Grounding the Future of Physics in The Leibniz-Clarke Correspondence

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The Past and Future of Leibniz-Clarke

In the famous series of arguments between Gottfried Leibniz and Samuel Clarke known as *The Leibniz-Clarke Correspondence*[1], the two philosophers (shown in Figure 1) offered competing viewpoints on Newton's physics and the corresponding theological and metaphysical implications. Princess of Wales, Caroline of Ansbach[2], who was conflicted between the two perspectives, facilitated this philosophical debate, considered to be the most important one of the 18th century. I will argue that Einstein's General Theory of Relativity (GR) through its curved spacetime complicates the dispute

Figure 1. Gottfried Wilhelm Freiherr von Leibniz (1646-1716) (left), Samuel Clarke (1675-1729) (right). Born in Leipzig, Germany, Leibniz was a leading physicist of his day and father of modern rationalism. He also invented calculus independently of Newton and made major contributions to the natural sciences, computer science, the law, and theology. Clarke was a British theologian, classical scholar, and philosopher. Theologically, he was unorthodox, known for his Unitarian tendencies.

[1] Clarke, Samuel, Gottfried Wilhelm Leibniz, Isaac Newton, and H. G. Alexander (editor and Introduction), The Leibniz-Clarke Correspondence: Together with Extracts from Newton's Principia and Opticks (Manchester: Manchester University Press, 1956)

[2] According to Londa Schiebinger in her book The Mind Has No Sex? (Harvard University Press, 1996), pp. 45-6, Princess Caroline was one of Leibniz's pupils in Germany, and she moved to England upon the succession of her father-in-law George I to the throne. Her Leibnizian views were challenged with her arrival in Newtonian England where she came to know Clarke. She appointed herself the mediator of the Leibniz-Clarke Correspondence.

between Leibniz and Clarke, since the theory proves invalid the notion that space is homogenous, uniform and symmetrical. With that being said, there are direct linkages between exchanges in the debate and modern day physics and mathematics. For example, the hypothetical spatial shift of the universe Clarke raises to question Leibniz's relationism corresponds with symmetry transformations known as *diffeomorphisms* that preserve the manifold structure of curved spaces, the equivalent of the metric field in GR (See Figure 3).

Figure 2. Princess of Wales, Caroline of Ansbach, later to become Queen of England.

Depending on one's perspective with respect to GR, as we will see, spacetime need not be comprised of "points" but rather can be understood as the "set of all possible *events* in the universe" (my emphasis) in the past, present, and future[3]. GR, as I will demonstrate, supports Leibniz's argument since according to Einstein, space as opposed to what fills it "has no separate existence" for if the gravitational field, represented by the metric tensor $g_{\mu\nu}$, were to be removed, absolutely nothing would remain. Spacetime "does not claim an existence on its own, but only as a structural quality of the field", Einstein explained in "Relativity and the Problem of Space" published in

[3] Geroch, Robert, General Relativity: From A to B (Chicago: The University of Chicago Press, 1981), p. 8

1952.[4] On time itself, GR complicates (in the sense that time is curved) the main arguments made by the two early Modern philosophers. On one hand, in GR and the Special Theory of Relativity (SR), time is not the sum total of all universal instants, but on the other hand, it is defined over individual events in spacetime which corresponds with Leibniz's relationist

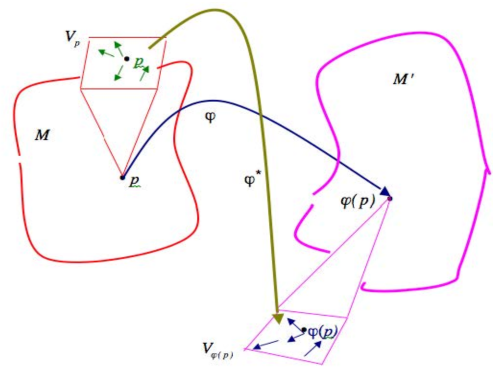

Figure 3. The carry-along ("drag along") of a manifold map in an active diffeomorphism. Similarly, $\varphi: M \rightarrow M'$ naturally "carries along" tangent vectors at $p \in M$ to tangent vectors at $\varphi(p) \in M'$. That is, it defines a map $\varphi^*: V_p \rightarrow V_{\varphi(p)}$ from the tangent vector space V_p at p to the tangent vector space $V_{\varphi(p)}$ at $\varphi(p)$. Once again, we have a one-to-one equivalency between the two manifolds. Source: Dr. Thomas Ryckman

understanding of time. The simultaneity of events is relativistically determined by observers' light-cones[5], which produces counter-intuitive results at the least, and some mathematically curious but physically impossible outcomes (Figures 4a and 4b). I will also discuss the parallels between the 18th century debate and the split between background independent and dependent theories in quantum physics. Overall, as I will demonstrate, *Leibniz-Clarke* foreshadows the foundational issues of contemporary theoretical physics. Before delving into Leibniz's points against Newton, and Clarke's counterarguments, we must first consider how Newton distinguished absolute from relative space, time, and motion in *The Principia*[6].

In the Scholium following the eighth definition of that text, Newton outlines the properties, causes, and effects of absolute and relative space, time, and motion. While he

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[4] Einstein, Albert, "Relativity and the Problem of Space" (1952), www.relativitybook.com/resources/Einstein_space.html

[5] Light is what illuminates the events, and its rate of transmission (the maximum speed in the universe) to observers is limited by its constant speed, a key variable in both SR and GR.

[6] Newton, Isaac, and Andrew Janiak (editor). Philosophical Writings (Cambridge, UK: Cambridge University Press, 2004)

defines absolute space as "homogenous and immovable"[7], he does not prove the existence of space ontologically so much as posit primary and unmoving places (what space consists of) as reference points by which to determine absolute motions. For example, a body that is only relatively at rest with respect to a moving ship, but is moving truly and absolutely if the earth is truly at rest[8]. This is a mere thought experiment, since Newton suggests "it is possible that there is no body truly at rest" or even if there is in the regions of the fixed stars, it "cannot be known from the position of bodies in relation to one another in our regions whether or not any of these maintains a given position with relation to that distant body."[9] Since absolute places cannot be known by our senses, we use relative places and motions in their stead to approximate. Nevertheless, absolute motion is theoretically defined with respect to unmoving places. Places that are unmoving are "those that all keep given positions in relation to one another from infinity to infinity."[10] Thus, Newton's concept of absolute space is indeed, a relative notion, since it refers to places that are relatively at rest. Newton's concept of absolute space is not *probative* but rather serves as a useful concept for physics.

Newton does delineate two properties and effects of absolute motion. First, parts, which are relatively at rest with respect to a whole, participate in its absolute motion. This is the case of a passenger in a moving vehicle. Second, absolute circular motion can be distinguished from relative motion in terms of its centrifugal effects. This was demonstrated by one of Newton's most famous experiments, in which water initially

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[7] Ibid., 64
[8] Ibid., 65
[9] Ibid., 66
[10] Ibid., 67

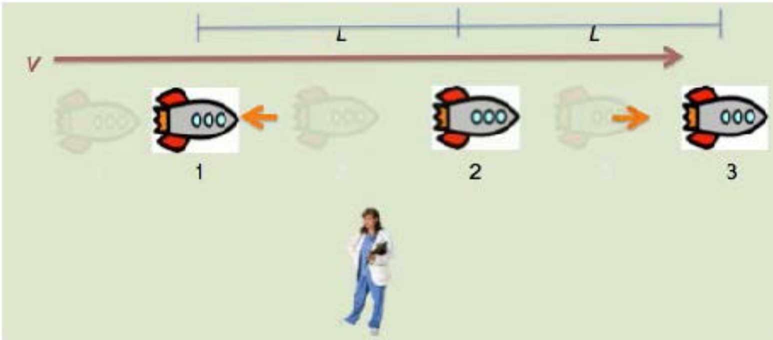

Figure 4a. Simultaneity is observer-dependent. The person in Shuttle 2 sends out two light beams to Shuttles 1 and 3 simultaneously (from his standpoint). Even though Shuttle 2 is moving rapidly, the light does not travel any faster to reach the Nurse (in contrast to other matter, the speed of light is constant and independent of the motion of its source). Consequently, because the Nurse is closer to Shuttle 1, she observes the light reach it before Shuttle 3. Source: Dr. Thomas Ryckman

demonstrated by one of Newton's most famous experiments, in which water initially revolves in a bucket that is set in motion by the unraveling of an attached cord. The water subsequently recedes from the middle and rises up the sides of the bucket, assuming a concave shape while it is relatively at rest with respect to the vessel. The water's rise shows that it is receding from the axis of motion, and also that it does not depend on a change of position with respect to surrounding bodies. The latter distinction is proven since the water was relatively at rest with respect to the bucket when its "true circular motion" was greatest and that its relative motion was greatest when there was no endeavor on the part of the water to recede from the axis.[11] Thus, for Newton, the absolute motion of a body does not require relative motion.

Absolute time "flows uniformly" and "cannot be changed" and is without reference to anything external, according to Newton. Things are placed in time in an order of succession, but in an absolute way. This is in contrast to relative time, which is used to account for natural days, considered equal for the purpose of measuring time, but which

[11] Ibid., 68-9

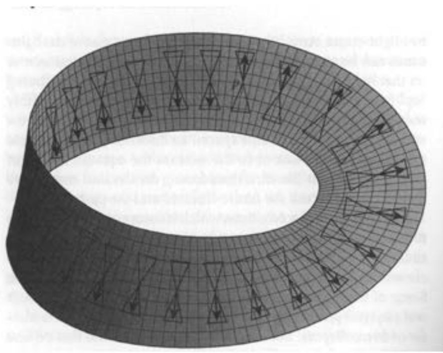

Figure 4b. In a non-orientable surface such as the Möbius strip (shown here), one can model a two-dimensional spacetime where going back in time is possible. Drawing light-cones in such a spacetime, the direction originally called "future" at the point of departure *p* points into the past after completing the round-trip. Source: Philosophy of Physics: Space and Time by Tim Maudlin

are actually unequal. Newton argues that pendulum clock experiments as well as eclipses of the satellites of Jupiter prove absolute time, derived from astronomical equations.[12]

Leibniz's Challenge to Newton in The Leibniz-Clarke Debate

Leibniz does not believe in the reality of space, nor does he use absolute space when thinking about physics. He also does not support Newton's concept of absolute time. Motion, for Leibniz, "is not something entirely real", he declared in his *Discourse on Metaphysics*, for "when several bodies change position among themselves, it is not possible to determine, merely from consideration of these changes, to which body we should attribute motion or rest."[13] Clarke, representing Newton in *Leibniz-Clarke*, is explicit in defining space as a property that is one, infinite, and indivisible, in his Third Reply. Leibniz argues, instead, for his relational theory of space for three main reasons: 1) Epistemologically, space can be understood purely on the basis of relations between bodies; 2) In a homogenous and uniform space all points would be indistinguishable, in violation of his Principles of Sufficient Reason (PSR) and Identity of Indiscernibles (PII); and 3) Space cannot be absolute because it would have the divine properties of infinity and eternity. Leibniz defines place as a relation to fixed co-

[12] Ibid., 64, 66
[13] Leibniz, Gottfried Wilhelm Freiherr von, Discourse on Metaphysics and Other Essays (Indianapolis: Hackett Publishing Company, 1991), §18

existents.[14] Therefore, A and B share the same place, if they each maintained the same proximity to C, E, F, and G, at different times. Space is that which comprehends all places. Furthermore, Leibniz questions what a “real space”, void of all bodies, would contain. Clarke cannot rebut Leibniz’s relational theory of space, except by suggesting God could move the universe to another place, producing a shock from the acceleration, to the bodies that inhabit it.[15] It is true that acceleration is absolute, and not in the same category as Leibniz’s accounting of relative motion. The argument over this scenario is theological in nature, with Leibniz expressing confidence that God would never move the universe forward or backward in space without reason. The second reason against absolute space, according to Leibniz, is that since a uniform space is symmetrical, it is impossible that God, “preserving the same situations of bodies among themselves, should have placed them in space after one certain particular manner, and not otherwise.”[16] Figure 5 illustrates the different ways in which space could be arranged. In other words, it is a violation of the PSR that God would choose arbitrarily. Clarke objects that the

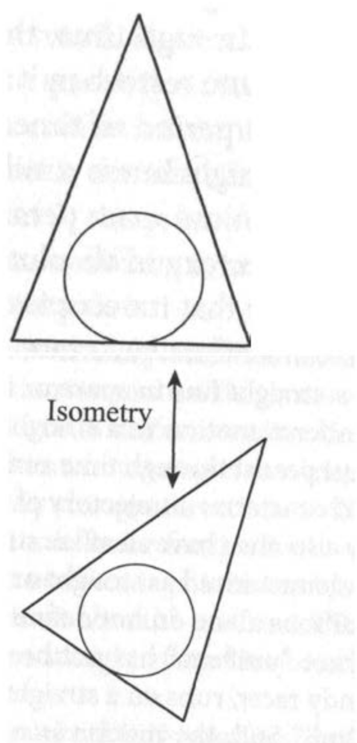

Figure 5. The shift from the top figure to the bottom figure is one that reflects both translational and rotational symmetry. It produces no actual change in the relations between points. Source: Philosophy of Physics: Space and Time by Tim Maudlin

[14] Ibid., L, V, §47
[15] Ibid., C, V, §52-3
[16] Ibid., L, III, §5

Figure 2. Princess of Wales, Caroline of Ansbach, late to become Queen of England.

indifferent parts of space should not hinder God's will.[17] With respect to the PII, absolute space violates that Leibnizian principle if we imagine transferring all the matter from one region to another since no "qualitative description could distinguish one from the other", as Tim Maudlin distills in *Philosophy of Physics.*[18] More simply, absolute space implies an infinite number of distinct yet qualitatively identical points, meaning that by the PII, it cannot exist. GR is consistent with the PII since this Principle precludes physical laws expressed in terms of symmetries, but rather supports the restriction of properties to be relational in nature, that is, to describe entities in relation to all other entities. An event in GR is defined as an occurrence (for example, the firing of a gun), which has extension in neither space nor time. GR is a theory that models the *relationship* between events, and therefore stays true to Leibniz's PII.

The third reason Leibniz has to object to space being absolute is that Clarke is defining it in terms of a property that has extension. A body "cannot leave its extension" if it changes space, and that as a property, it cannot first belong to one material substance, then an immaterial substance, and then to God himself.[19] To which Clarke replies that space is one and immense; however, Leibniz would maintain that this conflates divine properties with those of space. God would "depend upon space", which is an absurdity.[20]

For Leibniz, motion is not absolute relative to a fixed entity such as space. Rather, it is relational with respect to bodies considered at rest, and it is relative in the sense that A at

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[17] Ibid., C, III, §5

[18] Maudlin, Tim, Philosophy of Physics: Space and Time (Princeton and Oxford: Princeton University Press, 2012), p. 41

[19] Ibid., L, V, §37-39

[20] Ibid., L, V, §49

rest while B moves 2 units to the east is equivalent to B at rest while A moves 2 units to the west. Leibniz's view is that only relative motions are meaningful and that there are no bodies *truly* at rest (Figure 6). Newton's view that curvilinear motions are absolute but rectilinear ones are relative is called into question by Leibniz's mathematical derivation of curves, which are in fact compositions of infinitely many rectilinear tangent lines (Figure 7). In the curved spacetime of GR, moving on non-straight as opposed to straight lines does indeed correspond with Newton's view, since the former refers to accelerating motion, which is absolute. At the same time, as we have seen, there is no "absolute space" with which to refer any kind of motion.

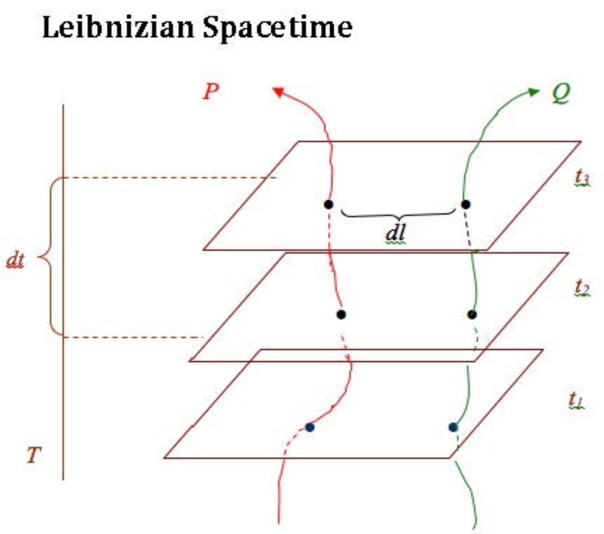

Figure 6. Only vertical lines signify true rest. For Leibniz, all bodies are in relative motion, even when there is an appearance of rest. Source: Dr. Thomas Ryckman

In the same way Leibniz sees space as an order or relation, he defines time in similar terms. If time were an absolute entity, it would be without reason for God to create everything in a certain year as opposed to a year before, which is in violation of the PSR.[21] Leibniz understands time to be an "order of successions"[22] that become "instants" which "perish continually" and therefore reasons that it cannot be an eternal or absolute entity[23]. Clarke does not directly respond to that claim, but does argue that God's will would be sufficient to create the world at a particular point in time even if there is no true difference

[21] Ibid., L, III, §6
[22] Ibid., L, III, §4
[23] Ibid., L, V, §49

between alternative starting points. The context for the arguments over time in *Leibniz-Clarke* reflects more of an emphasis on pure theology in comparison with the discussions of space and motion, reducing our ability to 'superimpose' GR onto that issue dealt with by the two philosophers.

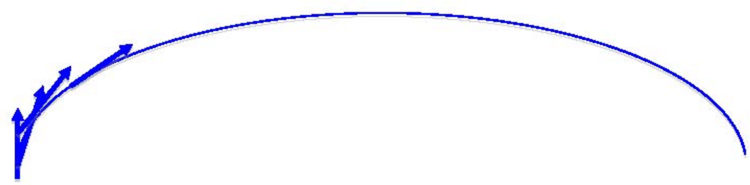

Figure 7. Source: Dr. Thomas Ryckman

The Symmetries of Space for Leibniz and Clarke

Though Leibniz and Clarke had their share of differences, they both relied on Newton's presumed geometrical structure of absolute space of E^3: the three dimensional geometry described by Euclid's postulates. This space is highly symmetric, and the symmetries are demonstrated by isometries, which are defined as "mappings of the space onto itself that preserve distances among the points."[24] There are two kinds of symmetries – translational, which refers to a moving of all points an equal distance in a rectilinear fashion, and rotational, or a turning of points about an axis (See Figure 5). Translational symmetry is called homogenous and rotational symmetry is called isotropic. E^3 is completely homogenous and isotropic, and it is these spatial features, which are pivotal in *Leibniz-Clarke*. As Figure 5 demonstrates, the symmetry of Euclidean space is such that "a system of matter would fit in any place and with any orientation."[25] Any pair of those transformations are equivalent to each other and thus, in an absolute Euclidean space, "God

[24] Maudlin, Tim, Philosophy of Physics, p. 34
[25] Ibid., p. 37

will produce neither of them" because they are equally good and "none has the advantage over the other", according to Leibniz.[26] Leibniz relies heavily on the PSR to make his case. Maudlin hypothesizes: "if we abandon [the presumption of E^3] and postulate a space that lacks these [homogenous and isotropic] symmetries, the PSR argument cannot get off the ground."[27] As we will seek to understand in greater detail, this hypothesis is very relevant once we think about physics within the context of GR.

The Roots and Model of Einstein's General Theory of Relativity

The General Theory of Relativity has its roots in what Einstein dubbed to be the "happiest thought of his life"[28] – that the gravitational field only has a relative existence. The Principle of Equivalence states that uniform acceleration without gravity feels the same as being at rest in a homogeneous gravitational field. Furthermore, acceleration (free fall) in a gravitational field is the equivalent of hovering freely in outer space where there is no gravity. The significance of this Principle is that Einstein discovered that inertia, or the tendency for a body to remain at rest or in motion, is directly related with gravity. Together they constitute the inertio-gravitational field, which is relative to the state of motion of the observer. However, the gravitational field is not perfectly uniform, since bodies fall slightly angled toward the center of the earth, rather than in parallel

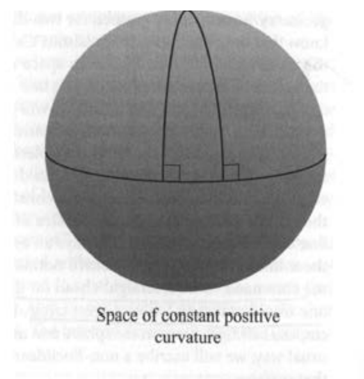

Figure 8a. Triangles formed by the two lines of longitude and the segment of the equator have a sum of interior angles greater than 180° in spaces such as these. Source: Philosophy of Physics: Space and Time, by Tim Maudlin

[26] Ibid., L, IV, §19
[27] Ibid., 39
[28] Dr. Thomas Ryckman lecture, UC Berkeley, April 10th, 2014

lines.[29] Each point of the field corresponds with a metric tensor $g_{\mu\nu}$, which determines how the volume of matter-energy changes. There is a reciprocal relationship and equality between the curvature of spacetime and the volume and density of matter-energy. This gravitational equation is known as the Einstein Field Equation: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa T_{\mu\nu}$, which reads from left to right as spacetime curvature tells matter-energy how to move, and from right to left as matter-energy tells spacetime how to bend. Since spacetime curvature itself carries energy and so is a source of itself, the complete distribution of matter and energy only constrains rather than determines spacetime curvature. The tensors describe a spacetime that has a variable curvature that Maudlin defines as follows: "it can be flat in some places, positively curved in others, and negatively curved in yet others. Or [it] may always have the same sort of curvature but different amounts in different places."[30] Figures 8a and 8b illustrate spaces that are constant positive and negatively curved respectively. As we have seen the curvature in part depends on the distribution of matter-energy, and vice-versa. Geroch provides a useful analogy in the form of a steel ball placed on a rubber sheet. There is an interplay between the matter and the curvature of the sheet (Figure 9). In a more complex illustration, it is the curvature of the sheet that produces dynamical effects on the

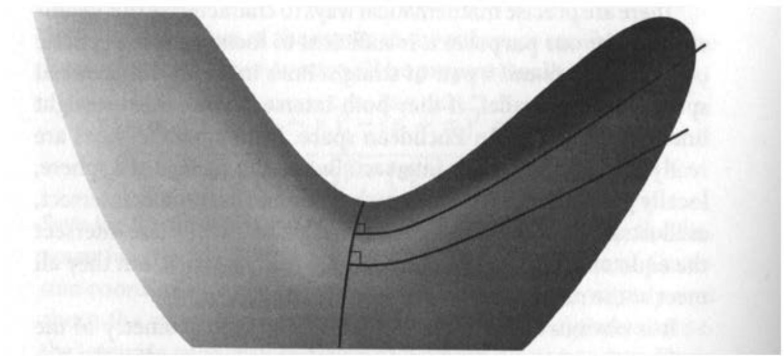

Figure 8b. In a negatively curved space, the sum of interior angles of a triangle is always less than 180°. Source: Philosophy of Physics: Space and Time, by Tim Maudlin

[29] Maudlin, Tim, Philosophy of Physics: Space and Time, p. 135
[30] Ibid., 130-1

movements of the matter (Figure 10). To place the curvature of spacetime in a more concrete context, one can think of the actual shape of the spherical earth in comparison to its depiction in a flat world map – obviously the latter visualization distorts the spatial relationships between different points on the globe. Einstein realized that physics had a distorted view of spacetime in the same way. Where there are massive objects such as stars in the universe, the pace at which time progresses is slower as one moves toward the center of mass– in Figure 11, the middle section refers to the inside of a dense star where the experienced time per turn around the spacetime is shorter, since in that region, gravitational acceleration (i.e., density) is greatest. This insight is drawn from SR, in which moving clocks tick more slowly. Space, represented as one goes through the hourglass shape (in this hypothetical particular region of spacetime) is also curved due to varying degrees of density. We know this since falling objects appear to fall along a curved path, when in fact they are moving in nearly straight lines in a curved space.

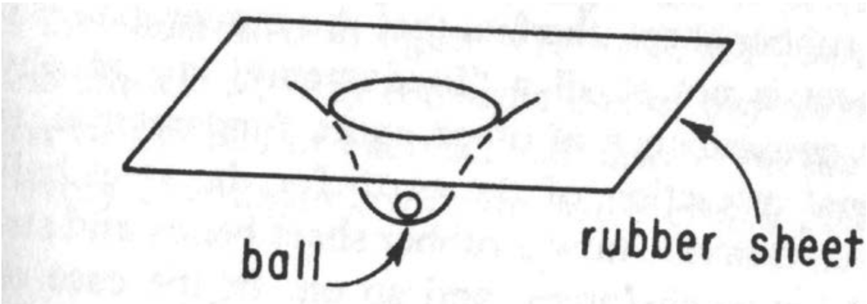

Figure 9. Source: General Relativity from A to B by Robert Geroch

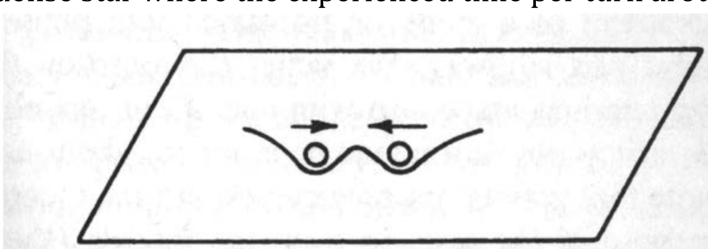

Figure 10. Source: General Relativity from A to B by Robert Geroch

Discussions of gravity in *Leibniz-Clarke* anticipate how Einstein dealt with that phenomenon in GR. Newton uncovered gravity but famously failed to find its cause or mechanism. In Leibniz's Fifth Paper of the Correspondence, he argues gravity is either miraculous or produced by motions of some fluid or other bodies – "A body is never moved naturally, except by another body which touches it and pushes it; after that it continues until it is prevented by another body which touches it."[31] This hypothesis is close to Descartes' "plenum", where vortices of aether propel the planets and comets to move around in orbits and other paths, respectively (Figures 12a and 12b). In one sense, this model is similar to Einstein's gravitational field[32] since in GR, "there is no '*force* of gravity'"[33], and it is in fact bodies which have an impact on each other through their effects on spacetime curvature. Spacetime geometry acts as an "intermediary" between multiple bodies, Geroch explains.[34] This can be illustrated in Figure 10 where there are two massive bodies in the world, and "each moves in a certain way in response to the curvature caused by the other".[35]

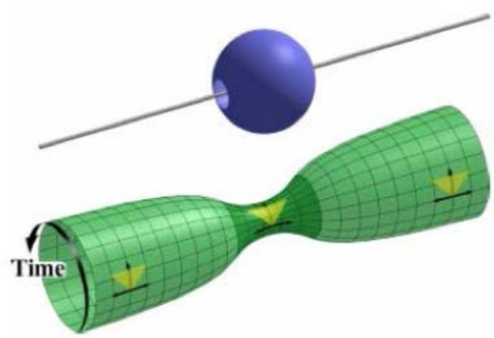

Figure 11. Source: "Visualizing curved spacetime" by Rickard M. Jonsson, Chalmers University of Technology and Goteborg University, Göthenburg, Sweden

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[31] Ibid., L, V, §35
[32] Indeed, in his essay, "Relativity and the Problem of Space," Einstein concludes that GR represents an extension of Descartes' intuition since there is no space without the gravitational field. "[The existence of an empty space] requires the idea of the field as the representative of reality, in combination with the general principle of relativity, to show the true kernel of Descartes' idea; there exists no space 'empty of field.'" See footnote #19 for citation.
[33] Ibid., 135
[34] Ibid., 181
[35] " "

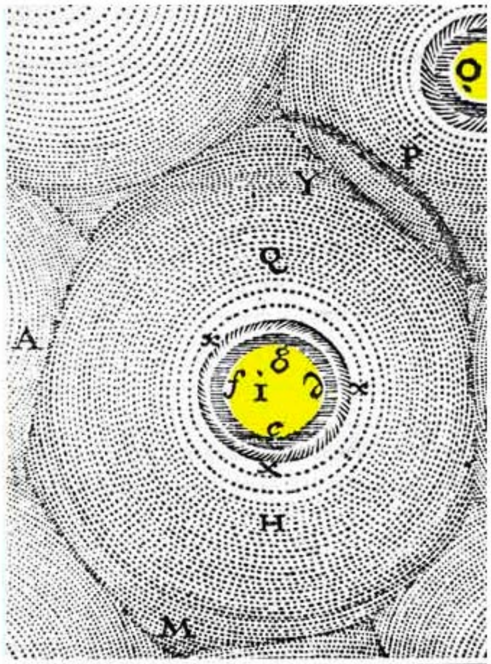

Figure 12a. Vortex around sun carries planets along in Descartes' plenum. Source: Dr. Thomas Ryckman

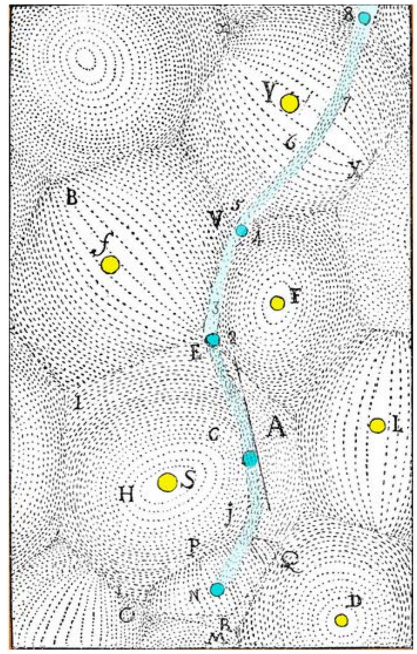

Figure 12b. Path of a comet through celestial space according to Descartes. Source: Dr. Thomas Ryckman

Would God perform a diffeomorphism on spacetime?

As Figure 3 shows, so long as the tensors remain unchanged, the matter-energy can be moved via a new function, and the two functions will describe the exact same gravitational field. The diffeomorphism preserves the differentiable structure, mapping smooth curves onto smooth curves. The functions only differ by a coordinate transformation. Though the dynamically curved spacetime in GR is clearly not uniform, a diffeomorphism represents the equivalent of a shift of the universe discussed by Leibniz and Clarke. The two spatial locations in the diffeomorphism in Figure 3: M = $<M, g_{\mu\nu}, T_{\mu\nu}>$ and M' = $<M', \varphi^* g_{\mu\nu}, \varphi^* T_{\mu\nu}>$ contain the same spacetime structure and physical content distribution, representing the same field. It seems then that Leibniz may have the same concern over attributing a reality to spacetime and the metric field as he did with the uniform and symmetric space taken as a premise in *Leibniz-Clarke*. To return briefly to the correspondence – Clarke's space has a reality since there is a difference depending on its location, whereas Leibniz's space is purely comprised of relations, and so therefore it makes no difference where in the universe these relations are situated. In order to place GR within the context of *Leibniz-Clarke*, we must more precisely understand the philosophical debates surrounding Einstein's claim that spacetime is a structural quality of the metric field.

If spacetime is constituted of "parts" – regions and points, then that would favor Clarke's viewpoint since there would be different yet indiscernible situations. There are at least a couple of variations within this school of thought known as *manifold substantivalism*. Clarke, who defines space as a property and also in terms of extension, represents a combination of the two substantivalist versions: field theories contend spacetime points are individuals and the field quantities are properties, while particle theories posit that particles are individuals and spacetime locations are among their properties. Reconciling this viewpoint with the theological debate within *Leibniz-Clarke*: Leibniz's PSR would *not* be violated if God moved the universe from one region to another since the substantivalist sees these two alternatives as distinct states of affairs. Of

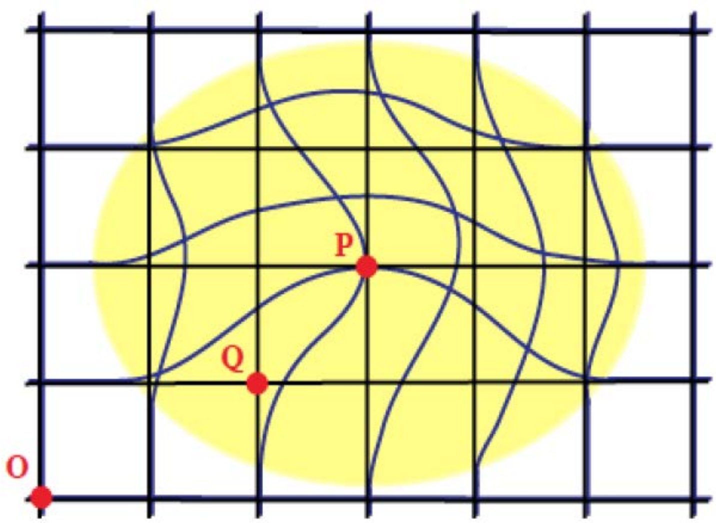

Figure 13a. Suppose $[g(x), T(x)]$ is a solution assigning metric $g_{\mathbf{P}}$ to **P** with coordinates $(x^1,x^2)_P = (3,2)$. If the field equations are invariant under $x \rightarrow x'$, then $[g'(x'), T'(x')]$ is also a solution, assigning metric $g'_{\mathbf{P}}$ to **P** with coordinates $(x^1,x^2)_P = (2,1)$. But if $[g'(x'), T'(x')]$ is a solution, so is $[g'(x), T'(x)]$ assigning metric $g'_{\mathbf{P}}$ to Q with coordinates $(x^1, x2)_Q = (2,1)$. This means that g'_P yields two different spatial points, and that g_P and one of the g'_p solutions yield the same spatial point but different coordinate values. Source: Dr. Thomas Ryckman

course, this understanding of spacetime is not what Leibniz had in mind for space, since it assigns a very concrete definition to what he saw as an abstract entity.

Furthermore, there are a number of contemporary objections to manifold substantivalism. First, the past and future cannot be distinguished nor can distance relations be defined. Second, spacetime points do not have an "active power", an implication of this theory. Third, through Einstein's 'point-coincidence' solution to the 'Hole Argument' (Figures 13a and 13b), we know spacetime points are individuated only through the physical metric field, even if the mathematical function transforms. The points themselves do not have a physical reality – rather, it is defined by the set of intersections of world lines of bodies (their trajectory over time), or physical events.

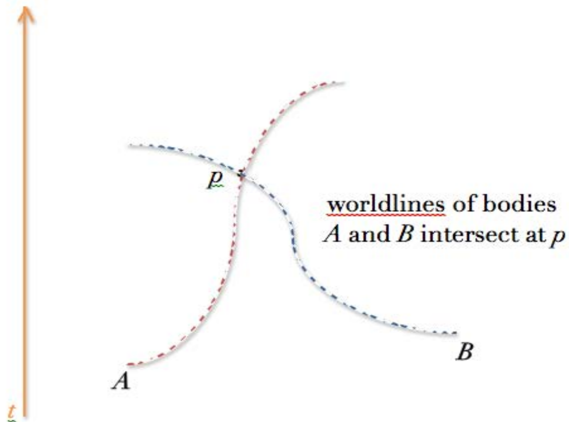

Figure 13b. Einstein soon realized (in 1915) that all that is possible to observe are "point coincidences", i.e., intersections of world lines of bodies, or physical events. These alone have physical reality. Coordinates are just arbitrary labels of point-coincidences of events. Source: "The Foundation of the General Theory of Relativity", 1916, §3; and Dr. Thomas Ryckman

There are two similar perspectives that build off of the objections to manifold substantivalism: metric field substantivalism and relationism[36]. The relationist and metric field substantivalist would agree that what constitutes reality is "the set of spacetime points that are actually occupied by material objects or processes"[37]. One concern for

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[36] Substantivalists stress the continuities between the absolute inertial structures of Newtonian space and Minkowski space-time and GR. Relationists argue only relations of contiguity between various dynamical fields are physically meaningful (Dr. Thomas Ryckman lecture, UC Berkeley, April 22nd, 2014)
[37] Friedman, Michael, The Foundations of Space-Time Theories (Princeton: Princeton University Press, 1986), p.217

relationists and these more sophisticated substantivalists is how to account for points that possibly *will* be occupied in the future. Nonetheless, I would argue that it is these schools of thought that are most consistent with Einstein's perspective and that of Leibniz. For if spacetime's reality is only as great as the events that occur on the metric field, the "shift" in *Leibniz-Clarke* represents nothing more than the equivalent of a change in its mathematical description, rather than its physicality. Would God perform a diffeomorphism on spacetime? The answer to that question of course depends on whether He is a relationist or a manifold substantivalist.

Relationism vs. Absolutism in GR

> If the world be finite in dimensions, it is moveable by the power of God and therefore my argument drawn from that moveableness is conclusive. Two places, though exactly alike, are not the same place. Nor is the motion or rest of the universe, the same state; any more than the motion or rest of a ship, is the same state, because a man shut up in the cabin cannot perceive whether the ship sails or not, so long as it moves uniformly. The motion of the ship, though the man perceives it not, is a real different state, and has real different effects; and, upon a sudden stop, it would have other real effects; and so likewise would an indiscernible motion of the universe. To this argument, no answer has ever been given. (Clarke, IV, §13)

As the above quote demonstrates, for Clarke, who draws on Newton's example of a moving ship, absolute motion is indeed possible. This motion, if not with respect to other bodies, must be with respect to an entity – space, which for Clarke, is fixed. In comparison with the spacetime of GR, there is a partial overlap insofar as there is a "world structure" in the words of mathematician Hermann Weyl. We know there is this structure because of the inequivalence of different states of motion. Weyl echoes Clarke: "Without a world structure the concept of relative motion of several bodies has… no more foundation than the concept of absolute motion of a single body."[38] In GR, it is with respect to the affine[39] structure of spacetime that one can determine whether a given particle is accelerating or rotating. In this sense, there is an 'absolutism' in GR. However, it is not a classical absolutism for this structure is not fixed but rather "dynamically depends on surrounding matter and energies"[40]. Through the steel balls on a rubber sheet analogy supplied by Geroch, we know there is a dynamic relationship between the curvature of spacetime and the distribution of matter-energy. Moreover, the gravitational field itself moves with respect to other fields.[41] In this context, then, there is a merging of absolutism with relationism, but one with a greater degree of the latter. When we consider the philosophical difference between background dependence, wherein the structure limits the evolution of matter but is not acted upon by said matter, and background independence, wherein the structure is always and everywhere dynamical, GR falls into the latter category.

Does Determinism fail in reality, or just in GR?

> For God, being moved by his supreme reason to choose, among many series of things or worlds possible, that, in which free creatures should take such or such resolutions, though not without his concourse; has thereby rendered every event certain and determined once for all; without derogating thereby from the liberty of those creatures: that simple decree of choice, not at all changing, but only actualizing their free natures, which he saw in his ideas. (Leibniz, V, §6)

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[38] Weyl, Hermann, Philosophie der Mathematik und Naturwissenschaften (Germany: R. Oldenbourg, 1926)
[39] Affine structures are those where there is a distinction between straight lines and other lines. If a particle deviates from a straight line, it is accelerating on absolute terms.
[40] Dr. Thomas Ryckman lecture, UC Berkeley, April 17th, 2014
[41] Rovelli, Carlo. "Quantum spacetime: What do we know?", "There is no absolute referent of motion in GR: the dynamical fields 'move' with respect to each other" (p. 108)

The gravitational field influences and even determines the metrical laws of the spacetime continuum. (Einstein, "The Meaning of Relativity", p. 67)

As we have seen, the Einstein Field Equations mathematically describe the curvature of spacetime in GR. Specifically, there are ten equations that one solves for independent values of the metric tensor $g_{\mu\nu}(x)$. Because of this mathematical predictability, there is a 'global' determinism in the sense that the past and future states of the world can be calculated based on the instantaneous state of the distribution of matter-energy and the corresponding curvature of spacetime (Figure 14). A more radical form of determinism -local determinism, fails when one revisits the implications of the Hole Argument, since descriptions of fields outside the region do not uniquely determine the fields within the region in question. In 1917, the determinism in the field equations was complicated by Einstein's addition of a cosmological term Λ as a coefficient of $g_{\mu\nu}$. The Jesuit priest George Lemaître, a physicist at Université Catholique de Louvain in Belgium (Figure 15), showed that there are solutions to the field equations with this constant demonstrating the universe

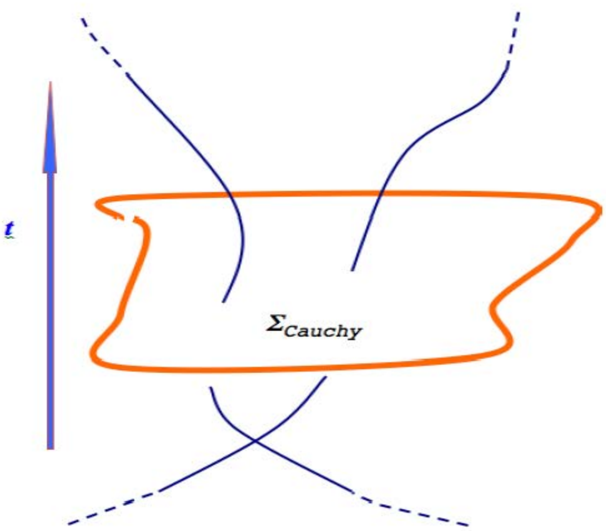

Fig. 14. A Cauchy 3-D space-like hypersurface that intersects every causal curve without endpoint exactly once. Source: Dr. Thomas Ryckman

Fig. 15. Einstein thought Lemaître's Big Bang hypothesis was mathematically correct but "physically abominable." Source: Dr. Thomas Ryckman

began with a singularity ("The Big Bang") and subsequently expanded. The cosmological term represented a force that acted counter to gravitational attraction, since the centriptetal force serves to direct bodies toward the center. By modeling density as we go back in time to an initial condition of high density, Lemaître charted different scenarios of how the world evolves, but all of which begin with The Big Bang (Figure 16). The other kind of singularity poses potential problems for determinism since it represents a breakdown of spacetime. A black hole is when spacetime curvature reaches such a high level, that the velocity required to escape from it is greater than the speed of light, and therefore nothing can escape from it. It is thus within these black holes that there is a suspension of the laws of nature as Einstein collaborator Peter Bergmann indicated in 1980, suggesting a form of indeterminism, posing a problem for GR – since there is empirical evidence that a typical galaxy "could well contain tens or even hundreds of millions of stellar black holes."[42] As I will show, the black holes could represent the key to understanding the history of the universe before The Big Bang, and its trajectory well into the future.

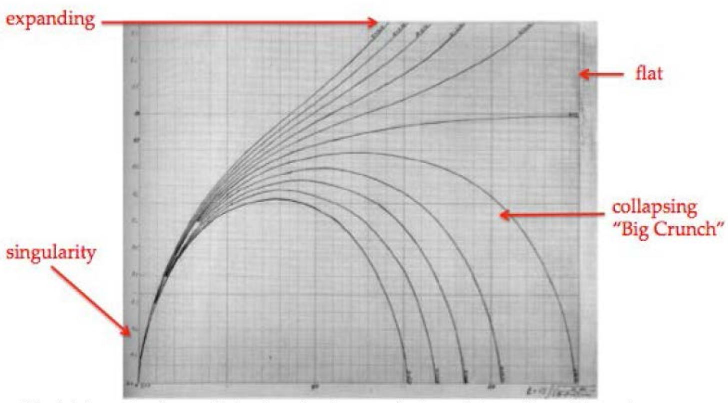

Fig. 16. Lemaitre's graph depicts the time evolution of the radius of the universe. The most recent data are compatible with an accelerated expansion (top curves). Source: Dr. Thomas Ryckman

[42] Dr. Thomas Ryckman lecture, UC Berkeley, April 24th, 2014

The Search for a Unified Theory and the Importance of Foundational Questions

> For every property of nature which might be otherwise, there must be a rational reason which is sufficient to explain that choice.
> – G.W. Leibniz, Principle of Sufficient Reason

Theoretical physicist Carlo Rovelli has declared that his field is at a crossroads: finding a new synthesis between Quantum mechanics (QM), which formulates a relational theory of physical systems based on probabilities and epistemological considerations[43], and GR, which "describes the world as a set of interacting fields including $g_{\mu\nu}(x)$ and possibly other objects" and defines motion only in terms of "positions and displacements of these dynamical objects relative to each other."[44] Through both theories, we know that we live in a quantum spacetime. To understand what that means, Rovelli argues, physics must return to philosophical and conceptual questions: What is matter? What is causality? What is the meaning of motion? Is motion to be defined only with respect to objects or to space? What is the role of the observer? What is time? It is the answers to these questions, which will govern the future of a theory of quantum gravity, for instance.

Physics continues to rely on notions of absolute time, when in fact GR shows that it is a problematic variable since there is no "true time"[45]. GR's focus on events is an extension of Leibniz's definition of time to be the mere ordering of things. Matter may also become increasingly secondary since in QM, basic observables such as length, area, or

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[43] Callender, Craig and Nick Huggett (editors), Physics Meets Philosophy at the Planck Scale: Contemporary Theories in Quantum Gravity (Cambridge, UK: Cambridge University Press, 2001), Rovelli, Carlo, "Quantum spacetime: What do we know?" chapter, "What we can say about the properties that the system will have the day after tomorrow is not determined just by what we can say about the system today, but also on *what we will be able to say about the system tomorrow*," p. 104

[44] Ibid., 108

[45] Ibid., 112

volume are mere proxies for geometrical features of the gravitational field – therefore a state of spacetime "will be a continuous quantum superposition of states whose geometry has *discrete features*, *not a collection of elementary discrete objects*."[46]

Echoing Aristotelian and Cartesian accounts of motion, Einstein's GR suggests the dynamics of the gravitational field are fully relational. If one thinks of GR in absolutist terms, in the sense that location can be defined with respect to the gravitational field, Rovelli contends that is misguided since the field itself moves through its vibrations[47]. We know from QM that every dynamical object has quantum properties. Therefore, spacetime must exhibit quantum properties. Despite this very apparent way to synthesize GR and QM, conventional Quantum Field Theories (QFTs) assume a fixed, non-dynamical stage as the background metric structure, akin to the entity Clarke argued for in his correspondence with Leibniz. This is the approach taken by string theory[48], which makes "definite predictions about the type of particles that exist in nature" and postulates "supersymmetry", such that for every force particle (boson) there is a

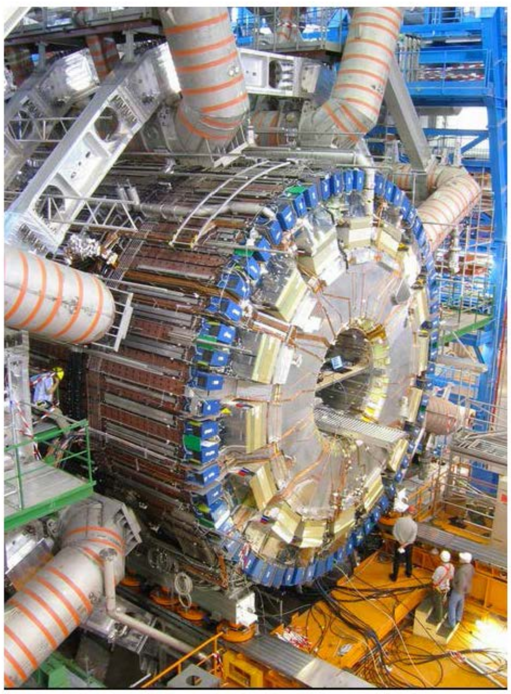

Figure 17. ATLAS detector at the Large Hadron Collider (LHC) at CERN in Geneva. Source: Dr. Thomas Ryckman

[46] Ibid., 110
[47] Ibid., p. 108
[48] There is evidence that string theories (on fixed backgrounds) are consistent to 2nd order in a certain approximation scheme. Source: Dr. Thomas Ryckman lecture, UC Berkeley, May 1st, 2014

corresponding matter (fermion) partner[49]. However, recent experiments at the Large Hadron Collider in Geneva (Figure 17) have not been able to find any signs of supersymmetry.

To construct a better theory, Rovelli makes two major recommendations: first, there should be no independent time variable ‘along’ which dynamics ‘happen’ – rather we can use statistical descriptions of system states; second, the meaning of QM is that the properties of any system are contingent relative to a second physical system. Loop Quantum Gravity (LQG), a unified theory (of GR and QM, that is) whose founders include Rovelli, argues space is analogous to an extremely fine fabric woven together by “one dimensional intersecting quantum excitations” which can be represented by spin networks (Figure 18) - abstract graphs that are purely relational structures. How can relational structures be understood without unitary time? Rovelli explains that diffeomorphism invariant quantities (i.e., those that are independent of coordinates) “express the value of certain variables ‘when and where’ certain other quantities have certain given values.”[50] In other words, properties of systems can only be determined vis-à-vis relative notions of space and time.

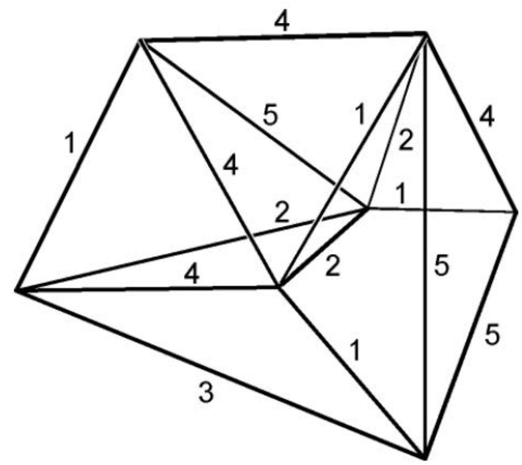

Figure 18. Roger Penrose invented spin networks in the 1960s. Shown is an example with integers labeling the edges; the integers are in units of Planck’s constant and represent ‘spins’. To correctly calculate an interaction, the numbers have to sum up to +1, 0, or −1. Source: Dr. Thomas Ryckman

[49] Dr. Thomas Ryckman lecture, UC Berkeley, April 29th, 2014
[50] Ibid., 114

Lee Smolin, a fellow founder of LQG, argues Leibniz's PSR is fundamental to relational and background independence and by extension the ultimate cosmological theory of everything – one that postulates the origins of our universe and the prospects for a multiverse (a population of universes).[51] Background independence not only facilitates a physics of dynamical processes but also an evolution of laws in different regions and epochs of the universe. The link with sufficient reason is that mathematical consistency alone, Smolin reminds us, cannot account for the current set of laws we observe governing phenomena. Explanations of a unique initial state of the universe that are not falsifiable close off further inquiry and violate the PSR. Rather than see what Leibniz dubbed "one of the greatest [principles]"[52] as unattainable since we rarely know the complete reason why something in nature has a given property rather than not, Smolin maintains we can still be faithful to the PSR "by accepting explanations that leave room for further developments that may improve our understanding of the past."[53] This approach is in contrast to what Smolin calls the Newtonian paradigm, which distinguishes between the role of initial state and dynamical law. In small subsystems, scientists can observe what aspects of evolution

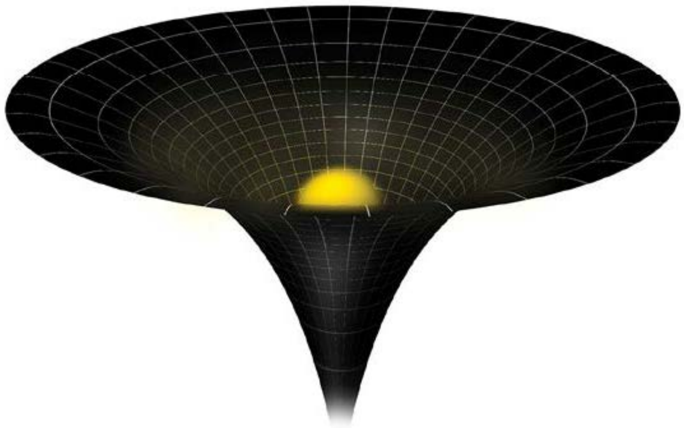

Figure 19. Bouncing star. Instead of evaporating, black holes could end their lives as exotic stars. Source: NewScientist.com

[51] Smolin, Lee, "A perspective on the landscape problem", February 16th, 2012
[52] Leibniz, Gottfried Wilhelm, Philosophical Papers and Letters: A Selection, ed. Leroy E. Loemker. 2d ed., (Dordrect: D. Reidel, 1969), p. 227
[53] Lee Smolin, "A perspective on the landscape problem", p. 10

are due to state and which are derived from a dynamical law, by repeating the experiment with many different initial states. In the case of the universe, there is only a single history, and so therefore any theory must furnish its own sufficient reason for initial conditions and the evolution in physical laws.

Figure 20. Artist's representation of a Pluralistic scenario, or what is known as a 'Multiverse'. Source: Coasttocoastam.com; Artist: Sam del Russi

What then are the implications for an evolving set of natural laws? In the 1960s, John Wheeler theorized quantum effects would eliminate the singularities of GR in black holes (Figure 19) such that those regions of spacetime would expand again, "forming new regions of spacetime to the future of where those singularities would have been."[54] Indeed, this idea corresponds to one of the three possibilities Smolin identifies as a global structure of the larger universe: in this scenario, the Big Bang was the result of a 'bounce' (the elimination of singularities through quantum effects cited above) of a black hole singularity, meaning for every black hole there will be a universe produced once it collapses. With at least 10^{18} black holes in our universe, this is what Smolin calls the Branching scenario, since each universe has one parent but many progeny.[55] The other two scenarios are: Pluralistic, meaning an infinite population of universes (Figure 20) that were derived from a primordial state by a one stage process, each distinct from each other; and Linear cyclic in which there is a succession of universes, each with a single parent and a

[54] Ibid., 6
[55] Ibid., 16

single ancestor. Staying true to the Leibnizian idea of explaining why laws are what they are, Smolin delineates the parameters that govern changes in laws in each of the scenarios: these range from balancing density increases (which result from a shrinking of the universe) that lead to more black holes against the trend of fewer stars (due to a smaller universe) producing fewer black holes (Branching), to avoiding paradoxes (involving infinity) of comparing probabilities of given properties[56] in an infinite population of universes (Pluralistic), and finally to 'attractors' which serve as a convergence point for evolving laws such that the changes are small from generation to generation (Linear cyclic).

Smolin convincingly argues that the future of physics lies in transcending the Newtonian paradigm, which takes the initial state as an input without explanation, and

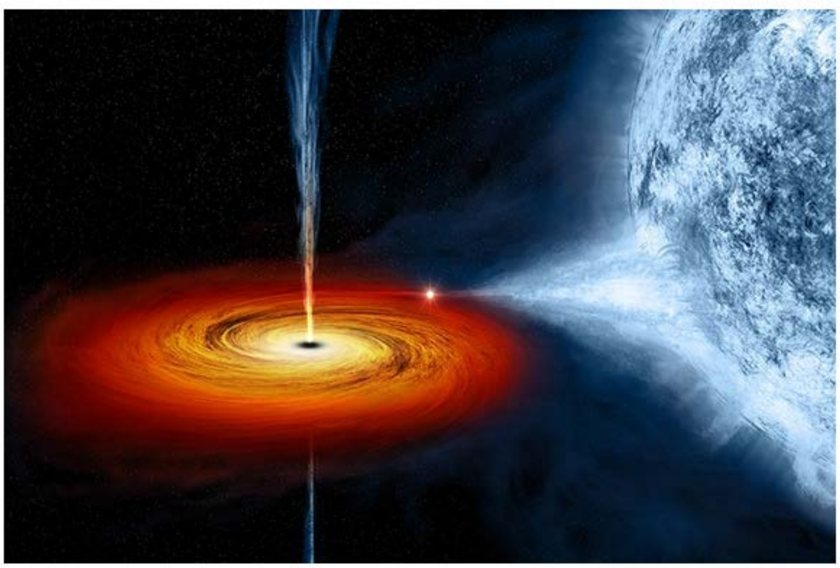

Figure 21. This artist's conception of Cygnus X-1 shows the black hole drawing material from companion star (right) into a hot, swirling disk. Source: Space.com

instead constructing theories that posit an evolving set of laws in a falsifiable manner, paying homage to Leibniz's Principle of Sufficient Reason. In addition, a relationist unified theory (again, in the spirit of

[56] In an infinite population of universes, probabilities of "Outcome A" in comparison with "Outcome B" become difficult to discern when the frequencies of both outcomes are infinite.

Leibniz[57]) is more falsifiable and by its very nature of removing background layers from previous theories and finding solutions that explain dimension and topology which had been fixed, it spurs advancements in scientific knowledge that should culminate in a greater understanding of the causal history of the universe and its future, illustrating the importance of the Leibniz-Clarke debate to modern day theoretical physics. Ultimately, the truest possible cosmological theory may require a granting of Princess Caroline's wish – a rapprochement between the relationists and the string theorists who rely in some sense on an absolutist framework, to forge a unified theory that reflects the full extent of the universe, in space and time.

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[57] The philosophical alternative to the Leibnizian model is Platonic which emphasizes symmetry in a spacetime background and in classification of particles that transform under this symmetry. Dr. Thomas Ryckman lecture, UC Berkeley, May 1st, 2014