).

[9]The spacetimes of General Relativity and ordinary experience might or might not be the same thing. Arguably, at local and everyday scales, space and time behave much like Newtonian spacetime - whether one sees this spacetime as GR spacetime or as something that emerges from the relativistic description depends on one's views on inter-theoretic relations and emergent ontology.

[10]A well known reference is Nathan Seiberg's (2006b), but the ideas and term were around before this, for example in Cahill and Klinger (1996).

[11]This section owes a great deal to Thébault (2021)'s presentation of the problem.

[12]For more on the philosophy of symmetry, see, for example Baker (2010); Ismael and Van Fraassen (2003); Ismael (2021); Dewar (2019); Dasgupta (2021); Greaves and Wallace (2014); Wallace (2022a).

[13]See Dewar (2022), Weatherall (2019a) and Weatherall (2019b) or overviews of theoretical equivalence and Wallace (2012) for an argument that emergence is relevant to Newtonian theories.

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