48
SPACE AND TIME

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Introduction

The question that has dominated discussion of space and time in the philosophy of science concerns their *ontological status*. Newton, famously, claimed that space was an entity in its own right (1999 [1687]: 408). His *substantivalist* position was lambasted by Leibniz, who argued for the *relationalist* view that space is nothing "besides the order of bodies among themselves" (Leibniz 1956 [1716]: 26). Both views attracted adherents in the two centuries that followed, before the context was radically transformed by Einstein's theories of relativity.

In the first half of the twentieth century, philosophical consensus judged that general relativity vindicated Leibniz's relationalism (Reichenbach 1959). With the demise of logical empiricism, opinion changed. Newton was portrayed as making a respectable inference to the best explanation, from inertial effects to the existence of absolute motion and thus to absolute space. This inference (suitably modified) was thought to remain legitimate in general relativity. Recent historical and philosophical work reveals this to be a badly misleading caricature of Newton's arguments (Rynasiewicz 1995). But arguably this recent scholarship casts Newton, and his realism about spacetime structure, in even better light.

Another question concerns the *explanatory role* of space and time. The idea that Newton advanced an inference from inertial effects to the existence of space suggests a picture in which space exerts something like a causal influence on its material contents. Some think that this gets the order of explanation exactly the wrong way round: it is not that, for example, rods and clocks are constrained to behave as they do by the geometric structure of the spacetime in which they are immersed. Rather, goes the claim, it is the correlated lawlike behavior of rods and clocks that underwrites spacetime's geometric structure.

Two important topics are not discussed further below. The first is *conventionalism*: to what extent is our attribution of a particular geometry to physical space and time a stipulative convention? The second is the so-called "arrow of time" and in particular how the time asymmetry of thermodynamics is related to supposedly time-symmetric fundamental physics. Those interested in pursuing these topics are referred to the suggestions for further reading at the end of this chapter.

Space and time in classical mechanics

Newton was the progenitor of what we now recognize as physics, but he built on the work of a number of near contemporaries. In particular, he was indebted to Descartes for his first law of motion, the *principle of inertia*, which states that every body continues in its state of rest or uniform motion unless its state is changed by an applied force. This law plays a foundational role in Newtonian mechanics. Exaggerating slightly, the whole business of mechanics is to account for observed deviations from the inertial motions specified by the first law, in terms of the second law and particular force laws.

The principle of inertia also occupies a central place in Descartes's physics and yet he elaborated a philosophical account of motion hopelessly incompatible with it (Descartes 1985 [1644]). Descartes claimed that a body's motion, as ordinarily understood, is its change of position with respect to some arbitrarily chosen reference bodies, taken to be at rest. In addition, he identified a body's *true motion* with its motion from the vicinity of those bodies in immediate contact with it that are regarded as at rest.

Newton subjected Descartes's views to devastating criticism in a manuscript, known as "De Gravitatione," not published until the 1960s (Newton 1962). Newton details at length what he saw as absurd and self-contradictory aspects of Descartes's position. His most telling criticism, as Stein (1967) emphasizes, is the following.

According to both of Descartes's definitions, no body has a determinate velocity, and there is no definite trajectory it follows. For consider motion in the ordinary sense. This consists in change of position with respect to arbitrarily chosen bodies regarded as at rest. But which bodies can be regarded as at rest? Descartes cannot appeal to the sun or the fixed stars, for these are all in relative motion (both according to Descartes's vortex theory – as Newton painstakingly points out – and according to the mechanics Newton was to develop). What of motion in the strict sense? Here the matter is even worse. A body's motion is defined with respect to those bodies in immediate contact with it, which (for any body "truly moving") are continually changing. Nothing in either picture allows us to identify at some time the exact places through which a body has traveled, and so *a fortiori* nothing can tell us whether those places constitute a straight line which the body has traversed at a uniform rate. Descartes's account of motion cannot be combined with the principle of inertia, which requires that there be a fact of the matter about whether a body is moving uniformly.

Differential geometry and the notion of spacetime provide an illuminating framework in which we can clearly state which spacetime structures Descartes acknowledges, and which additional structures the principle of inertia requires. Figure 48.1 is a spacetime diagram depicting aspects of Descartes's universe. There is an objective fact about how spacetime divides into instantaneous states of the world ("simultaneity surfaces"), the geometry of each of which is Euclidean. There are facts of the matter about the relative temporal intervals (T_{AB} and T_{BC}) between instants. At each instant, the world is a plenum of only one kind of stuff, whose only attribute is extension. There must be facts of the matter about the identity over time of the parts of the plenum (such as *a* and *b* in the diagram) for there to be facts about the relative

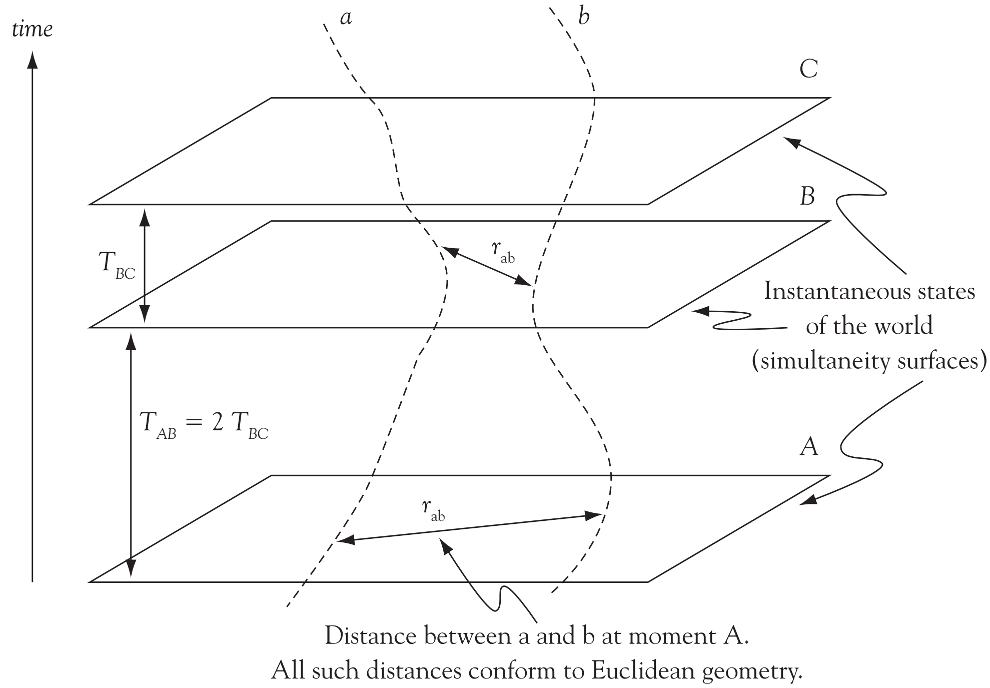

Figure 48.1 Descartes's spacetime

motions of such parts. But, crucially, these cross-time identities between the parts of the material world are the only links between instants.

Without some additional structure, no determinate motion can be assigned to body *a*. Newton's solution was to postulate the existence of "absolute places": things truly distinct from bodies whose relative positions remain constant. This additional structure is depicted in Figure 48.2: point *q* at *B* represents the same point of absolute space as point *p* at *A*. There is therefore a determinate fact of the matter that *a* moves (changes its absolute place) between *A* and *B*. There being a fact of the matter about the relative temporal intervals between instants (i.e., a temporal metric) is also essential in securing a fact of the matter about the uniformity of such motion.

Newton's absolute space successfully grounds the distinctions that his laws require, but it underwrites some unneeded, physically undetectable distinctions too. A *frame of reference* is a standard of rest, simultaneity, and time with respect to which determinate motions can be assigned to bodies. Now imagine judging motion relative to a frame of reference moving uniformly relative to Newton's absolute space but otherwise matching Newton's framework from instant to instant. This frame agrees with Newton's on whether bodies are moving uniformly and, crucially, on the magnitude of their accelerations and hence on the forces to which they must be subject. In other words, Newton's laws do not pick out a unique standard of rest. Instead a whole family of frames of reference (the *inertial frames*) suffice to ground the distinctions that the laws require. Although a body's acceleration is empirically determinable, its velocity with respect to absolute space is not. The *relativity principle* is the statement of this equivalence among the inertial frames.

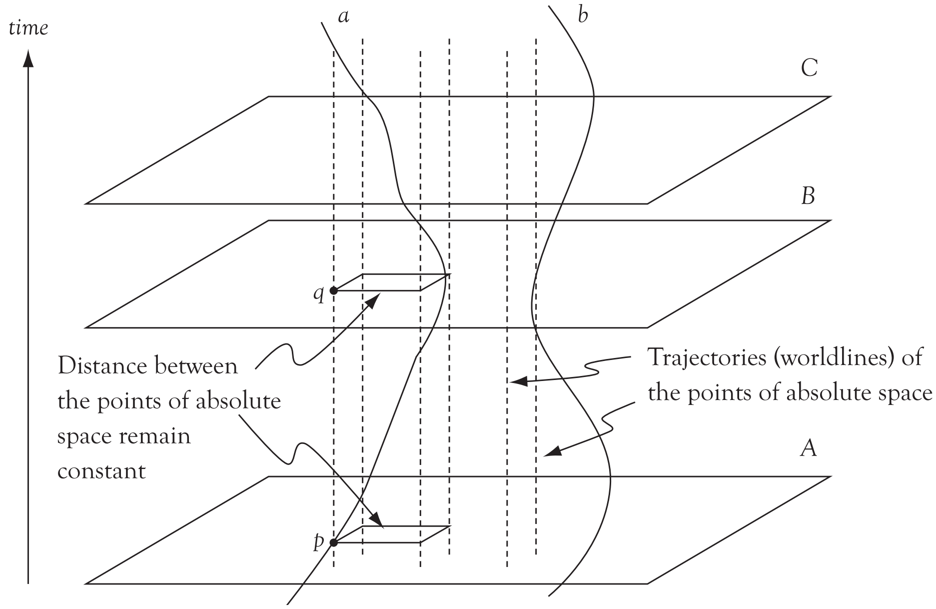

Figure 48.2 Newtonian spacetime

In the context of the dispute over the reality of space, the situation presents something of a dilemma. On the one hand, to make sense of the successful laws of mechanics we have to acknowledge more spacetime structure than Descartes and Leibniz were prepared to countenance. On the other hand, Newton's manner of securing a sufficiently rich structure introduces more than is required. Is there a third way?

Substantivalism, relationalism, and Mach's principle

Newtonian mechanics is formulated in terms of the simultaneity structure, instantaneous Euclidean geometry, and temporal metric common to Descartes's and Newton's spacetimes. It additionally requires some extra *transtemporal* structure. Geometrically, the additional structure required is a standard of *straightness* (for paths in spacetime), provided in differential geometry by a mathematical object called a *connection*. The possible trajectories of ideal force-free bodies correspond to straight lines in spacetime that do not lie within surfaces of simultaneity. These straight lines fall into families of non-intersecting lines that fill spacetime. Each family of lines forms the trajectories of the points of the "space" of some inertial frame. Newton's laws can be recast in a coordinate-free manner that makes explicit reference to this geometrical structure.

Now one interpretation of this structure reifies, not Newton's absolute space, but *spacetime*. One conceives of spacetime as a genuine entity literally endowed with the geometric structure that the connection, among other things, encodes. In general there are two relationalist strategies to resist such *spacetime substantivalism*:

(1) Replace Newtonian physics with an alternative theory that transparently makes do only with Cartesian spacetime structure (or an even weaker structure).
(2) Provide a relationalist interpretation of standard Newtonian mechanics.

Either way, one must provide a reduction of the empirically identifiable inertial frames.

The first strategy is famously associated with Ernst Mach. Newton claimed that the surface of water in a bucket suspended from a wound cord and then released becomes concave because it is rotating with respect to absolute space. Mach noted that one might instead attribute the effect to the water's rotation with respect to the fixed stars. This points towards the possibility that detectable local inertial structure is determined by distant masses. Inertial effects might result from bodies' non-uniform motion with respect to the average mass of the universe.

One theory along these lines was repeatedly rediscovered during the twentieth century. Although it recovers various welcome Newtonian features, it also predicts a mass anisotropy effect of a size ruled out by experiment. In the 1980s, however, Barbour and Bertotti discovered a new way to formulate a form of Machian mechanics (for references, see Barbour 1994).

One standard formulation of Newtonian dynamics involves a system's *configuration space*, Q. For a system of N massive point-particles, each point of its $3N$-dimensional configuration space corresponds to a specification of the positions of each particle in absolute space. As the system evolves, the point in configuration space representing the system's instantaneous state traces out a continuous curve. In the Lagrangian formulation of mechanics, one considers curves representing possible histories for the system in the product space formed from Q and a one-dimensional space T representing time. The physically possible history between two instantaneous states is the one for which a particular function of such histories (the *action*) takes a minimum (or, in general, an extremal) value.

Barbour and Bertotti reject Q in favor of the *relative configuration space* (Q_{RCS}), the points of which represent only the relative distances between particles. Their theory involves a metric defined on Q_{RCS} through a process Barbour calls "best matching." Imagine rigidly shifting infinitesimally differing relative configurations with respect to one another so as to extremize a trial "distance" function between them. The relative placement of the two configurations that extremizes the function is their "best matched" position, and the distance function so defined provides a metric on Q_{RCS}. Shortest paths (with respect to this metric) between two points of Q_{RCS} then represent the physically possible sequences of relative configurations for the system.

Note four features of Barbour and Bertotti's theory. First, it is clearly relational; the only spacetime structures involved in the theory are the simultaneity surfaces and the Euclidean nature of the distances between material points with respect to such surfaces. Second, although the temporal metric and inertial structure of Newtonian mechanics do not feature in the foundations of the theory, they do emerge from the dynamics. The best matching process described in the previous paragraph yields a preferred way of identifying the points of space from instant to instant (the identification provided by the "best-matched" relative positioning). The temporal metric is recovered as a simplifying parameter. Third, the sequences of relative configurations predicted by the theory exactly match those of a subset of the solutions of standard Newtonian theory, namely Newtonian solutions with zero overall angular momentum. In Popperian terms this makes Barbour and Bertotti's the better theory: it is more falsifiable. The relative standing of the two theories becomes particularly interesting when one notes that our universe appears to have no overall rotation. The Machian theory then looks superior both because it saves the phenomena with less postulated theoretical structure and because it predicts and explains a striking feature of our universe, namely its non-rotation. Finally, the theory generalizes to relativity. A particular formulation of general relativity itself conforms to a natural extension of the framework. This suggests a novel interpretation of general relativity, as well as new ways in which general relativity might be generalized in the search for new theories.

While Machians offer a *dynamical* reduction of inertial structure, the alternative anti-substantivalist strategy allows that inertial structure may feature in a theory's formulation but seeks an interpretation of the familiar equations that offers a *metaphysical* reduction. One suggestion is that relationalists are simply entitled to claim that, as a matter of physical necessity, the evolution of the relative distances between bodies is constrained so that they obey Newton's laws with respect to some sets of coordinate systems on space and time. Relationalists are not thereby committed to the independent reality of the spacetime structure encoded in these coordinate systems. This gives rise to questions of explanatory priority. The view involves the claim that it is the lawlike behavior of bodies that grounds spacetime's having the inertial structure that it has. It is not the independent existence of this structure, together with the way the laws of nature constrain bodies to conform to it, that explains the behavior of bodies.

Huggett (2006) has pursued a related approach within the Mill–Ramsey–Lewis framework for laws of nature. He suggests that, in a Newtonian context, the relationalist can take the total history of the relative distances between all the particles in the universe, together with facts about their masses and other intrinsic properties, to exhaust the fundamental facts about the world. If the pattern of relative distances is such that, relative to some spacetime coordinate systems, the particles obey Newton's laws together with simple force laws, then such equations will clearly constitute the description of the universe that best combines simplicity and strength. In this way, Huggett claims, a relationalist ontology can underwrite Newton's privileged inertial frames. It is not clear whether the strategy successfully extends to relativity.

Special relativity

In the nineteenth century, electric and magnetic phenomena were unified by Maxwell's equations for the electric and magnetic fields. Light was recognized to be a type of electromagnetic radiation: a propagating wavelike disturbance in electric and magnetic field values. Such electromagnetic waves were thought to be disturbances of a substantival entity, the ether. Just as the speed of sound in air is independent of the speed of its source, so this picture accounted for the fact that the speed of light is independent of the speed of its source and (in the ether's rest frame) isotropic.

At one level, this picture is no more in conflict with the physical equivalence of inertial frames than the fact that some particular body of air is at rest in some particular inertial frame. But the picture does privilege the rest frame of the all-pervading ether. It also suggests that we should be able to determine our velocity with respect to this privileged frame by observing an anisotropy in the velocity of light. Famously, experiments performed by Michelson and Morley failed to detect any anisotropy. But of equal importance for Einstein was that the conceptual difference between rest and uniform motion relative to the ether appeared to have as little empirical reality as Newton's distinction between rest and uniform motion with respect to absolute space. Maxwell's equations predict that a relative motion between a conductor and a magnet will induce an electric current in the conductor. From the pre-relativistic perspective, the explanation of this effect is very different depending on whether the magnet or the conductor is at rest in the ether. But since the effect is the same in either case, this looks like a difference without a difference. Einstein's genius was to see how to restore the strict equivalence of inertial frames consistently with the isotropy and the source-independence of the speed of light.

In 1905 Einstein derived the *Lorentz transformations*; coordinate transformations between inertial frames that are consistent with both the relativity principle and the constancy of the speed of light. A key step was his recognition that two frames in uniform relative motion can disagree about which sets of events are simultaneous. Suppose that in the inertial frame of reference in which I am at rest I measure the two-way speed of light to be isotropic. This suggests that light signals are a sensible way for me to synchronize distant clocks. I fire a light pulse at a distant mirror and record when I receive its reflection. If I regard the reflection event as occurring at a time half way between the original emission event and the reception event, I will also judge the one-way speed of light to be isotropic. But now suppose you are moving uniformly with respect to me. If the relativity principle is true, our rest frames are strictly physically equivalent, and such a synchronization method must be equally legitimate for you. As is shown in Figure 48.3, by their both encoding this method of synchrony, the two frames will disagree about which sets of event are simultaneous.

The Lorentz transformations predict that moving rods contract and that moving clocks run slow. For consider: I measure the speed of light to be $c = 3 \times 10^8$ ms^{-1}, but so does someone moving relative to me at $c/2$. If I am to predict that they also measure the velocity of light to be c, I must judge that their measuring rods and clocks are contracted and dilated relative to mine. (The situation is entirely symmetrical: consistently with the relativity principle, they judge my rods and clocks to be contracted and dilated by the same amount. Our disagreement about which events are simultaneous is an essential element in what makes this symmetry possible.) In this way the spatial and temporal intervals between any two events becomes a frame-relative matter. But the *spacetime interval*, $\Delta s^2 = \Delta t^2 - \Delta x^2$ (in units where the speed of light is 1), is a frame-invariant quantity.

As Minkowski showed, this fact finds natural expression in terms of the attribution to spacetime of an elegant geometric structure. Spacetime is thought of as a (pseudo-)

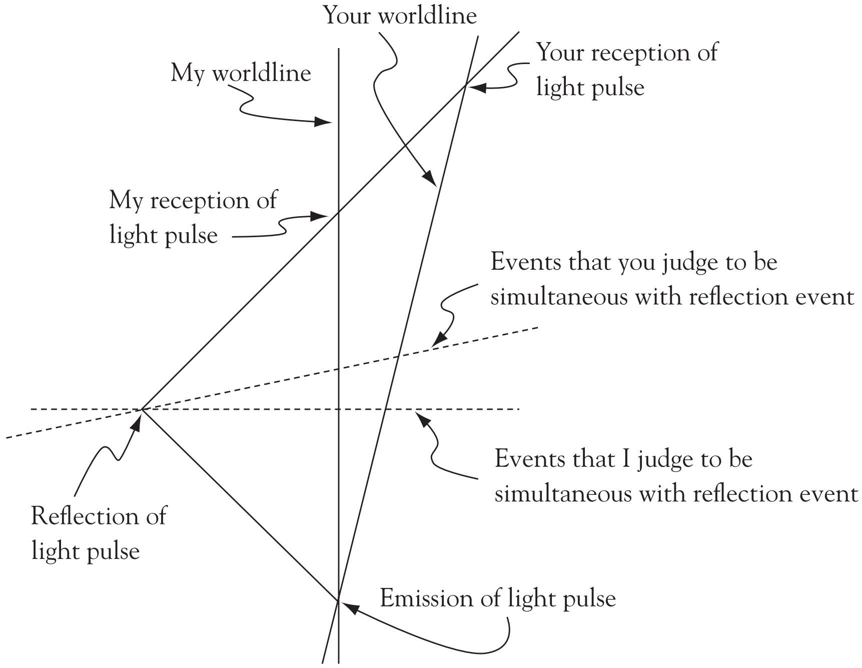

Figure 48.3 The relativity of simultaneity

metric space: there is an objective fact about the spacetime *distance* between any two spacetime points. With respect to any point p of spacetime, points in the rest of spacetime fall into three classes: (i) points that are *spacelike* related to p (points for which $\Delta s^2 < 0$; they cannot be connected to p by any signal); (ii) points that are *timelike* related to p (points for which $\Delta s^2 > 0$; they are points that can be connected to p by signals traveling at less than the speed of light); and (iii) points that are *lightlike* related to p (points for which $\Delta s^2 = 0$ and which are connectable to p by signals traveling at the speed of light). The lightcone at p (the set of points *lightlike* related to p) separates points spacelike related to p from the two sets of points timelike related to p in its past and future (see Figure 48.4). Even the privileged inertial trajectories receive an interpretation in terms of the spatiotemporal metrical structure: they are paths of greatest temporal length between any two timelike related points. The inertial connection thus no longer needs to be postulated as an independent element.

The geometric structure of Minkowski spacetime features in the formulation of any specially relativistic theory. This is transparent in generally covariant, coordinate-free formulations of the equations, where the Minkowski metric structure is explicit. But it is equally true of the "standard" formulations of the equations, which hold true only relative to privileged inertial coordinate systems related by Lorentz transformations. These coordinate systems are the spacetime analogues of Cartesian coordinates on Euclidean space: the coordinate intervals encode the spacetime distances. Minkowski geometry is thus implicit in the standard formulation of the laws. Recall the spacetime substantivalist interpretation of Newtonian mechanics: spacetime itself is regarded as a genuine entity literally possessing the geometric structure in terms of which

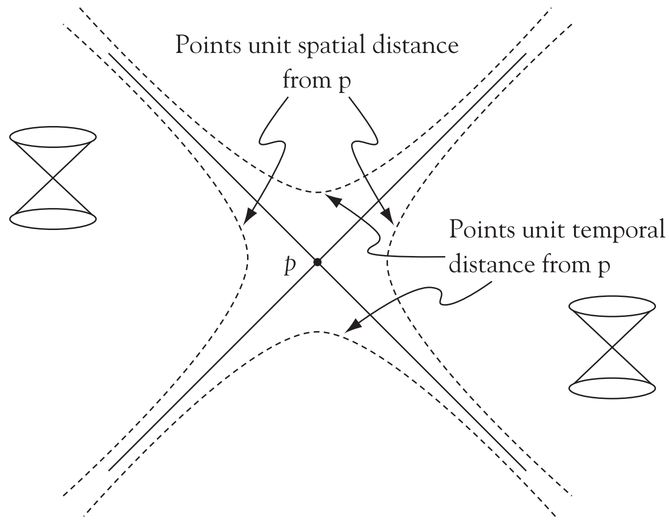

Figure 48.4 Minkowski spacetime

Newtonian mechanics is formulated. The elegant, unified nature of the geometric structure of Minkowski spacetime is even more suggestive of this view.

Substantivalists typically hold that certain phenomena can be explained by appeal to the geometry of spacetime. Such substantivalist explanations do not involve simplistic appeals to geometry. Consider the "twin-paradox" scenario. Of two initially synchronized clocks, one remains on earth while the other performs a round trip at near the speed of light. On its return the traveling clock has ticked away less time than the stay-at-home clock. The geometrical facts behind this phenomenon are straightforward: the inertial trajectory of the stay-at-home clock is simply a longer timelike path than the trajectory of the traveling clock. The substantivalist, however, does not offer as a brute assertion the claim that a clock's ticks must match the spacetime distance along its trajectory. Clocks are complicated systems the parts of which obey various (relativistic) laws. One should look to these laws for a proper understanding of why the ticks of such a system will indeed correspond to equal temporal intervals of the system's trajectory. But since, for the substantivalist, those laws make (implicit or explicit) reference to an independently real geometric structure, an explanation that appeals to the details of the laws will, in part, be an explanation in terms of the postulated geometric structure.

As in the case of Newtonian mechanics, there is an alternative, relationalist point of view. Rather than interpreting the equations as expressing the lawlike ways in which the material content of spacetime is constrained to be adapted to independently real spacetime structure, one might view the lawlike constraints on the behavior of material systems, and in particular the Lorentz symmetries inherent in those laws, as underwriting the geometric structure of spacetime. The latter point of view has been pursued by Brown and Pooley (see, in particular, Brown 2005). To reduce things to slogans, the issue is whether rods and clocks do what they do because spacetime has the geometrical structure that it has (and the laws constrain them to be adapted to this structure in ways that can be made perfectly explicit and perspicuous), or whether spacetime has the geometric structure that it has because rods and clocks (are constrained by Lorentz-invariant laws to) do what they do.

A full defense of the second view arguably requires further articulation of the relevant notion of laws and, in particular, how the symmetries of such laws should be understood independently of spacetime's geometric structure. But there is one reason why one might be tempted to pursue this anti-substantivalist program. The geometrical structures of the spacetimes of classical mechanics and special relativity place constraints on the evolution of the material content of spacetime. In at least this sense, spacetime *acts* on matter. But matter has no effect on spacetime's geometric structure. This violation of the *action–reaction principle* lies behind the anti-realist attitude that some hold towards the spacetime structures of these theories. As we shall see, this asymmetry is abolished in general relativity.

Special relativity and the philosophy of time

Three debates dominate the philosophy of time. First there is the debate between eternalists and their opponents. Just as distant places are standardly taken to be no less real than our immediate spatial locality, *eternalists* regard past and future times as no less real than the present moment. They are opposed by *presentists*, who think that only the ever-changing present moment exists, and by those who endorse a "growing block" model of the universe in which the past and present, but not the future, exist.

The second debate is between *tensers* and *detensers*. Tensers believe that tensed language is ineliminable in any metaphysically adequate account of reality. They believe in observer-independent tensed facts. Detensers, in contrast, view tense as an indexical device, and believe that tensed language can be given tenseless truth-conditions, just as truth-conditions for sentences involving "here" and "there" can be stated in language that presupposes no particular spatial location.

The third debate concerns how ordinary objects persist through time. *Perdurantists* hold that an object's existence at more than one moment is analogous to a spatially extended object's (partial) existence in more than one place. Objects extend through space in virtue of being composed of distinct parts wholly and exactly located at distinct spatial locations. Perdurantists claim that objects persist in virtue of having numerically distinct *temporal parts* exactly located at the different times at which they exist. Perdurantists are opposed by *endurantists*, who deny that persisting objects are made up of momentary temporal parts.

The first two debates are closely related to another question: is there real *becoming* and temporal passage. Critics of the combination of eternalism and detenserism charge that it depicts a static world devoid of real change. Defenders respond that change is simply a matter of objects exemplifying different properties at different times. The felt passage of time involves nothing more than experiencing subjects enjoying a sequence of different perspectives on reality at the different times at which they exist. The idea of an objective flow of time over and above these appearances is, eternalist detensers claim, incoherent.

Eternalism, detenserism, and perdurantism all involve the claim that time is, in particular ways, like space. The views therefore find a natural home in relativistic spacetime, in which a distinction between spacelike and timelike relations is drawn but space and time themselves do not feature. But while perdurance is natural from the point of view of relativity, persistence by endurance is not obviously incompatible with Minkowski spacetime. In contrast, relativity favors an eternalist detenser view much more strongly.

The trouble with the alternatives is that their formulation requires something like a *present moment*, either to be the literal extent of reality or to be the boundary between what has objectively become and what is yet to occur. Properly relativistic spacetime simply admits no such thing. Pre-relativistic spacetimes also do not include a privileged moment. But they do offer a privileged family of simultaneity surfaces, each of which can be understood as representing the present moment as time passes (in whatever sense is required).

The tenser can choose to regard the relativistic picture of the world as incomplete. While this view is logically compatible with relativity, it prompts an immediate question: are the extra-relativistic facts observable? For anyone who believes that in principle no experiential phenomena fall outside the domain of (relativistic) physics, including phenomena associated with our idea that time passes, the tenser's postulated additional metaphysical facts lack motivation. They are unobservable to the extent that even the nature of our temporal experience fails to constitute evidence for them.

The best-known explicit argument to the effect that relativity rules out a tensed view of time was given by Putnam (1967). He was roundly criticized by Stein (see, especially, Stein 1991), but ultimately it is not clear that the two should be seen as disagreeing (Saunders 2002). Stein criticizes Putnam for using concepts that are inappropriate in relativity. But Putnam's argument is easily reformulated without those concepts (just as the definitions of eternalism and detenserism above can be made relativistically acceptable by replacing reference to "times" with reference to appropriate spacetime notions). On the other side, Stein's definition of "that which has become as of some spacetime point" (in terms of the past lightcone of the point) seems entirely congenial to the eternalist, who is surely obliged to give an account of temporal passage, at least as experienced. Stein's point-relative definition makes sense in such a context, but it cannot ground a more robust ontological distinction without relativizing what is real to spacetime points.

General relativity

Special relativity restored the full equivalence of inertial frames. Einstein next sought both a relativistic theory of gravity and a theory that generalized the relativity principle to frames of reference in arbitrary relative motion. A key step on the way to general relativity was the *equivalence principle*. In Newtonian theory the gravitational force on a body depends linearly on its mass. As a result the rate at which bodies accelerate in a gravitational field is independent of their mass and constitution. Bodies subject to a homogeneous gravitational field will describe the same trajectories with respect to an inertial frame as those described by force-free bodies with respect to an appropriately accelerated frame. Einstein generalized this, postulating a full equivalence between physics in the presence of a uniform gravitational field and in a uniformly accelerated frame.

Another key idea was that the theory should be *generally covariant*: its equations should hold true in coordinate systems related by smooth but otherwise arbitrary transformations. The group of these transformations contains as a proper sub-group transformations between frames of reference in arbitrary states of motion. Hence any generally covariant theory would seem to embody a generalized relativity principle. Einstein's equations of 1915 are indeed generally covariant, but the modern understanding of the principles that led Einstein to their discovery could not be further from Einstein's original view.

As Kretschmann noted in 1917, general covariance appears to be a constraint only on a theory's formulation and not its empirical content. Newtonian and specially relativistic theories were subsequently formulated generally covariantly. General covariance thus cannot implement a generalized relativity principle for these theories involve only restricted relativity principles involving the equivalence of frames adapted to the theories' spacetime structures. It is the existence of non-trivial symmetries of these structures that leads to a plurality of equivalent frames. *Arbitrary* frames of reference in such theories are not physically equivalent.

The points of comparison between a specially relativistic theory and its generally relativistic analogue are instructive. Both theories involve a (pseudo-)metrical spacetime structure of the kind discussed under "Special relativity." The generally covariant equations that determine locally how material fields in spacetime must be adapted to this structure are also identical. The *sole* difference is that the spacetime structure of the specially relativistic theory is stipulated to be *flat*, while that of the generally relativistic theory is curved. Einstein's field equations relate the curvature of spacetime to the stress–energy properties of its material content, and thus matter finally *acts back* on spacetime.

Spacetime's variable curvature means that, in general, extended privileged coordinate systems adapted to spacetime's geometrical structure do not exist. However, for each point in spacetime, there are privileged *local* coordinate systems centered around the point. In such coordinate systems the equations governing matter reduce to their "standard" special relativistic form at that point. This requirement is what is nowadays known as the *equivalence principle*.

The equivalence of an accelerated frame and an inertial frame containing a uniform gravitational field is secured by denying the existence of the latter. What were previously thought to be such things (for example, to a good approximation, short-lived, spatially restricted frames comoving with the surface of the earth) turn out to be non-inertial, accelerated frames. The true inertial frames are the (infinitesimal) "freely falling" frames. In general relativity there is no force of gravity. Phenomena previously attributed to the action of a force are either to be recognized as artifacts of describing things with respect to accelerated frames or as manifestations of spacetime curvature.

In the picture just sketched, substantivalism is vindicated. Previously immutable spacetime structures are now dynamical players, on all fours with the contents of spacetime. There would seem to be little hope of a relationalist eliminative reduction of spacetime structure along the lines of Brown's dynamical approach to special relativity. Brown himself is a realist about the metric field, but does not regard himself as a substantivalist. He views the metric field as just another dynamical field that only merits a geometric interpretation in virtue of the special way it interacts with other fields. At this point it is not clear how much of substance remains in dispute. All sides think the metric field represents something genuinely physical. The substantivalist stresses the continuities between its role in general relativity and the role of the analogous structures in pre-relativistic theories (structures universally regarded as representing properties of spacetime). Brown stresses that the field connects to the physical geometry exemplified by material systems only through the unique way in which it couples to other fields. But this is also true of the analogous fields in pre-relativistic theories.

There remains the Machian route. In the standard formulation of general relativity, the field encoding the *four*-dimensional geometry of spacetime is taken as one of the basic variables. But the equations can be recast so as to describe the evolution of the geometric structure of *three*-dimensional space. This decomposition is well known and is central to one of the main approaches to quantum gravity. What Barbour's Machian perspective stresses is that this decomposition can be understood in genuinely three-dimensional terms. According to the Machian, four-dimensional spacetime structure, in particular distances along timelike curves and the privileged inertial trajectories, emerges from the relational dynamics of three-dimensional space.

In one sense the picture is substantivalist: the theory's basic entity is (instantaneous) space itself. But in another sense relationalists are vindicated because the transtemporal structure that led Newton to postulate absolute space is seen as redundant. The interesting interpretative question is no longer whether spacetime structure is reducible to properties of the material contents of spacetime, but whether three-dimensional or four-dimensional structure is fundamental.

The hole argument

Some reject the substantivalist interpretation of general relativity because of the *hole argument*. The argument, originally due to Einstein and revived in the 1980s by Stachel, was cast as an explicitly anti-substantivalist argument by Earman and Norton (1987). It revives one of Leibniz's objections to Newton's absolute space, which I rehearse briefly.

According to Leibniz, defenders of absolute space are committed to the following violation of the *principle of the identity of indiscernibles*. Absolute space is homogeneous and isotropic: no point of space differs qualitatively from any other in its purely spatial characteristics. But since the parts of space are supposed to be real individuals, we have to recognize as a possible world distinct from the actual world a universe in which the entire material content of the universe occupies (at each moment) a location 5 feet to the North, say, of the position it actually occupies (at that moment). Such a universe is in every way identical to the actual world except for facts about where things are in space.

Unobservable global location differences might look suspicious, but many modern substantivalists were happy to bite the bullet. The twist provided by the hole argument is that, for generally covariant theories, such differences lead to a generic and radical breakdown in determinism.

Let (M, g_i, φ_i) be a model of a possible spacetime. M is a four-dimensional manifold of points intended to represent the points of spacetime. Defined on it are various fields: the g_i represent the geometric structure of spacetime and the φ_i represent its material content. A non-trivial diffeomorphism of the manifold, d: $M \rightarrow M$, is a differentiable bijective mapping of the manifold onto itself. It can be used to define a new model, $(M, d^*g_i, d^*\varphi_i)$, involving new fields that are defined in terms of the old by the map induced by the diffeomorphism. The two models are isomorphic: they differ solely over *where* on the manifold structurally identical sets of fields are placed. If (M, g_i, φ_i) is a model of a generally covariant theory, T, $(M, d^*g_i, d^*\varphi_i)$ is also a model of T, no matter what diffeomorphism is used to generate it. In particular, d might be a *hole diffeomorphism*: a map that is non-trivial only in a restricted region (the so-called "hole"), for example, all of M to the future of some three-dimensional spacelike "slice."

Various manifold points common to (M, g_i, φ_i) and $(M, d^*g_i, d^*\varphi_i)$ are mapped to different field values in each model. This suggests that certain spacetime points are represented as having different properties by each model and therefore that the substantivalist should interpret the two models as representing distinct possible worlds. But when d is a hole diffeomorphism, (M, g_i, φ_i) and $(M, d^*g_i, d^*\varphi_i)$ represent spacetimes that are identical up to some time but that then differ – a clear violation of determinism.

The models (M, g_i, φ_i) and $(M, d^*g_i, d^*\varphi_i)$ differ only over *which* points of M are assigned the various properties common to both models. One way to deny that T is indeterministic is thus to deny the existence of spacetime points. It is less clear whether those who believe that the points of M represent real, concrete spacetime points must accept that (M, g_i, φ_i) and $(M, d^*g_i, d^*\varphi_i)$ represent distinct yet genuinely possible worlds. In the wake of Earman and Norton's hole argument, most philosophers concluded they do not.

One route to this conclusion returns to Leibniz. Leibniz mounted an exactly parallel argument against the existence of atoms. Suppose that the actual world contains two intrinsically identical atoms, *a* and *b*. Leibniz argued that anyone committed to the existence of such things must admit as a genuinely distinct possible world a universe that differs from the actual world solely in the switching of *a* and *b*. The two worlds differ solely over which objects (*a* and *b*) have the various sets of relational characteristics common to both worlds. But many philosophers are skeptical of such *haecceitistic* distinctions, and believe that they can be given up without giving up the fundamental reality of the individuals involved, whether material atoms or spacetime points.

Earman himself believes that this response leaves philosophical discussion of general covariance irrelevant to the concerns of physicists grappling with the project of unifying quantum mechanics and gravity. Some workers in this field do draw from the hole argument the conclusion that general relativity breaks decisively from previous theories precisely in embodying a relational conception of space and time. But it is unclear that terms such as "relational" are being used to map out exactly the same notions by physicists and philosophers. In seeking to identify the conceptually novel elements in general relativity, physicists have recently focused on its *background independence*. As mentioned, in classical and specially relativistic theories, spacetime structure constrains the evolution of the material content of spacetime but is not acted back upon by matter. It is thus a background against which the dynamics is defined; it is not itself a dynamical player. In general relativity this asymmetry is abolished. But this notion of background independence would seem to have little to do with the hole argument.

See also Conventionalism; Explanation; Logical empiricism; Physics; Realism/anti-realism; Symmetry; Underdetermination.

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Further reading

Both Larry Sklar's *Space, Time, and Spacetime* (Berkeley: University of California Press, 1974) and Barry Dainton's *Time and Space* 2nd edn (Chesham: Acumen, 2011) are accessible and wide-ranging, covering conventionalism, the direction of time, and the substantivalist–relationalist debate. Roberto Torretti's *Relativity and Geometry* (Oxford: Pergamon Press, 1983; New York: Dover, 1996) is a masterful, historically sensitive philosophical study of Einstein's theories of relativity. John Earman's *World Enough and Space–Time: Absolute versus Relational Theories of Space and Time* (Cambridge, MA: MIT Press, 1989) is an incisive study of the substantivalist–relationalist dispute from its historical origins up to the immediate responses to his and Norton's Hole Argument. Norton's "The Hole Argument," in Edward N. Zalta (ed.) *Stanford Encyclopedia of Philosophy* (http://plato.stanford.edu/entries/spacetime-holearg) gives references to more recent discussion. For a non-technical debate about the relevance of some of these issues to conceptual problems in quantum gravity, see Earman's "Thoroughly Modern McTaggart: Or, What McTaggart Would Have Said If He Had Read the General Theory of Relativity," *Philosophers' Imprint* 2 (2002) (http://www.philosophersimprint.org/002003); and Tim Maudlin's reply in the same issue. Robert DiSalle's *Understanding Spacetime* (Cambridge: Cambridge University Press, 2006) focuses on issues orthogonal to the substantivalist–relationalist debate, emphasizing how conceptual analysis of the concepts of space and time implicit in scientific practice has been crucial to theoretical progress. Chapters 3 and 4 contain a sympathetic but critical discussion of conventionalism. For a version of the logical positivists' conventionalism, see Hans Reichenbach's *The Philosophy of Space and Time*, trans. Maria Reichenbach (New York: Dover, 1957). Independently of general theses concerning conventionalism, there is the question whether *simultaneity* is conventional in relativity. Central to this debate is a uniqueness result proved by David Malament in "Causal Theories of Time and the Conventionality of Simultaneity," *Noûs* 11 (1977): 293–300. Robert Rynasiewicz's "Is Simultaneity Conventional Despite Malament's Result?" *Philosophy of Science* 68 (2001) (Supplement): S345–S357, provides a way into this literature. Huw Price's *Time's Arrow and Archimedes' Point* (Oxford: Oxford University Press, 1996) and David Albert's *Time and Chance* (Cambridge, MA: Harvard University Press, 2000) are two recent books devoted to the problem of the direction of time. A central topic is the so-called "past hypothesis": that the state of the early universe was a state of very low entropy, and in particular whether these initial conditions stand in need of explanation. In "Measures, Explanation and the Past: Should 'Special' Initial Conditions Be Explained?" *British Journal for the Philosophy of Science* 55 (2004): 195–217, Craig Callender argues that it does not. In "The 'Past Hypothesis': Not Even False," *Studies in History and Philosophy of Modern Physics* 37 (2006): 399–430 (an issue of the journal devoted to the arrow of time), Earman argues that the hypothesis cannot do the work its defenders claim. In "Bluff Your Way in the Second Law of Thermodynamics," *Studies in History and Philosophy of Modern Physics* 32 (2001): 305–94, Jos Uffink examines the status of time asymmetry in thermodynamics itself. Those interested in the compatibility of relativity and an objective passage of time should start with Howard Stein (1991). The Supplement to *Philosophy of Science* 67 (2000) contains symposium papers on the topic by Savitt, Hinchliff, Callender, and Saunders. A number of recent papers are also found in Dennis Dieks (ed.) *The Ontology of Spacetime* (Amsterdam: Elsevier, 2006). The nature of persistence in relativity has attracted attention only recently. For an overview and references, see Ian Gibson and Oliver Pooley, "Relativistic Persistence," *Philosophical Perspectives* 20 (2006): 157–98.

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