EINSTEIN'S CURVED SPACE-TIME AND SCIENTIFIC REVOLUTION

Kyoung-Eun Yang*

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1. Introduction

The theory-change from Newtonian to Einsteinian physics has been cited as a classic example of a great *scientific revolution* by both scientists and philosophers. Above all, the defenders of a revolutionary account of this theory-change point out that radical change is involved notably in a difference between the concepts of space-time in the Newtonian theory of gravitation and in Einstein's theory of gravitation (the general theory of relativity), that is, flat space-time in the former vs. curved space-time in the latter. For example, Kuhn in his *Structure of Scientific Revolutions* (1962) maintains that these differences between the two theoretical frameworks show that the conceptual change involved was revolutionary:

> One [set of scientists] is embedded in a flat, the other in a curved, matrix of space. Practicing in different worlds, the two groups of scientists see different things when they look from the same point in the same direction.[1]

Misner, Thorne, and Wheeler (1973) famously summarize this revolutionary feature of Einstein's theory as "space acts on matter, telling it how to move. In turn, matter reacts back on space, telling how to curve".[2] Within Einstein's theory of gravitation, the gravitational interaction emerges from curved space-time. In contrast, its predecessors adopt the gravitational interaction (i.e., the gravitational field) posited independently from rigid and flat space-time:

> The EEP [Einstein's Equivalence Principle] arises from the idea that gravity is universal; it affects all particles (and indeed all forms of energy-momentum) in the

* Korea National University of Education, Graduate School, 250 Taeseongtabyeon-ro, Gangnae-myeon, Heungdeok-gu, Cheongju-si, Chungcheongbuk-do, South Korea. E-mail: newtleib@gmail.com

[1] Kuhn 1962, p. 150.

[2] Misner, Thorne, and Wheeler 1973, p. 5.

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same way. *This feature of universality led Einstein to propose that what we experience as gravity is a manifestation of the curvature of spacetime*. The idea is simply that something so universal as gravitation could be most easily described as *a fundamental feature of the background on which matter fields propagate, as opposed to as a conventional force.*[3]

This seems to suggest that Einstein's theory of gravitation can be viewed as revolutionary in terms of different understanding of the relationships between the gravitational field and the structure of space-time (i.e., between matter and space-time).

This essay criticizes this revolutionary claim and provides my own evolutionary account of the theory-change. The basic strategy of my argument is to employ the 'dynamical perspective of space-time structure' developed by Harvey Brown (2005), and Robert DiSalle (2006) in order to consider this case of theory-change. Contrary to a conventional wisdom that the structure of space-time explains dynamical laws, the dynamical perspective views that dynamical laws provide the physical foundations of space-time. This view, then, enables us to turn our attention away from the discontinuity between the structures of space-time in the Newton-Einstein theory-shift to the continuity of their dynamical laws. This essay would argue that although there are discontinuities in the conceptual change of space-time, the continuity in dynamical laws is much more important. From the dynamical perspective of space-time, we can see the essential role of dynamical laws that determine the structure of space-time. Accordingly, the continuity between flat and curved space-time theories can be identified within the principle of inertia which specifies inertial motions, i.e., by means of the law of inertia within Newtonian dynamics and the principle of equivalence within the general theory of relativity. Once the dynamical perspective of space-time is taken into consideration, my evolutionary view claims that inertial motions are the essential parts exhibiting high degree of continuity throughout the Newton-Einstein theory-change. Hence the theory-change is by no means based on "a reconstruction of field from new fundamentals, a reconstruction that changes some of the field's most elementary theoretical generalizations".[4] In other words, as Einstein himself pointed out, the theory-change is viewed as one which "slowly leads to a deeper conception of the laws of nature" based on results of "the best brains of successive generations".[5] For this reason, Einstein rarely employed the term "revolution" to characterize his theories of gravitation.[6]

Before engaging our case of the theory-change, the following section motivates the dynamical perspective of space-time by considering the failure of

[3] Carroll 2003, p. 151, my italics.

[4] Kuhn 1962, p. 85.

[5] Klein 1975, p. 113.

[6] Cohen 1985.

van Fraassen's argument on the multiple possibilities of specification of an inertial frame. The moral learnt from this section provides a wherewithal to explore, in the third section, the relationship between the Newtonian theory of gravitation and the Newton-Cartan theory of gravitation. These two alleged rival theories are chosen within our context, because the relationship between these two theories maintains the identical structure to the one between Newtonian and Einsteinian theories of gravitation in terms of the difference between the concepts of space-times. And the fourth section clarifies to what extent this theory-change is evolutionary.

2. Van Fraassen on the Multiple Possibilities of Specification of an Inertial Frame

In a section of his *Scientific Image*, van Fraassen provides a specific case study showing that Newtonian mechanics (construed realistically) has an infinite number of empirically equivalent, but logically incompatible rivals.[7] This claim is based on an interpretation of Newton's *Principia*. In the Scholium, Newton (1726) begins with distinctions between 'saved phenomena' and 'postulated reality' and between the 'apparent motions' and 'true motions' of a particular body. The apparent motions of a planet are relative motions that depend on the position of the observer. True motions, on the other hand, are those that can be uniquely defined in the Absolute Space that provides the framework for Newtonian mechanics. Van Fraassen (1980, 45) assumes that Newton takes Absolute Space to exist in a literal sense. Van Fraassen defines *TN* as Newtonian mechanics, and *TN*(v) as any theory that entails that the centre of mass of the solar system moves at constant velocity v with regard to Absolute Space. Because of Newton's famous 'hypothesis' – that the centre of mass of the solar system is at rest in Absolute Space – Newton's own dynamics can be identified as *TN*(0). But as Newton himself in effect pointed out, if *TN*(0) is empirically adequate, then we can construct an infinite number of *TN*(v_i)'s, which are also empirically equivalent to, but logically incompatible with, *TN*(0). Here it seems that there is a genuine underdetermination of theory, because there is no way of selecting the 'best' theory from this infinite set, as the one which can most justifiably claim to represent the real world.

Van Fraassen, as already mentioned, in effect assumes that Absolute Space can be understood as existing in a literal sense. Given this, absolute position and velocity also seem to be physically significant concepts. Although absolute velocity, which is the rate of change of absolute position, cannot be measured, it is a well-defined term in the kinematics of Newtonian dynamics. *TN*(0) and *TN*(v) thus represent different pictures of the world. The main line

[7] van Fraassen 1980, pp. 44-50.

of reasoning in van Fraassen's argument is that empirically equivalent but logically incompatible theories result from the realist's interpretation of space. Consequently, realists about space-time confront a major epistemological difficulty. Constructive empiricists, on the other hand, do not believe that we need to select one particular *TN*(v) as the realistic account of the world; all *TN*(v) are equally empirically adequate (with respect to all possible phenomena) and hence all are equally good from the constructive empiricist perspective.

Apparently, Newton himself thought that Absolute Space exists and absolute position is a physically significant concept. In *de Gravitatione*, he characterized the parts of space from our "exceptionally clear idea of extension".[8] According to this account, it seems that space is taken as having substantial existence analogous to that of a material body independent of matter in space. And concerning absolute position. Nevertheless, I believe that van Fraassen's argument stems from a careless interpretation of Newtonian theory that emphasizes a space-time as existing "over and above" the dynamical laws. Although Newton clearly thought that Absolute Space and position have physically significant meanings, and although we must admit a certain absoluteness to make sense of inertial trajectories of moving bodies, absolute position and velocity should in fact be discarded in Newtonian *dynamics*. Nor is this a retrospective, or *post hoc*, judgement – Newton himself recognized the problem of positing superfluous structure in Cartesian concept of space, and expressed his concern in *De Gravitatione*:

> [I]t is impossible to pick out the place in which a motion begins, for this place no longer exists after motion is completed, so the space passed over, having no beginning, can have no length; and hence, since velocity depends upon the distance passed over in a given time, it follows that a moving body can have no velocity, just as I wished to prove at first.[9]

This is because

> the whole space of the planetary heavens either rests (as is commonly believed) or moves uniformly in a straight line, and hence the communal centres of gravity of the planets are the same …[10]

Slowik suggests that Newton recognized the requirement to "equip space and time with the *necessary* structure to discern inertial motion",[11] and employed Absolute Space to complete this task. Nevertheless, the lack of sophisticated mathematical techniques made Newton posit a "stronger" space-time structure than was needed for the laws of motion.[12] Newtonian space-time pro-

[8] Hall and Hall 1962.
[9] *Ibidem*.
[10] *Ibidem*, p. 301.
[11] Slowik 2002, p. 38.
[12] *Ibidem*.

vides *superfluous* structures, i.e. absolute position and velocity to capture absolute motions such as acceleration. This redundancy is witnessed by the fact that a set of absolute positions is actually identified by the principle of Galilean relativity. In his Corollary V to the laws of motion in the *Principia*, Newton again expressed his concern about the relativity of motion: "When bodies are enclosed in a given space, their motions in relation to one another are the same *whether that space is at rest or whether it is moving uniformly straight forward* without any circular motion".[13] The Galilean principle states that physics is identical within any reference frame that moves in a uniform and rectilinear way with respect to Absolute Space. Thus we can see that Absolute Space, as Newton himself realized, has a physically superfluous structure, which is not supported by a dynamical principle. The multiple possibilities of inertial structure are best thought of as an equivalence class representing a single inertial structure. Given the principle of Galilean relativity, it is better to get rid of remnant structures. Neo-Newtonian (Galilean) space-time can be formulated without absolute position and velocity because they are excess structures, which have no physical significance.

Another way to look at this superfluous structure is from the perspective of the space-time and the dynamical symmetries of Newtonian theory. Within Newtonian dynamics, the Galilean group is the *dynamical symmetry* leaving Newton's equations invariant. On the other hand, the *space-time symmetry* that characterizes the invariant geometric structure is the group of Euclidean rotations and translations. This is a smaller group than the Galilean one.[14] Due to these ill-adjusted symmetries, Newtonian space-time has an excess structure that enables us to identify absolute position. Given the group of dynamical symmetries, which is larger than the group of space-time symmetries, absolute rest and absolute velocity cannot be distinguished by any empirical means. Within neo-Newtonian space-time, the space-time symmetry becomes the Galilean group by getting rid of absolute position. In this modification of Newtonian space-time, the group of space-time symmetries is identical to that of the dynamical symmetries.

The problem with van Fraassen's argument is, therefore, that it employs superfluous space-time structure, which is not supported by a law of motion. If the situation that van Fraassen cites is considered from the coordination between the laws of motion and space-time structure, it is easy to see that the empirically equivalent space-time theories he points to are not in fact genuine rivals. Given that the superfluous space-time structure, which is posited over and above dynamical laws, has neither empirical nor theoretical grounds, it is difficult to consider it as doing real work within Newtonian dynamics. Van Fraassen constructs an infinite number of empirically equivalent theories by

13 Newton 1729, p. 423.

14 Earman 1989, pp. 45-55.

attaching space-time structures that makes no physical contribution to the original theory *TN*. Absolute position is irrelevant to the dynamical laws of *TN*. Moreover, as Newton himself saw, it was recognizably irrelevant at the time and not merely in retrospect. If *A* is a remnant structure within *TN*, then it can be stripped away, not just without *empirical* loss, but without any *theoretical* loss whatsoever. Call the stripped down theory *TN* – *A*. This should be regarded as the real theory, because adding *A* back by conjoining it with *TN* – *A* to regain *TN*, adds nothing that really makes an assertion about the world. Hence, two apparently distinct theories, *TN*(0) and *TN*(v) cannot be viewed as genuine rival theories.

3. Earman on the Newtonian Theory vs. the Newton-Cartan Theory of Gravity

Earman seems to provide a more convincing case in support of the empirical equivalence thesis by providing two different formulations of classical theories of gravity. Earman considers two theories:

> *TN* (a theory with force and Euclidean space) [the Newtonian theory of gravity] is opposed by a theory [the Newton-Cartan theory of gravity] that eschews gravitational force in favour of a non-flat affine connection (a theory with non-Euclidean geometry, and without force) and which predicts exactly the same particle orbits as *TN* for gravitationally interacting particles.[15]

In the case of the Newtonian theory of gravity with neo-Newtonian space-time, its models are formulated by (1) the four-dimensional differentiable manifold, (2) the spatial metric, (3) the temporal metric, (4) the flat derivative operator associated with the connection on the differentiable manifold, (5) the gravitational potential, and (6) the Newtonian mass-density function. The first four geometrical objects represent the structure of neo-Newtonian space-time, and the other objects represent the contents that govern the dynamics. Within this space-time, the connection of curvature of which is vanishing, the inertial motion of a given body is represented by its geodesics. And over and above the space-time, the gravitational field is posited as a fundamental force which acts at a distance. The gravitational field is expressed as the negative gradient of the gravitational potential Φ. And Poisson's equation relates the gravitational potential Φ to the mass density function ρ. The equation of motion can be written as $md^2x_i/dt^2 = \times m\partial\Phi/\partial t$ ($i = 1,2,3$), which can be read as the mass *m* times acceleration equates to the gravitational force acting on the given body with mass *m*. From this formulation, non-inertial motion of a given body is described as a trajectory deviating from a geodesic. A notable characteristic of these space-time structures is their immutability in the sense

[15] Earman 1993, p. 31.

that they are posited independently of dynamical structure, i.e., of the gravitational potential and the mass-density function. In this way, the Newtonian theory of gravity can be described as the gravitational field which acts at a distance over and above a rigid space-time structure.

In contrast, the Newton-Cartan theory of gravity is a geometrized formulation of the Newtonian theory of gravity. Given the equivalence principle, by absorbing the gravitational potential into the connection, the gravitational interaction within this framework emerges from the curvature of space-time, rather than as a fundamental force. The physical motivation for "geometrizing away" Newtonian gravity stems from the conventionality of the choice of the affine connection and the gravitational potential. Friedman provides an example to show the motivation behind modifying the Newtonian theory of gravity (Friedman 1983, 95-6). Instead of a given gravitational potential Φ set in an inertial frame $[x_i]$ (of which the equation of motion is $md^2x_i/dt^2 = \times\, m\partial\Phi/\partial x$), we can set a new gravitational potential $\Psi = \Phi + x_j\, d^2b_j/dt^2$, which is measured in a different frame $[y_i]$ moving with the acceleration d^2b_i/dt^2 with respect to the original inertial frame $[x_i]$ ($i, j = 1,2,3$). As a result, a new equation of motion can be written as $md^2y_i/dt^2 = \times\, m\partial\Psi/\partial y = 0$, which has an extra gravitational potential $x_j\, d^2b_j/dt^2$ replacing the acceleration d^2b_i/dt^2.

These two gravitational potentials satisfy the same dynamical theory, and thus are empirically equivalent. On the basis of local conditions alone, we cannot single out which one is the true gravitational potential. The possibility of having different potentials suggests that the connection Γ^i_{jk} is also underdetermined. The alternative choice of the gravitational potential in terms of space-time geometry means that the flat connection, of which all components vanish, is now replaced by the non-flat connection with a non vanishing component $\Gamma^i_{00} = \Phi_{,i}$. The law of motion within geometrized framework is $d^2x_i/dt^2 + \Gamma^i_{jk}(dx_j/dt)(dx_k/dt) = 0$. In other words, since the geodesics in the non-flat connection now represent the free falling trajectories, the motions of a given body are due to the structure of curved space-time. In this way, the difference between the two frameworks seems to become manifest:

> In the geometrized formulation of the theory, gravitation is no longer conceived as a fundamental "force" in the world, but rather as a manifestation of spacetime curvature (just as in relativity theory). Rather than thinking of [gravitating] point particles as being deflected from their straight natural (i.e. geodesic) trajectories, one thinks of them as traversing geodesics in curved spacetime.[16]

Are these two theories genuine rivals? The main reason for thinking so is the different status given to the gravitational interaction within them. The gravitational interaction within the Newtonian theory of gravity is posited

[16] Malament 2007, p. 266.

as a fundamental force, which propagates independently of neo-Newtonian space-time. On the contrary, the gravitational interaction in the Newton-Cartan theory of gravity is related to the curvature of space-time. This difference seems to stem from the fact that the two theories are constructed from different ontological underpinnings. In spite of his reservation about characterizing the metaphysical properties of gravity, Newton seemed to hold that the independence of gravity and space-time is manifest. The force of gravity, without assigning a specific mechanism of gravity, is characterized as arising "from cause that penetrates the sun and planet without any diminution of power to act".[17] On the contrary, space-time is considered as the set of spatio-temporal relations between events: "it is only through their reciprocal order and position that the parts of duration and space are understood to be the very ones that they truly are".[18] Furthermore, space-time is not supposed to be influenced by matter. So, if the Newton-Cartan theory of gravity relates space-time structure with dynamics, together with the original theory it seems to provide a genuine example of two empirically equivalent but logically incompatible theoretical frameworks.

However, I would argue that Earman's reasoning in fact involves a trick similar to van Fraassen's. Earman also bases his case on superfluous space-time structure within Newtonian theory. As pointed out in Friedman's account, what differentiates the two theories of gravity is their different combination of the affine connection and the gravitational potential. In other words, the 'difference' of these space-time structures stems from a different division between the spatio-temporal structure and the dynamical structure. However, this division is by no means supported by a dynamical principle underlying gravitational interaction. According to the equivalence principle, a specific combination of the flat connection and the gravitational potential Φ within the Newtonian scheme is arbitrary. In other words, uniformly accelerating reference frames cannot be distinguished from the rest frame. Accordingly, the over-rigidity of spatio-temporal relations between events, which sets the components of the connection as vanishing, counts as superfluous structure. By incorporating the gravitational potential into the connection, this redundant space-time structure can be eliminated. Given that the element that makes the empirically equivalent rivals possible is superfluous structure of the Newtonian theory of gravity, it seems difficult to consider the two theories of gravity as genuine rivals.

However, couldn't it be argued that it is easy to demonstrate the continuity between the Newtonian theory and the Newton-Cartan theory of gravity if one in effect introduces ideas that belong to the later theory within the earlier one? However, this response is not tenable. For the judgement

[17] NEWTON 1726, p. 943. [18] HALL and HALL 1962, p. 103.

of what is "superfluous" within the former theory is not made by the latter theory since Newton explicitly recognized the above fact although he did not incorporate this consideration when he constructed his theory of gravity:

If bodies are moving in any way whatsoever with respect to one another and *are urged by equal accelerative forces along parallel lines*, they will all continue to move with respect to one another in the same way as they would if they were not acted on by those forces.[19]

And he also applied this idea to the case of the solar system:

It may be alleged that the sun and planets are impelled *by some other force equally and in the direction of parallel lines*; but such a force (by Cor. VI of the Laws of Motion) no change would happen in the situation of the planets to one another, nor any sensible effect follow…[20]

Accordingly, the Newton-Cartan theory of gravity modifies the previous space-time framework to eliminate superfluous structures that enable us to make a conventional choice of the gravitational potential and the connection.

These superfluous structures can be easily identified from the perspective of the coordination between the space-time symmetries and the dynamical symmetries. In the case of the Newton-Cartan theory of gravity, the group of both dynamical and space-time symmetries is the 'Maxwellian group', whose elements are invariant under transformations between rigid Euclidean, non-rotating, non-accelerating references. And in the case of the Newtonian theory of gravity, the group of space-time symmetry is the Galilean group, whereas the group of *dynamical symmetry* is *the Maxwellian group*. Although the space-time symmetries of both theories, which provide structures *sufficient* for the description of the bodies' motion, are distinct, we can see that the dynamical symmetries are identical. So, although the two examples in Earman's case are represented within apparently different ontological schemes (neo-Newton space-time vs. Newton-Cartan space-time), they are by no means genuine rivals if one considers the coordination between the structure of space-time and dynamical laws.

4. The Continuity between Flat Space-Time and Curved Space-Time Theories

It has been pointed out that the theory-change from flat space-time to curved space-time theories is by no means revolutionary. At this point, one can ask two related questions: Firstly, what misleads us to consider this case as an archetypal example of scientific revolution? Secondly, if this case does not ex-

[19] Newton 1726, p. 423, my italics.

[20] Newton 1729, p. 558, my italics.

hibit a radical discontinuity as the revolutionary account suggests, where can the essential continuity between these two theories be located?

An answer to the first question can be found in my discussion that the problems of both van Fraassen's and Earman's accounts stem from their use of superfluous structures of space-time, which are not supported by the laws of motion. They consider these theories as genuine rivals by emphasizing the theoretical elements of space-time, which are not properly coordinated with the laws of motion. So, they construct their arguments based on elements of space-time which have not empirical ground.

Another problem that is deeper than the aforementioned one stems from their premises that realists view space-time as an *independently existing entity*. From this premise, they consider the characteristics of theoretical entities as the foundation of the difference between the two alleged rival theories. When Earman claims that "[i]t ... makes good scientific sense to postulate this entity [space-time], because the explanation of various phenomena that are observable ... call for an absolute concept of motion",[21] his view is that space-time is supposed to exist as a substantival entity.

However, this ontological commitment to space-time is by no means tenable. As DiSalle (1995, 2006) points out, considering space-time as a substantival entity that explains the laws of motion is comparable to considering that Euclidean space exists as a substantival entity that explain geometric laws such as Pythagorean theorem. Yet, it is clear that the latter sounds absurd. Just as Euclidean geometric structure by no means causally explains its laws such as Pythagorean theorem, the geometric structure of space-time does not causally explain the behavior of bodies satisfying the laws of motion. Instead just as the axioms of Euclidean geometry encode "the constraints to which [geometric] measurement will conform," space-time geometry encodes the laws of the geometric behaviours of bodies.[22] So, space-time by no means makes sense of the behaviours of bodies. Rather the behaviours of bodies, which satisfy the laws of motion, make sense of the structure of space-time. With the faults of the premises interpreting the structure of space-time as having an existence independent of the behaviours of bodies satisfying the laws of motion, both arguments of van Fraassen and Earman mislead us to conclusions that their examples are genuine rivals.

What we can learn from these problems is that in order to comprehend the nature of the theory-change, we should turn our attention away from the structure of space-time to the dynamical laws of motion. This is because the latter are more fundamental than the former, as discussed. In case of the theory-change from flat to curved space-time theories, a dynamical law involved here stems from the equivalence principle. In consideration of the gravita-

[21] Earman 1989, p. 11. [22] DiSalle 1995, p. 324.

tional interactions inevitably involves the equivalence principle. This reflects the fact that a body's inertial mass is always the same as its gravitational mass. In the Newtonian theory of gravity, the identity of these two (apparently quite different) concepts is a mere coincidence. The former measures a body's resistance to acceleration, whereas the latter measures a body's susceptibility to gravity. Within the Newton-Cartan theory of gravity (or Einstein's general relativity), this connection is incorporated into a dynamical principle, which results in a new concept of *inertial motion*. So, the theory-change between two theories maintains an essential continuity in that both theories are founded on the laws of inertia, although the law is modified in curved space-time theories.

In more detail, the equivalence principle, according to Einstein (1916), stems from the fact that a given body should satisfy the same laws of motion whether this motion is considered locally with respect to a specific frame or to a frame uniformly accelerated by a homogeneous gravitational field. Hence, the true strength of the gravitational field cannot be identified simply by observing the motions in a frame of reference. In this way, the equivalence principle exhibits the close connection that exists between inertia and gravity. Einstein initially viewed the principle as extending the principle of relativity, which relativitizes the absolute acceleration of a system.[23] However, it has been pointed out that this role of the principle of equivalence is misleading.[24] This is because the distinction between accelerating and non-accelerating motion is manifest within curved space-time theories: the latter is represented by a geodesic line and the former is represented by a non-geodesic one. What Einstein in fact intended with this principle turned out to be the dual role of the metric tensor representing inertia and gravity.[25] According to Janssen,

> In its mature form, the equivalence principle says that inertial effects (i.e., the effects of acceleration) and gravitational effects are manifestations of one and the same structure, nowadays called the inertio-gravitational field. How some inertio-gravitational effect breaks down into an inertial component and a gravitational component is not unique but depends on the state of motion of the observer making the call, just as it depends on the state of motion of the observer how an electromagnetic field breaks down into an electric field and a magnetic field.[26]

Accordingly, the equivalence principle does not suggest a relativity of inertial and accelerating motions, but rather one of inertia and gravity.

The extended relativity of inertia and gravity then results in new concepts of inertial and accelerating motions. In order to see the way the concept of inertial motion becomes modified, we need to examine its counterpart within the framework of Newtonian mechanics. Within the Newtonian theory of

[23] Einstein 1952.
[24] Earman 1974, Norton 1985, Janssen 2005.
[25] Janssen 2005.
[26] Janssen 2005, p. 64.

gravity, the motion of a gravitationally accelerating body can be decomposed uniquely into two separate elements; (1) its inertial motion and (2) the acceleration with respect to inertial frames. The former is a natural tendency to be in a uniform and straight motion and the latter is a motion due to gravity. Within Newton-Cartan (or Einstein's) theory of gravitation, the equivalence principle states that the decomposition of motion into inertial and gravitating components is not unique. This results in a new concept of an inertial motion, which turns out to be the trajectory of a free-falling body in curved space-time. According to Penrose:

[In the Newtonian theory of gravity], an inertial motion was distinguished as the kind of motion that occurs when a particle is subject to a zero total external force. But with gravity we have a difficulty. Because of the principle of equivalence, there is no local way of telling whether a gravitational force is acting or whether what 'feels' like a gravitational force may just be the effect of an acceleration. Moreover, ... the gravitational force can be eliminated by simply falling freely with it. ... This was Einstein's profoundly novel view: regard the *inertial motions* as being those motions that particles take when the total of *non*-gravitational force acting upon them is zero, so they must be falling freely with the gravitational field.[27]

The equivalence principle selects gravitational free fall as the privileged state of motion, i.e., inertial motion.

The above account, then, turns our attention away from the structure of space-time to dynamical laws and principles in comprehending the theory-change from the Newtonian to the Einstein's theory of gravitation. Within both theoretical frameworks, dynamical laws and principles determine the structure of space-time in that these behaviors of bodies codify the spatio-temporal relations between events. Within Newtonian theory, these spatio-temporal relationships between events are represented by Newtonian space-time, which relates the inertial frames defined by the trajectories of bodies that are expressed in the laws of motion and the Galilean principle of relativity. Similarly, within the general theory of relativity, the spatio-temporal relations between events are represented as curved space-time constituting the patchwork of local inertial frames defined by the trajectories of free falling particles under the gravitational field. Given that free-fall trajectories are viewed as the geodesics in the general theory, the curvature of space-time encodes the information that the free-falling trajectories of two nearby particles exhibit relative acceleration. And this idea is clearly captured by Misner *et al.*:

[I]t was the whole point of Einstein that physics looks simple only when analyzed locally. To look at local physics, however, means to compare one geodesic of one test particle with geodesics of other test particles travelling (1) nearby with (2) nearly the

[27] Penrose 2004, pp. 393-4.

same directions and (3) nearly the same speeds. Then *one can 'look at the separations between these nearby test particles and from the second time-rate of change of these separations and the 'equation of geodesic deviation' … read out the curvature of spacetime'*.[28]

Accordingly, what curved space-time exhibits is the fact that the trajectories of two neighbouring free-falling bodies are encoded within the geometry of curved space-time, just as what flat space-time signifies is the fact that the motions of bodies are encoded within Euclidean geometry. So, when Misner *et al.*[29] famously wrote *"space acts on matter, telling it how to move,"* they were in fact summarizing the following essence of the general theory:

(1) [L]ocally, geodesics appear straight; (2) over more extended regions of space and time, geodesics originally receding from each other begin to approach at a rate governed by the curvature of space-time, and this effect of geometry on matter is what we mean today by that old word 'gravitation'.[30]

So, the structure of space-time in the general theory is determined by the behaviours of bodies just like its predecessors. Just as the geometries of Newtonian and Minkowski space-times encode information about the law of inertia that inertially moving particles move straight lines with constant velocity, the curvature of space-time of the general theory encodes the information that neighbouring inertially moving particles exhibit a relative acceleration.

In this way, the modification of the conceptions of inertial motion throughout the theory-change from the special theory to the general theory *underlies* the conceptual change of space-time. While inertial motions of bodies both within the special theory determine not only local but global inertial frames, a local inertial frame within the general theory cannot be extended into a single global inertial frame. Einstein's equivalence principle prohibits inertially moving observers from determining a global inertial frame. So, "physics looks simple only when analysed locally." This fact that the members of a set of locally inertial frames (that are determined by inertially moving bodies) are mutually disoriented (because of different distribution of the gravitational field) with respect to one another is characterized as the curvature of space-time.

This modification of the concept of inertial motion in accordance with the equivalence principle is an evolutionary process. This is because the modification is concerned with a change in the decomposition into inertial and gravitating motions, rather than a change of ontological commitment of the structure of space-time. In other words, what is essentially at stake in the two different formulations of classical theories of gravity is a difference concerning the way the motion of a gravitationally accelerating body can be decomposed into its inertial component and its gravitational one. Given that within

[28] Misner *et al.* 1973, p. 33, my italics.
[29] *Ibidem*, p. 5.
[30] *Ibidem*.

the two classical theories of gravity, these two motions are all represented by the relationships between events, there is no change in ontological commitment. The modification is instead concerned with the way the relationships between events, i.e., the world-lines of inertial observers and the world-lines of test particles subject to external force field, are differently comprehended by means of Einstein's novel understanding of gravitational interactions, which is involved in the equivalence principle. Given this additional feature of the gravitational field, the relationships between events within curved space-time theories are modified on top of its predecessor's characterization of the relationships between events. Hence, the theory-change from flat space-time to curved space-time theories is an essentially evolutionary process.

5. Answers to Possible Responses of a Revolutionary View

The defenders of a revolutionary view might claim that my thesis of continuity between Newtonian dynamics and Einstein's general relativity based on the central role of inertial motions could be challenged by its following conceptual changes; (1) within the general theory there is no separate law of inertia given that the concept of inertial motions under ordinary circumstances, as discussed in the previous section, can be derived from Einstein's field equations, whereas within Newtonian dynamics and the special theory inertial motion is posited independent from dynamical equations.

However, we can see that this response is not tenable if one considers where Einstein's field equations stem from. We have seen that Einstein's field equations stem from a Newtonian equation expressing the relative acceleration of neighbouring test particles. So, it is no surprise that Einstein's field equations contain the information of inertial motions of bodies. Given that Einstein's field equations can be viewed as a generalization of Newtonian equation, it is problematical to say that the notion of inertial motion in the general theory originates independently from its predecessors.

The advocates of an evolutionary view, who emphasize the central role of space-time, might claim that space-time geometry ensures a strong element of continuity in the Newton-Einstein theory-change. If gravitational field is weak and static, the velocities of a given body are small compared to the speed of light, Newtonian space-time can be recovered from a Riemannian manifold with variable curvature.[31] A flat Minkowskian space-time can also be recovered (locally) from the space-time of general relativity.

However, this continuity too is in fact difficult to capture unless one again focuses on the dynamical contents of space-time theories. We can see this in different tradition involved within the three theories. On the one hand, both

[31] Carroll 1997, p. 104.

Newtonian and Minkowskian space-time are developed in the tradition of Klein's Erlangen program, in which genuine geometric properties are characterized in terms of invariants under groups of transformations. The geometric properties that are not invariant under groups of relevant transformation are considered as conventional. Norton calls this tradition "Klein's subtractive strategy," which "over-describe[s] the space and then direct[s] which parts of the over-description should be accepted as geometrically real".[32] On the other hand, the general theory of relativity follows a different approach to geometry, that of "Riemann's additive strategy." According to this strategy, one begins with an impoverished description such as a bare manifold, and then adds further geometric entities such as a metric and an affine connection. Hence, trying to understand the continuities between the Newtonian theory and the Einsteinian theory of gravitation (the special and the general theory of relativity) space-time geometry by no means provides a complete picture. Yet, by emphasizing the dynamical contents in both theories, one can avoid this problem. While the mathematical structure ensures continuity across the theory-change, what is essential is the equations encapsulating geodesic motions, rather than space-time geometry.

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[32] Norton 1999, p. 130.

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Abstract · Einstein's Curved Space-Time and Scientific Revolution · *Both physicists and philosophers cite the theory-shift from flat to curved space-time formalism as revolutionary feature within Newton-Einstein theory-change. This essay argues against this that this conceptual change was 'evolutionary' and exhibits a high degree of continuity. The basic strategy of this essay is to employ the dynamical perspective of space-time developed by Harvey Brown, and Robert DiSalle, which selects the relationships between events – one specified by the laws of inertia at issue – as the essential elements within these two physical theoretical frameworks. This view turns our attention away from the structure of space-time to the dynamical laws, and also clarifies to what extent the theory-change is evolutionary.*

Keywords: *Motion, Curved Space-Time, Scientific Revolution, Dynamical Perspective of Space-Time.*